The Hunt for Efficiency in the Construction Industry – Food for Thought for Real Estate Developers

by

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Master of Science in Business Engineering, 2001

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Submitted to the Program in Real Estate Development in Conjunction with the Center for Real Estate in Partial Fulfillment of the Requirements for the Degree of Master of Science in Real Estate Development at the

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Submitted to the Program in Real Estate Development in Conjunction with the Center for Real Estate on January 12, 2018 in Partial Fulfillment of the Requirements for the Degree of Master of Science in Real Estate Development

ABSTRACT

For decades, construction productivity has been lagging behind the sectors of manufacturing, agriculture and many more, causing many problems to society. Importantly, productivity stagnation can generate housing crises by limiting the supply of additional structures, and prevents public authorities from developing their needed infrastructure. In this thesis, I assess the causes for such stagnation and provide a strategy to foster innovation.

My analysis finds that the causes of stagnation stem from a lack of competitiveness that arises from a scarcity of long-term relationships with clients, information asymmetry across stakeholders, poor owner and design specifications. Combined, these issues disincentive innovation, as tendering processes do not focus on suppliers’ productivity from efficiency gains or ingenuity in processes. In addition, built product size, complexity and uniqueness, as well as building codes inconsistency, all prevent the industrialization of the industry.

My strategy to improve productivity is multifold. The first prerequisite to improving the situation requires promotion of collaborative risk sharing delivery methods, adoption of digitized communication tools and supply chain management. A second prerequisite is a mindset switch towards built products configurability, upgradability and easy disassembly, which will minimize waste, unsustainability and brownfield project issues. Once those prerequisites are reached, then our short- and long-term goals for innovation could be realized.

Over the short term, transparency and true cost tendering will promote the industry with competitiveness and subsequent consolidation/integration that are necessary for productivity improvements. Over the long-term, the creation of a production-driven system will allow the industrialization of the industry, with standardization and repetitive manufacturing fostering continuous improvement. With such a rise of disruptive and innovative technologies, there will be a flow of at first efficiency gains and, potentially, in the long-run, productivity gains that meet the standards of the ever changing built environment.

Thesis Supervisor: Dr Andrea Marie Chegut
Title: Research Scientist, Center for Real Estate
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FOREWORD

“True mass production has won the respect of all people because it has been able to put into their hands the weapons by which their lives have been saved in war. Man now knows that mass production properly directed and properly disciplined will not only save lives but also set them free. The one outstanding fact of our time is that this can be done.

We no longer lack the means. It is now only a matter of directing our wills and our intelligence to the proper use of the mountains of materials and technologies at our disposal in order to solve the most pressing problems which concern the material welfare of mankind. (...)

Prefabrication in the truly industrialized sense is a very special approach to the problem of “house” – an approach made possible now, for the first time, when industry, research and material exist in the right relationship to one another, making possible an intelligent application of these resources to the needs of housing.”

Words of wisdom. The only shocking part is that Charles Eames, Entenza and Herbert Matter wrote their manifesto “What is a House” in the ... July 1944 (!) edition of Arts & Architecture. Today in 2017, more than 73 years later, housing mass production is still limited, and prefabrication accounts for a small margin of the construction industry. One may now wonder – what happened during all these years with innovation in the construction industry?
AN UNDERSTANDING OF FAMILY BEHAVIOR

drawn from any preconceived ideas and based on the most complete study of every facet of family life.

interpreted in terms of needs: spatial, chemical, psychological, social and environmental.

CORRELATED THROUGH
A LOGICAL APPROACH TO

ECONOMICS
AND ADAPTED TO
AN INDUSTRIALIZED SYSTEM OF MASS PRODUCTION

SUPPORTED BY AN INTELLIGENT PROGRAM FOR DISTRIBUTION TO

THE FAMILY

whose burden will be further lightened by

FINANCING to be rationalized to include all aspects and provision for automation in its application to mass housing and land use

SERVICING a definite part of the program, which would place maintenance in the hands of specialists.

A VOCABULARY OF MATERIALS & TECHNIQUES

drawn from all our experience as a nation organized for war production and from all related scientific development.

combined and applied in a way to best fill needs without compromise.
INTRODUCTION

The Construction Industry – Definition, Roles and Impacts

Construction is one of the first industries humankind developed, and since then it never stopped being essential for everyone, as it is fulfilling our basic physiological and safety needs that are described in Maslow’s Hierarchy of Needs. It is also critical to every human organization, as it is a vital determinant of where and how we live, work and play, and provides the context for all social interactions.

It is a true cornerstone of the world’s economy – not only by its colossal economic impact, but also because virtually all other businesses as well as public sector depend on the construction industry to develop and maintain their infrastructure. In this context, construction is a “horizontal” industry, serving all industry verticals (World Economic Forum, 2016).

Construction is also a complex system, composed partly of manufacturing (supplies and materials, components, equipment) and partly of services (engineering, design, surveying, consulting, and management). It involves thus the coordination of a very large number of different products and services and their transformation into a final product (Blayse and Manley, 2004), which shows construction in fact as an industry of industries, rather than a single industry - a meta-industry (Fernandez-Solis, 2007).

Construction has an impact on the environment. Of all industries, it is the largest global consumer of resources and raw materials. It consumes about 50% of global steel production and 40% to 50% of raw materials, representing some three billion tons per year (Roodman and Lenssen 1995, Anink et al. 1996). In particular, the building sector is a heavy consumer of materials with high-embodied energy content, such as cement and steel, whose production usually depends on the use of fossil fuels (United Nations Environment Program, 2007). In addition, all these heavy materials and components need to be transported to the construction site, with some materials (e.g. steel from China) sometimes requiring an intercontinental trip, which increases even more the release of carbon dioxide by the construction industry.
Construction matters: Construction-related spending accounts for 13 percent of global GDP

The construction sector is also one of the largest in the world economy, with about $10 trillion spent in 2016 on construction-related goods and services out of a global GDP of about $75 trillion or 13% of the global GDP (World Economic Forum, World Bank, 2016). These expenditures are projected to grow to $14 trillion by 2025. The sector typically provides 5% to 10% employment on a national level, and already employs about 112 million people globally (World Economic Forum, 2016).

In short, construction is profoundly important to society.

The Construction Industry - Efficiency

While technological advances have transformed and are transforming other industries like agriculture or manufacturing, the majority of construction companies operate much the same way as they did decades ago. Building practices appear to be rooted in tradition: they shy away from innovation and depend on cheap and unskilled human capital, showing the industry in a bad light to young professionals. On top of that, the construction companies usually rely on manual, disaggregated, and redundant processes for project planning and management (Orstavik 2015, KPMG 2016, LePatner 2007).

As a result, construction sector labor-productivity growth has suffered through the comparison to other industries. Global construction productivity has grown an average of 1 percent a year over the past two decades, which is significantly lower than the growth in the global economy (2.7 percent) and the manufacturing industry (3.6 percent), indicating clear underperformance by the construction industry (OECD, World Bank, McKinsey, 2017).
Globally, labor-productivity growth lags behind that of manufacturing and the total economy

Global productivity growth trends

![Graph showing productivity trends for construction, total economy, and manufacturing.](image)

<table>
<thead>
<tr>
<th>Year</th>
<th>Construction</th>
<th>Total Economy</th>
<th>Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>120</td>
<td>140</td>
<td>160</td>
</tr>
<tr>
<td>2010</td>
<td>180</td>
<td>200</td>
<td>220</td>
</tr>
</tbody>
</table>

*Based on a sample of 41 countries that generate 96% of global GDP.*

**SOURCE:** OECD; WIOD; GGCD-10; World Bank; BEA; BLS; national statistical agencies of Turkey, Malaysia, and Singapore; Rosstat; McKinsey Global Institute analysis

**Image 3:** Comparison of construction labor productivity with the ones of manufacturing and the global economy, McKinsey

In addition, such growth was flat and sometimes even negative in most advanced economies, which makes the comparison with other sectors even more striking as those advanced economies typically have high absolute productivity levels. This may be partly explained by the higher proportion of typically more complex brownfield projects compared to what is built in developing economies, as well as an increased focus on housing at the detriment of infrastructure. In the United States for instance, the sector's labor productivity is lower today than it was in 1968, whereas productivity in agriculture, manufacturing or retail have grown by 1600, 860 and 800 percent respectively since 1945 (McKinsey, 2017).

**In the United States, labor productivity in construction has declined since 1968, in contrast to rising productivity in other sectors**

Gross value added per hour worked, constant prices

![Graph showing productivity growth rates for various sectors.](image)

<table>
<thead>
<tr>
<th>Sector</th>
<th>1947-2010 Growth Rate</th>
<th>Total Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture</td>
<td>4.5%</td>
<td>16.1x</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>3.5%</td>
<td>8.6x</td>
</tr>
<tr>
<td>Wholesale and retail</td>
<td>3.4%</td>
<td>8.0x</td>
</tr>
<tr>
<td>Overall economy</td>
<td>1.9%</td>
<td>3.3x</td>
</tr>
<tr>
<td>Mining</td>
<td>0.5%</td>
<td>1.4x</td>
</tr>
<tr>
<td>Construction</td>
<td>0.1%</td>
<td>1.1x</td>
</tr>
</tbody>
</table>

Many sectors have transformed and achieved quantum leaps in productivity; construction has changed little, limiting productivity gains

Key advances, 1947–2010

**Image 4:** Comparison of US construction labor productivity with the ones of various industries, McKinsey
Besides those national and regional differences, such heterogeneity in the productivity growth is also observed across the industry. Large-scale players engaged in heavy construction tend to have much higher productivity than smaller players. Contractors involved in industrial infrastructure have, on average, the highest productivity at 124 percent of the whole construction industry, followed by civil construction players at 119 percent and large-scale housing contractors at 104 percent. On the other side, specialized trade subcontractors (such as mechanical, electrical and plumbing contractors) as well as small trade contractors (working on small projects such as single-family housing or refurbishment and repair) typically experience a productivity 20 percent lower than the sector average (McKinsey, 2017).

One of the main reasons for such discrepancy is that smaller-scale contractors have fewer resources to invest in research and development and deploy innovative tools and techniques. Another reason is the position of those contractors in the value chain. Large-scale contractors prefer to focus on the highest-value activities and choose to outsource to smaller-scale contractors only lower-value tasks. Last, smaller-scale contractors often are unable to gain advantage of scale benefits, as their projects are less standardized (higher differentiation of products, high share of manual and repair work, etc.).

**Consequences of this Productivity Lag on the Real Estate industry and Society**

The consequences of the above-described lag in productivity are very significant for the economy as a whole and societal well-being. First, the average price of construction projects has risen faster
than the consumer price index between 2008 and 2016 (McKinsey, 2017). Had the productivity growth been at par with the one of other sectors, it is estimated that it would have created value globally for an amount between $1.6 and 2.3 trillion (Blayse and Manley, 2004), which could have been distributed in lower rents and prices as well as higher wages for workers.

Second, construction costs are not only inflated by such lack of productivity – they are also notoriously tricky to forecast. Several studies observed enormous cost and time overruns on many construction projects. Recent analysis show average cost and time overruns relative to original budget and schedule of respectively 70 percent and 61 percent (McKinsey, 2017). Other studies demonstrated further that such variability was not spasmodic, but persistent and routine (Koskela and Vrijhoef, 2001). This means that construction costs net inflation effect is compounded by a high variability in project metrics – requiring a higher cost of return to take such risk into consideration.

Inflated construction costs and high variability team up with ever-increasing impact effects and inclusionary requests from public authorities, rarefaction of greenfield projects and higher price transparency for available properties to create a situation where profitable real estate development projects are getting scarce.

This increasing lack of profitability in the real estate development industry has in turn major societal consequences. It is no coincidence that a city notoriously eager to extract from developers and leading the country in terms of construction costs like Boston, is experiencing a housing crisis. Developed economies are expecting and already experiencing serious challenges to maintain and replace infrastructure.

Objectives

Now, one may wonder: how could this productivity lag happen? Take the US for instance - How could a nation as technologically advanced and business oriented let this situation last, whereas it spends upwards of $1 trillion on construction each year (LePatner, 2007)? And more importantly, what can be done to bring construction productivity back to the level other industries enjoy? This situation cannot last, for the costs have finally become too high.

The initial objective of this study was to approach this theme from a technology perspective. The idea was to analyze how innovation could improve the industry productivity, and to build a catalogue of existing and to-be-developed technologies that would help the industry to get back on track. Nevertheless, while investigating the root causes for the situation under scope, it became obvious that the issues construction is facing are not technology related. BIM, brick-laying robots, drones, 3D printers, virtual and augmented reality – disruptive technology already exist and are (almost) ready to go, but the current construction paradigms and the industry structure prevent the diffusion of such technologies. In this context, those issues – the core of so-called organizational innovation - are the primary theme of this study.
Contribution

Now, many academic papers have been published before on related topics, such as the absence of a proper production theory in the construction industry, or the reasons why production theories from the manufacturing industry are not applicable to construction, or developments of disruptive technology such as 3D printing or prefabrication. Likewise, very interesting professional publications have been recently issued, namely by McKinsey, KPMG and the World Economic Forum, to examine the productivity lag plaguing the industry.

Nevertheless, a number of those academic papers either get lost in overly theoretical debate, or focus on the development of one single technology. Furthermore, almost all of them focus on the “technology push” of innovation (i.e. innovation provided by industry supply), and do not consider potential “market pull” (i.e. innovation triggered by specific demand from industry clients).

On the other side, professional publications adopt rather a “full picture” approach by analyzing the industry as a whole. Unfortunately, they rather focus on fixing the industry as it is today, and only briefly consider a change in paradigm in production system. Also, they rather present a list of different issues rather than investigating interactions between those issues to separate root causes from consequences. For instance, some professional publications indicate that lack of digitization is a cause of low productivity. It is true, but lack of digitization is caused namely by the lack of skilled workforce able to use digital tools, and lack of innovation investment. Such low skilled workforce and general lack of investment in training, process and innovation is namely related to the industry fragmentation, which in turn is due to a lack of competitiveness in the industry, and the list goes on and on.

Those academic papers and professional publications share a common characteristic: they fail to provide a clear vision for the future of the industry. In this context, this thesis will first analyze issues currently plaguing the industry as the whole, but will focus as well on the interactions between those issues in order to isolate the root causes of construction inefficiency and provide provisory solutions for current projects. Second, this thesis will try and provide clear directions as to which characteristics a new production system should have to maximize its chances of success: this is all the more important as such new system may generate a structurally sound ecosystem that would solve de facto many of the current issues inherent to the current setup. This vision will also be approached from a “market pull” approach and will be complemented by a list of recommendations for clients or other interested parties to pressure industry supply into adhering to this strategy.

To develop my analysis, I employ the structure developed by Ozorhon, Abbott and Aouad (2014). In their work, they identify six components: innovation drivers, barriers to innovation, innovation enablers, innovation inputs, innovations, and innovation outputs.
Under this framework, the remainder of my thesis is outlined as follows. In Chapter 1, I examine the main causes explaining construction's lag in productivity (4). In Chapter 2, I analyze the drivers that may apply pressure on the industry to make things change (1/2). In Chapter 3, I examine various organizational innovations that could be used to transform the industry structure and develop a new paradigm to boost productivity in the sector (3/6). In Chapter 4, I analyze how each party may participate/encourage to the creation/development of this new paradigm, which a particular emphasis on the developer/owner (5).
CHAPTER 1: PRODUCTIVITY LAG - CAUSES AND CONSEQUENCES

However, to succeed in realizing innovations is difficult, first, because they lie outside of the routine tasks which everybody understands and secondly, because the environment resists in many ways that vary, according to social conditions, from simple refusal either to finance or to buy a new thing, to physical attack on the man who tries to produce it. (...) The resistance, which comes from interests threatened by an innovation in the productive process, is not likely to die out as long as the (...) order persists. It is, for instance, the great obstacle on the road toward mass production of cheap housing which presupposes radical mechanization and wholesale elimination of inefficient methods of work on the plot. (Schumpeter, 1943)

Since Charles Eames’ article, countless books and articles have tried and listed the main reasons underlying construction productivity stagnation. See for example one of the most recent and prominent reports by McKinsey Global Institute, called “Reinventing Construction: a Route to Higher Productivity”: such report lists a series of ten apparently unrelated root causes hampering current industry setup productivity and also suggests that a switch to a production-driven system would be more efficient than improving the current project-driven system.

We tested ten root causes for low construction productivity

<table>
<thead>
<tr>
<th>Root causes</th>
<th>External forces</th>
<th>Industry dynamics</th>
<th>Firm-level operational factors</th>
<th>Productivity impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing project and site complexities</td>
<td>Extensive regulation, land fragmentation, and the cyclical nature of public investment</td>
<td>Construction is opaque and highly fragmented</td>
<td>Design processes and investment are inadequate</td>
<td></td>
</tr>
<tr>
<td>Informality and potential for corruption distort the market</td>
<td>Poor project management and execution basics</td>
<td>Contractual structures and incentives are misaligned</td>
<td>Poor project management and execution basics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extensive regulation, land fragmentation, and the cyclical nature of public investment</td>
<td>Bespoke or suboptimal owner requirements</td>
<td>Insufficiently skilled labor at frontline and supervisory levels</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Informality and potential for corruption distort the market</td>
<td></td>
<td>Industry underinvests in digitization, innovation, and capital</td>
<td></td>
</tr>
</tbody>
</table>

SOURCE: McKinsey Global Institute analysis

Image 7: 10 root causes underlying construction inefficiency according to the McKinsey 2017 report

Nevertheless, those studies oftentimes do not investigate the relationships among those reasons - many of these are in fact consequences of others, and their effects compound. Likewise, analyzing such relationships may prove invaluable if one intends to leverage on those causes analysis to explore ways to improve the construction industry, as deconstruction is a scientific approach to changing the root causes of inefficiency. In this context, and in order to prepare for the suggestions analysis in chapter 3, we will examine not only the causes that have been evidenced in the past, but also their interactions with each other.
As shown in image 8 below, such analysis of causes and consequences will be carried out at different levels of the industry:

- Particularities of the built products (compared to other industries);
- Expectations and acts of/by customers and third parties;
- Construction processes;
- Current organization of the industry.

Image 8: Analysis of the causes underlying construction inefficiency at different levels of the industry (products, stakeholders, industry and processes)

The analysis of the causes and related consequences underlying construction productivity lag will be as follows. Subchapter 1.1 examines the root causes underlying productivity lag. Subchapter 1.2 focuses on the three main causes that prevents innovation from being diffused in the industry. Subchapter 1.3 and 1.4 documents the intermediary and main consequences for the industry efficiency.
Image 9: Analysis of the causes underlying construction inefficiency, showing hierarchy between root causes, main causes, intermediary consequences and main consequences.

Such analysis of the causes, consequences and relationships among themselves will prove valuable when examining the possible solutions to improve construction’s productivity and innovation diffusion.

Image 10: Analysis of the causes underlying construction inefficiency, overall figure showing all interactions between root causes, main causes, intermediary consequences and main consequences at all levels of the industry.
1.1. **Root Causes For the Lack of Productivity in the Industry**

This subchapter will examine the root causes underlying the three main causes for inefficiency in the construction industry as described in subchapter 1.2. Such root causes will be examined at the level of the industry's products, stakeholders and overall organization, as well as the interactions between such causes, particularly the interactions between root causes at the level of products and stakeholders on the one side, and root causes at the level of the industry on the other side.

![Diagram](image1.png)

**INTERESTED PARTIES**
- Public authorities
- Owners
- Designers

**BUILT PRODUCTS SPECIFICITIES**
- Products
  - Uniqueness
  - Complexity
  - Physical size
  - Immutability/Longevity
  - Societal impacts

**INDUSTRY**
- Demand unpredictability
- No-repeat-client culture
- Misaligned interests

Image 11: Analysis of the root causes underlying construction inefficiency's main causes at the level of construction's products, stakeholders and overall industry's structure

### 1.1.1. Built Product Specificities

Agriculture and manufacturing have experienced very sustained productivity growth but construction is lagging behind. One of the main reason is that the type of innovations and production theoretical concepts developed and used in manufacturing (i.e. standardization, mass production, production theories, etc.), that lead to such a productivity surge, cannot be directly transposed into the construction industry due to the following key differences arising from the built products specificities. These specificities create a construction environment that differs from the context often assumed for manufacturing innovation models (Slaughter, 1998).

#### 1.1.1.1. Uniqueness

The first construction products particularity is that it is very often bespoke: many designers create exotic shapes, textures and features to promote their client's image (whether it is at their client's request or not) or theirs. This over-personalization of the products effectively hampers standardization and mass production (although specific projects as hotels or prisons nowadays start considering modular constructions as their projects may be divided in standardized subparts as rooms or cells), as each project is unique.

In addition, built products have very diverse requirements and must adapt to very heterogeneous conditions, including geological, environmental and topographical complexities as well as various weather patterns. In this context, products design vary according to the peculiarities of their environment. Some places are earthquake-prone which generally require...
lightweight structures. Some other places are hurricane-prone which generally require heavyweight structure, and special ties to link various elements (roofs) together. Some other places are designed as flood-zones, some locations are fill-ins from the water, and the list goes on. On top of that, construction techniques may be influenced by the availability of natural resources and materials in the surroundings of the construction site: in the US, availability of wooden materials is an incentive for timber construction. Last but not least, construction regulations are very local and consequently heterogeneous across geographical areas. This lack of harmonization contributes as well to the heterogeneity of the built products.

1.1.1.2. Complexity

Construction is also extremely complex. First, construction is complex by nature. Construction and the buildings it produces integrate many systems interacting with each other and the environment. In this context, management of those systems requires multi-parametric optimization: a change in one system has impacts on other systems so it increases the variability of the overall productivity expected from an innovation in one single system. In this context, systemic changes produced by disruptive innovations may be probably more efficient, more attractive, and ironically less risky than non-disruptive innovations, as the impact of the latter on other systems will oftentimes act as a deterrent. In this context, the bar for innovation in the construction industry is set higher than in manufacturing where non-disruptive innovations may be managed more easily (Orstavik et al., 2015).

Secondly, in developed countries especially, the share of brownfield projects in (re)development keeps increasing. Consequently, the project does not start with a “blank sheet” as in manufacturing, but with an existing situation that needs to be coped with, from an environmental perspective for instance, or if a structure needs to be preserved. In urban environments especially, builders need to deal with constrained environments, sometimes-occupied sites, which complicates project management.

Real capital expenditure, renovation vs. new construction

<table>
<thead>
<tr>
<th></th>
<th>United States</th>
<th>Western Europe</th>
<th>Renovation</th>
<th>New construction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ billion</td>
<td>€ billion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential market</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>490</td>
<td>859</td>
<td>27</td>
<td>43</td>
</tr>
<tr>
<td>2015</td>
<td>417</td>
<td>608</td>
<td>35</td>
<td>60</td>
</tr>
<tr>
<td>100%</td>
<td>73</td>
<td>57</td>
<td>65</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>2015</td>
<td>2015</td>
<td>2015</td>
<td>2015</td>
</tr>
<tr>
<td>Non-residential market</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>239</td>
<td>514</td>
<td>33</td>
<td>41</td>
</tr>
<tr>
<td>2015</td>
<td>212</td>
<td>403</td>
<td>41</td>
<td>50</td>
</tr>
<tr>
<td>100%</td>
<td>67</td>
<td>59</td>
<td>59</td>
<td>59</td>
</tr>
</tbody>
</table>

NOTE: Numbers may not sum due to rounding.

SOURCE: IHS; McGraw Hill Construction; Euroconstruct; McKinsey Global Institute analysis

Image 12: Proportion of brownfield and greenfield projects in the US and Western Europe

25
Thirdly, many construction projects (especially infrastructure) have a size that is nothing to compare with products from the manufacturing industry. Mega projects in particular (budget superior to $1 billion) pose many coordination challenges from a project management perspective. Again, the increasing density in the location of the projects may have a compounding effect as well on such coordination challenges.

Overall, many academic studies confirmed that “high complexity negatively influences the extent to which firms and individuals can expect to succeed and experience significant economic gains from an innovation success. Indeed complexity creates uncertainty and makes stakeholders think twice more prone to stick with established methods and solutions in their work than they would have been if the level of complexity were lower” (Orstavik et all, 2015).

1.1.1.3. Physical size

The physical scale of the real estate products also triggers operational constraints. In case construction is not entirely performed on-site (which brings on its own other risks like weather) and part of the construction is prefabricated off-site in a factory environment, such scale may be problematic for the transportation of the components to the final site. Prefabrication and modular construction are not new concepts: they were tested many decades ago, but lack of profitability, due to transportation costs overwhelming productivity savings at the time, has limited their diffusion. A solution consists of decreasing the scale of prefabricated components, i.e. to switch from prefabricated modular construction to panelized construction, in order to facilitate those components’ transport.

1.1.1.4. Longevity / Immutability

As with what mentioned about brownfield projects, buildings last for decades and have a very long-term impact on their environment, which obliges to design the products not only within the original installation context in mind, but also taking into account potential future reuse over a very long time period, requiring strategies for repairing or modifying the products in the future if needed as structures must adapt to evolving demands.

Unfortunately, most of the time buildings are designed to be immutable. Neither volume nor main features are designed to be upgraded or modified (for instance, electricity lines and sewer pipes are often sunk in concrete which makes difficult any update) and as a consequence, many buildings reach their useful obsolescence way before their physical obsolescence. Some buildings sometimes cannot even be scrapped, either because the environment does not allow it (skyscrapers in a very dense environment like Manhattan), or because the building is of any historical significance and considered a landmark. As mentioned before, it makes construction more complex as it obliges the contractor to cope with an existing situation rather than to start with a blank sheet.
1.1.1.5. **Societal and Political Impacts**

The built environment has tremendous societal and political impacts on its environment. Because such impacts directly influence the safety, health, and well-being of the population, all portions of a product life cycle (design, construction, operation, and decommissioning) are regulated by stringent codes and regulations (McKinsey, 2017). Such abundant regulation has significant consequences for the sector productivity as detailed further.

1.1.2. **Interested Parties/Stakeholders**

1.1.2.1. **Public Authorities**

Construction (together with Real Estate) is one of the world’s most highly regulated sectors, and it has major impacts on its productivity.

![Image 13: Importance of regulation in construction compared to mining and agriculture](image)

First, this has an indirect impact on construction as it affects its demand: variances, permits and approvals are ranked among the most challenging forms of regulation to manage. In addition, land fragmentation often requires additional efforts from developers to assemble the land and cope with different zoning for different parts of the assemblage. Those lengthy and extensive review processes make it difficult for developers to assemble land quickly and build on a large scale, and, combined with the industry cyclicality, consequently limits the contractors' ability to accurately forecast demand.
Days to complete all permitting and approval procedures by country

<table>
<thead>
<tr>
<th>Country</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singapore</td>
<td>26 days</td>
</tr>
<tr>
<td>Australia</td>
<td>112 days</td>
</tr>
<tr>
<td>Cambodia</td>
<td>652 days</td>
</tr>
</tbody>
</table>

Median 150 days


Second, technology evolves much faster than regulation. In this context, many regulations, whether related to construction, land uses, or else, are outdated and no longer adapted to the current situation. In addition, this is aggravated by the fact those regulations were written at the time in a very inflexible and overly prescriptive way: they focus on the means to perform a project instead of results to be achieved, which would have made the situation less problematic. Consequently, regulation oftentimes block innovation, like the high-rise buildings that could technically be made in Cross-Laminated Timber, but are forbidden by current regulation.

Third, and a very critical point: there is absolutely no harmonization in the construction regulations from a geographical perspective. Zoning in particular is a very local regulation. This lack of harmonization contributes to the heterogeneity of the built products, and obviously hampers any tentative to try and develop standardization and mass production.

One final side comment is related to innovation incentives. Innovation has been a topic examined by many academia: some of their reports have produced very interesting insights. In particular, one of the conclusions that could be drawn collectively from reports by Hendry (1989), Audretsch (1995) and others is that for single firms (i.e. on the micro level), innovation is risky and very often unsuccessful. Some go as far as comparing investing in innovation to gambling or buying a lottery ticket (Orstavik et all, 2015). Interestingly, construction companies
are oftentimes blamed for their conservatism and lack of efforts to improve productivity, whereas it appears from those reports that their behavior is actually very rational: in many cases, innovation is so risky that it makes total economic sense to avoid investing in it on a micro level. The issue with construction is that this industry is too fragmented for it to work on a macro level either. Slaughter (1998, 2000), Orstavik (2015) and others have pointed out that innovation is a higher hanging fruit for firms in construction than in any other industry as modern construction is a “project-based, systems-producing enterprise depending on large and heterogeneous sets of project stakeholders.”

In this context, there may be a dichotomy between what stand-alone contractors interests tell them to do, and the well-being of all in the long term, as innovation is economically irrational on the short-term for contractors at the micro level, but rational and even necessary for the overall system and over time. If this theory is correct, it would mean that society advancement actually depends on individual contractors disregarding the normal calculations of risk and profitability to invest in innovations the return of which is uncertain. Conclusion is that the lack of proactive innovation incentives by public authorities to help solve this dichotomy and avoid this dead-end, may partly explain the lack of innovation within the construction industry.

1.1.2.2. Owners Preferences and Sophistication

One of the main differences between the construction industry and other industries such as manufacturing is that mass customization is rarely used in construction (it is slowly increasing for specific products like prisons or hotels). Owners (together with designers) tend to have a bias for developing unique specifications, which makes standardization and repeatability difficult.

Many owners also lack a large enough portfolio scale to allow them to be involved in frequent construction projects and develop sufficient experience in order to prevent information asymmetry and to allow them to have an informed opinion of the most efficient designs and construction techniques as well as their cost and quality. This lack of scale further prevents them for driving change in the market and spurring the development of more efficient construction methods. Those two effects are magnified by the fact that most owners view construction as a business enabler than a core driver of their business (KPMG, 2016) and maybe do not dedicate as much time to efficiency in the construction projects they commission, as they should.

Last, during procurement, owners rarely attach importance to innovation or processes. Most of the time, contracts are awarded to the lowest bidder without any regard on efficiency or variability, which is often a bad choice as high level and frequent occurrence of change orders show that contractor bids rarely reflect true cost.

1.1.2.3. Inadequate Design

Design professionals oftentimes are biased against standardization, either because they want to promote their brand and/or their clients' through originality of design, or because they believe
repeatable design is bland, generic, unappealing, and inefficient – therefore, they are inclined to offer bespoke solutions to every customer (McKinsey, 2017). Whereas some factors, such as land fragmentation and local code heterogeneity, indeed favor bespoke design, this also hampers standardization, mass production and productivity.

In addition, few contemporary architects have firsthand knowledge of actual construction methods and techniques – the days of architects as “master-builders”, supervising design and construction are long gone. Nowadays, many architects focus rather on design and push technical responsibilities and liabilities onto other parties, as evidenced in the forms recommended by the AIA (LePatner, 2007). This results sometimes in disputable constructability and incomplete drawings that inevitably lead to change orders, fueling the already conflictual relationships between owners and contractors (LePatner, 2007; McKinsey, 2017).

Last, the constant evolution of building technology and increasing complication of the final products lead to frequent misunderstanding between architects and owners as the latter may be unable to visualize or sufficiently understand the implication of different designs before construction starts. Again, some owners lack the scale to develop sufficient expertise in order to allow them to have an informed opinion on whether a design fits their needs (McKinsey, 2017).

1.1.3. Industry

1.1.3.1. Information Asymmetry between Owners and Contractors

As discussed in section 1.2.2. (Owners preferences and sophistication), many owners lack sufficient expertise in construction to make informed decision about which design to accept or which contractor to hire, either by lack of scale or by lack of interest (most of them are active in another industry but need real estate to function as construction is a horizontal industry). Consequently, many owners focus on cost when hiring contractors instead of relevance of the proposed construction processes and/or completeness of the contractors’ offers.

It is worth noting as well that the current structure of the construction industry makes it extremely difficult to grasp. Although many products from the manufacturing industry are informationally efficient enough to allow the consumers to make an informed choice, many construction processes have craftsmanship features and are tacit by nature. The fact that this lack of theoretical basis, documentation, and adequate planning, appear in several parts of projects makes it almost impossible even for a well-informed owner, to make decisions on complete information (Orstavik et all, 2015). Some other informationally inefficient industries solved this problem by regulation (finance, legal counselling) or intermediaries, but sadly it did not happen in the construction industry, as architects’ lack of involvement in the construction process do not allow them to act as intermediaries to protect owners’ interests.
1.1.3.2. **Misaligned Interests**

Within the construction industry, typical contractual structures (lump sum, Guaranteed Maximum Price, etc.) usually outsource/push risk down the chain instead of sharing risk among all parties, partly due to the nature of the construction process and the industry fragmentation (division of projects into discrete packages that are purchased sequentially). In this context, contractors and subcontractors end up bearing all or most of the risk in a project from a theoretical perspective (unless they manage to use information inefficiency at their advantage to push risk back to owners through change orders as detailed further). This has two main consequences on productivity and innovation.

First, contractors and subcontractors may react by developing risk aversion to protect themselves from this risk unbalance. As they bear all theoretical construction risk, they have an incentive to search for the safest solution instead of the most efficient one, and to favor conservative, well-tested construction methods while more efficient but unproven, riskier innovations (techniques and materials) may exist.

Second, this risk unbalance creates misaligned interests between owners and contractors (and among contractors as well): owners desire no risk as well as the lowest cost and the shortest schedule possible, whereas contractors need to deal with all risks and desire to maximize their profit. Such tension hampers productive and trusted cross-organizational cooperation, which complicates the progress toward a common goal of higher productivity. A recent construction survey indicated that contractors and suppliers identified misaligned contracts as the most important root cause of low productivity, whereas owners rather focused on other causes (McKinsey, 2017), which may show there is a generalized misunderstanding between contractors and owners about how to improve productivity in the industry.

1.1.3.3. **Non-Repeat-Client Culture**

In addition, construction has no culture of “repeat client” or “client loyalty” like car industry has, as most owners lack scale, build very infrequently and usually re-hire contractors on the lowest bid in any way, whereas contractors could as well mitigate bad reputation from the past by simply reforming under another name (which they seem to do, as firm turnover is twice the national average - LePatner, 2007).

This culture has two consequences: first, it does not incentivize contractors to restrain themselves from trying to increase their margins by using change orders, which as a direct impact on productivity. Second, it is the main reason why construction is so vertically fragmented, which hampers communication, coordination, and diffusion of innovations or standardized processes.

1.1.3.4. **One-off Alliances**

Such no-repeat-client culture as well as the traditionally sequential tendering process have a consequence on the organizational structure of the industry: those projects form an almost-
always-temporary alliance among independent organizations whereas supply chain is usually more permanent in the manufacturing industry. Such fragmentation hence hampers diffusion of innovations within the industry and affect trans-organizational cooperation and coordination. As a result, construction is entirely a project-based industry, whereas manufacturing and other industries are rather production-based.

1.1.3.5. **Unpredictability of Demand**

Construction demand is also somewhat difficult to forecast for individual contractors. As Real Estate is a horizontal industry itself, construction is dependent on business cycles and as such may be very cyclical. In addition, the “no-repeat client” culture makes it difficult to create a reliable pipeline. Last, the permitting process can be lengthy and erratic, holding back projects for years sometimes.

This lack of demand predictability has consequences on innovation as a shift to productivity-based competition is only possible if “(...) contractors can build the scale (and repeatability) needed to drive cost efficiencies from productivity gains that outweigh revenue losses from lower price points and fewer customer claims, and provide payback on up-front and ongoing investments in technology or skill building. Many contractors are reluctant to take the risk of investing in large off-site manufacturing facilities without the assurance of a solid pipeline of sufficient volume of repeatable future work” (Orstavik et al., 2015).

In addition, lack of demand predictability limits the contractors' ability to standardize and modularize construction designs (McKinsey, 2017), and hampers retention and training of skilled workforce.

1.2. **Main Causes for the Lack of Productivity in the Industry**

This subchapter will examine the main causes underlying construction’s poor productivity at the level of the industry’s structure and processes, as well as the interactions between root causes described in subchapter 1.1, and those main causes.
1.2.1. Poor Processes

As already mentioned, the manufacturing industry, along with other industries, has enjoyed decades of steady productivity increases, mainly due to changes in templates of production. Such changes have been made possible by academia and big players’ R&D departments’ substantial efforts to create and develop proper formal production theories: manufacturing has a “record of successfully developing and using robust mathematical models to improve productivity, system comprehension and event forecasting” (Antunes and Gonzalez, 2015; Hopp and Spearman, 1996; Kumar and Suresh, 2009). Those theories have been developed partly thanks to standardization and mass production: routine-based repetitive production can be perfected over time through task specialization, repetition and learning, which allows for a reduction of complexity that makes such complexity more manageable. Unfortunately, no such formal theories have been developed in the construction industry, and the production concepts and theories that have been developed by the manufacturing industry cannot be translated directly into construction for the following reasons:

- **Lack of standardization**: most construction projects are designed to be unique. In addition, the industry is highly fragmented: horizontally as most of the construction output being produced by small-players, and vertically as projects are contractually structured as one-off alliances between owners, contractors and manufacturers. Those facts prevent standardization and mass production: to keep the comparison with manufacturing, construction projects are rather similar to, and never reach the stage beyond, prototypes. Consequently, construction lacks the long-term cross-project task repetitiveness that would be required for continual improvement concepts: complexity and risk hence cannot be reduced and managed.

- **Informality**: construction is a very informal industry – it is still much embedded in craftsmanship and is focused rather on the “know-how” rather than on the “know-why”. Without explicit theories, it is impossible to access concepts and methods of other templates and re-create them in construction (Koskela and Vrijhoef, 2001).

- **On-site production**: construction involves a number of unique challenges related to the fact that at least some of its processes need to be performed on-site, due to the physical size and nature of the built products. As construction takes place in a range of climates and geographies, those sites are exposed to unpredictable and heterogeneous weather conditions, resources, accessibility and space, whereas many other industries can manage their production processes in a standardized factory environment with stable access to workforce and raw materials.

This mix of anachronism and inertia has dear consequences for the industry. First, informality deprives construction from the benefits from efficient manufacturing production theories, such as general concepts of transformation, flow and value that would be integrated in sound formal production theories – current processes, involving the division of project in sequential tasks, are almost only related to de facto transformations, whereas flows and especially values, are overlooked. This explains many present shortcomings of the industry, such as excessive
consumption of raw material (value), disconnection of activities (flow), frequent delays compared to schedule (flow) and high levels of rework due to production errors (flow and value).

Second, it creates planning and project management issues. Current construction management practice is undermined by the informality embedded in the industry. Such informality precludes the “appropriate level of ability to handle the uncertainty and complexity involved in construction projects. This results in project failures in terms of finishing projects within deadlines and budgets” (Antunes and Gonzalez, 2015). In essence, the dynamics of the production system are overlooked: informality renders plans inefficient and inapplicable, and forces management to focus on dealing with the consequences of deviation from such plans rather than anticipating and tackling the causes of such deviations. This gap between plan and execution creates a constant crisis atmosphere caused by myopic control – management is too much bottom up, and not top down enough.

Third, lack of standardization prevents the development of a routine-based repetitive production that could be perfected over time through task specialization, repetition and learning. Together with heterogeneous on-site construction environment, it also precludes the creation of performance tracking which would allow for process continuous improvement. As a consequence no lesson can be carried forward from project to project, as opposed to manufacturing where operations are continuously tracked and large quantities of data are tracked and analyzed, allowing for a quick remedy if something wrong is detected.

1.2.2. Fragmentation

Construction is notoriously fragmentized. This is one of the major factors hampering innovation and productivity. As they have different causes and consequences, we examine construction horizontal fragmentation separately from the vertical one.

1.2.2.1. Horizontal Fragmentation

Horizontal fragmentation arose and grew in the construction industry (and conversely, construction never managed to consolidate as much as other industries) due to different factors:

- As a general rule, barriers to entry are very low in the construction industry, which allows for plenty of new entrants;
- The industry culture, based on craftsmanship, and lack of theoretical foundations prevent development of standardization and mass production;
- The nature of the industry provides for a very heterogeneous context: products requirements differ widely based on sociologic preferences and environmental constraints, there is a lack of geographic harmonization in construction regulations, and materials' availability depends on the project location (or else has impacts on construction costs under the form of materials transportation costs). Such heterogeneity makes scale economies difficult and minimizes the potential benefits of consolidation;
- Construction demand is also somewhat difficult to forecast for individual contractors. Many contractors are reluctant to take the risk of investing in large off-site
manufacturing facilities without the assurance of a solid pipeline of sufficient volume of repeatable future work” (Orstavik et all, 2015).

- The use of “mutable cost contract” distorts competition and allows potentially inefficient small contractors to win tenders as they bid under their cost, i.e. non-competitiveness of the industry prevent big players from winning contracts on the basis of their true performance, whether based on scale economies or efficiency;

- Competition distortion left aside, the fact that many owners select contractors on the lowest cost basis, favors specialized contractors that limit their bids to products they know very well, at the detriment of generalized larger-scale contractors;

- Even if those generalized larger-scale contractors win tenders, they tend then to outsource themselves parts of the projects to smaller subcontractors in anyway. Indeed, current contractual structures allow general contractors to use outsourcing in order to parcel risk away among different subcontractors. Such risk distribution is enhanced by the use of liens that allow the ultimate risk to be borne by owners in case of non-payment of subcontractors by general contractors.

Such horizontal fragmentation has, in turn, many consequences on innovation and productivity, all centered around the same statement: if construction innovation lags behind, it is mainly not because of technical issues, lack of idea generation or creativity capabilities, but partly because the industry is unable to effectively adopt and utilize even existing innovations.

First, the fact that construction companies have typically very thin and volatile margins (within the bottom quartile across industries - McKinsey, 2017) is aggravated by the small average size of industry players. The smaller and the less profitable and sophisticated the firm, the less likely it has resources to invest in R&D or even look for innovations developed elsewhere and adopt them, and the less likely the scale to make such innovation profitable. Recent studies have demonstrated that construction mid-size companies (with annual turnover between $ 1 and 5 billion) statistically rank among the most cutting-edge ones: they have more resources and more scale than smaller companies, and are more flexible than bigger companies (KPMG, 2016). Unfortunately, they are not plenty in the construction industry.
Second, fragmentation makes inter-sectorial and cross-sectorial communication and coordination difficult (especially with parties with potentially conflicting interests), which leads to additional costs and delays, as well as restricts the potential for intra- and inter-project knowledge transfer, limiting the reach of innovation across the industry. In particular, the lack of industry leadership caused by fragmentation complicates the working relationship with academia, compared to other industries where top universities' research departments cooperate hand-in-hand with big players to test and put their findings into production.

1.2.2.2. Vertical Fragmentation

Innovation in the industry also suffers from the fragmented nature of its supply chain (we are talking here about relationships between contractors and manufacturers, not between contractors and subcontractors). Such fragmentation has been caused by the following factors:

- As many owners build infrequently and lack portfolio scale, the resulting “no-repeat client” culture results in projects being treated as one-off supplier-client alliances;
- Industry practice in terms of contracting methods, i.e. division of tasks into sequential packages that are then tendered, is by nature antithetical to supply chain integration, and cause the couplings between firms to be actually determined by owners rather than by intra-sectorial strategic considerations;
- Tendering and contracting processes focus generally on cost rather than keeping on board previous alliances that worked well. The non-competitiveness of the industry
leads to almost random selection of contractors, which explains the instability of the supply chain;

Such vertical fragmentation has several consequences for productivity and innovation within the industry. First, fragmentation causes construction planning to be inefficient. Contractors are rarely consulted during planning phase and those contractors, in turn, have very limited contacts with their raw materials and components suppliers as most of the time, they select such suppliers on a project-to-project basis. The resulting disconnection between all the members of the supply chain leads to poor planning and constructability of designs. Second, lack of communication and coordination between unrelated parties, each with their own vested interest, creates project management issues that cause budget overruns and delays. Third, as each project is usually treated as a unique event, learning outcomes from such event are rarely carried forward within organizations in terms of techniques, procedures or strategic relationships. Finally, even if some learning outcomes were, opacity created by fragmentation would prevent the diffusion of such learning outcomes within the industry.

1.2.3. Non-Competitiveness and Lack of Incentive to Invest

Many owners believe that their tender process (usually 7 competitors) allows them to obtain the lowest cost and best quality possible, as competition will oblige contractors to provide them with their best terms. The problem is that sometimes, the dice are loaded.

1.2.3.1. Cost Perspective

Competition among contractors lead to unwanted consequences for the owners – the emergence of a bidding strategy that all but works at their advantage. Industry practice now encourages the use by contractors of a two-fold strategy to win tenders. First, contractors have long realized that owners often lack the expertise and interest to truly investigate their offers and focus only on price. In this context, and keeping in mind the second part of the strategy, they strategically bid at a loss to win the contract, and effectively gain control on the project.

Second, once they won the contract and construction has started, they switch their mentality from a highly competitive supplier into a monopolist one – they have almost total control on the project costs, schedules and the way it is run. It is too late for the owner to realize that the price mentioned in the offer is not the true cost. Some practitioners call this a “mutable cost contract” (LePatner, 2007). Contractors can now simply use their contractual position and superior informational advantage to escape the confines of the original price. Sadly (for the owners), disputable constructability in the design and evolving owner requirements (not even to mention the crazy situation when contractors are asked to bid on incomplete drawings) give them plenty of opportunities to use change orders to realize the profit they desire: such change orders are competition free as they have already been awarded the job.

What can owners do at this point? Not much – they often have no good option for recourse when faced with spiraling costs and delays (Orstavik et all, 2015). Delays can be very costful to owners, especially in commercial real estate. As contractors may hold them hostage and stop
the project, they oftentimes have an economic incentive to accept whatever cost increase proposed by the contractor instead of risking a delay in the project. Such power unbalance lead some contractors to make owners pay even for their own mistakes. In an era when economic power has shifted from suppliers to consumers in many other industries (Orstavik et all, 2015), construction is only competitive by appearance; actually, it is a very monopolistic one.

This situation is aggravated by three factors. First, as discussed in Section 3 of the Root causes, owners often choose contractual structures that push risk down onto contractors, instead of sharing risk (and remuneration) among parties. This kind of contracts structure is conflictual, and contractors usually win. Second, construction has no culture of “repeat client” like the car industry has. Third, fact is many contractors have been very successful with this current not-very-demanding strategy and would probably lose from a move to a more efficient system that would require a lot of effort and investment. Manseau and Seaden (2001) note in this context that “a suspicion has lingered that the industry is in the grips of particular stakeholder interests that uphold the status quo at the expense of the industry as a whole and of society. It would seem, therefore, that significant challenges remain in terms of industrial organization and innovation.”

1.2.3.2. Quality Perspective

As previously mentioned, many owners tend to focus on cost when hiring contractors, which sometimes is detrimental to quality or efficiency of the proposed construction processes: contractors try to propose the lowest bid possible and are tempted to leave quality aside as they are not competing on quality in any way. And if they did, substantial asymmetrical information may encourage contractors to still produce sublevel quality as demonstrated by the theory of “Market for lemons” (Akerlof, 1970). Originally applied to the market for second-hand cars, it assumes that rationally risk-adverse owners will conservatively value construction products or services on which they have very limited information to take into account the risk those products or services may be of suboptimal quality. In turn, contractors would have no rational economic incentive to provide superior quality in construction, as such quality will not be reflected in pricing. Extending this “self-fulfilling prophecy”-like logic, the lemon market logic represents an economic disincentive also for any quality-related innovation in construction.

Non-repeat client culture, information asymmetry and non-competitiveness of the industry do not incentivize contractors to improve productivity, as they typically can compensate budget shortcomings with change orders, whether they are justified or not: the cost related to the lack of productivity within the construction industry is most of the times borne by the owners and indirectly the end users, not by the contractors. As already mentioned, many contractors have been successful with the current situation so far and may probably lose from a move to a more efficient system that would require a lot of effort and investment. This contrasts with information-efficient industries where customers are in the position to make an informed choice, which promotes competition and triggers innovation.
1.3. **Intermediary Consequences**

1.3.1. Insufficiently Skilled Labor

Construction employs a majority of low- to medium-skilled workers. This may be explained by a number of reasons. First, current construction processes are obsolete compared to other industries. Second, cyclicality of demand (especially for large infrastructure projects) makes it difficult to keep a stabilized level of employment within firms, which does not allow time and does not incentivize those firms to invest to train very mobile workers. Third, construction is highly fragmented and is mainly composed of a number of small-players that have limited resources to invest in training. Finally, lack of competitiveness also plays a role: as contractors may bid at a loss and compensate such loss through change orders, there is not much incentive for them to increase productivity.

Aside their level of skills, construction workers are getting scarcer and scarcer, and consequently aging. This may be explained by changes in sociologic expectations – young people nowadays prefer to study and to work in more innovative and less physically demanding environments.

![Image 17: Average age of US construction workers](image)

This situation has an adverse impact on the firms' capacity to integrate innovation. Many construction workers lack the skills to quickly adapt to disruptive sophisticated innovations, especially the ones demanding digital skills. This is even more critical for older workers as they are less likely to be receptive the training necessary to implement new technology.

1.3.2. Underinvestment in Digitization

Construction is among the least digitized industry: for instance, only 20 percent have a single, fully integrated project management information system (KPMG, 2016). Such lack of digitization is due to the same causes underlying workforce's insufficient skillset: cyclicality of demand and fragmentation hamper investment in digitized tools, whereas non-competitiveness do not incentivize firms to even make the effort. On top of that, digitization potential disruption to a low-to mid-skilled workforce makes the situation even more complicated: “technology means nothing if you don’t have the right people with the right skills and background running the project” (KPMG, 2016).

In addition, many construction firms that are trying to digitize their operations often use the wrong strategies. For instance they rarely invest in a synchronized fully integrated system, spanning across project planning, design, construction, operations, and maintenance: automatized systems are paired with manual systems that end up being bottlenecks, and self-developed bespoke systems are
often preferred to standardized solutions, complicating exchange of information with other stakeholders. This lack of procurement discernment is compounded with weak implementation: without a proper overall IT strategy, these systems are often configured and installed poorly, simply replacing the former systems, preventing the firm from obtaining the best from those new tools. Last but not least, many respondents to a study (KPMG, 2016) admit that they lack the expertise and resources to make an optimal use of the data generated by their own systems in any way.

This lack of digitization has three consequences on the industry productivity. First, construction firms deprive themselves from digital tools that would improve and facilitate communications with stakeholders, whether owners and architects or manufacturers and subcontractors. Second, tools available to the frontline labor force would also improve operational efficiency within the firms, such as planning, stock management, task repartition, task reporting, issue reporting and transport – studies have shown that there is a robust correlation between the level of digitization in an industry and its productivity growth (KPMG, 2016). Third, lack of digitization hampers the adoption of disruptive technologies that require a digital connection. For instance, automation, 3D printing, drones, augmented and virtual reality all require digital data to function.

1.3.3. Opacity

Opacity is the last of our intermediary consequences, before we tackle the final impacts on the industry productivity. Based on our analysis of all those causes, it appears clearly that the lack of construction innovation is not due to a lack of idea generation and creativity capabilities: a lot of innovations, from BIM to automation, 3D printing, drones, VR, AR, already exist. The problem lies rather in the adoption and diffusion of those existing innovations, and in this context opacity plays a huge role in preventing innovation diffusion. Many factors contribute to this opacity:

- The industry has a very craftsmanship culture. In the absence of any elaborated and sound theoretical background, many processes are very informal by nature. In addition, many workers may view innovation as a threat to their job security as it jeopardizes the value of their experience, hence undermining the adoption of new technology.
- Many projects are designed (at the initiative of the owner, the designer, or both) to be unique. In this context, technology, processes and learning outcomes from those projects are often thought to be inappropriate for other projects, which is not necessarily the case. In this context, different solutions to similar client requirements may be developed time after time, which undermines productivity.
- Most projects are managed via short-term one-off alliances of disparate suppliers, without any long term supplier-customer strategy. In addition, division of projects into sequential packages and industry fragmentation do not facilitate communication and cooperation within the industry.
- Industry under-digitization prevents standardization of design, constructability and planning, which may favor innovation diffusion through industry-wide comparison of different processes and techniques.
This opacity limits knowledge transfer and innovation diffusion within the industry. Informality and project uniqueness restrains firms from learning from their own projects and prevents the development of an organizational memory (Dubois and Gadde, 2002). This is no better outside the firm: fragmentation, under-digitization and lack of long-term supplier relationships limit knowledge transfer and innovation diffusion between firms or with academia.

Besides innovation diffusion, it also impacts the competitiveness of the industry. This opacity restricts for construction the informational efficiency that allows other industries’ consumers to make informed choices. In particular, it prevents the development of reliable benchmarking data about construction cost and contractor efficiency, which prevents owners to shop around.

1.4. **Main Consequences**

1.4.1. **Inadequate Project Management**

In the case Blake Construction Co vs JC Coakley Co (1981), Associate Judge Kern likened the construction site to a battlefield: “except in the middle of a battlefield, nowhere must men coordinate the movement of other men and all materials in the midst of such chaos and with such limited certainty of present facts and future occurrences as in a huge construction project.”

Indeed, the inherent complexity of the built products is maximized by the fact most of construction tasks are performed on-site, with very heterogeneous weather conditions, resources, accessibility and space, whereas many other industries can manage their production processes in a standardized factory environment with stable access to workforce and raw materials.

In such a difficult environment, many of the causes previously detailed explain the typically deficient project management that characterizes the construction industry. Inherent informality of the construction processes and lack of digitization complicates task reporting and on-site communication within a firm. Fragmentation and opacity also hampers cross-organizational coordination and cooperation, as construction projects often require the temporary alliance of many subcontractors from different industry sub sectors: the moving parts can seem nearly countless.

As a result, lack of collaborative front-end planning, poor transition from planning to construction, as well as inefficient task scheduling, reporting and coordination, ultimately cause weak project management, which in turn create the ground for mistakes, task re-performance and ultimately a high level of change orders, which explains the industry low productivity.

1.4.2. **Underinvestment in Innovation**

Final consequence is the industry generalized underinvestment in technology and innovation. This is evidenced namely by government reports showing poor rates of investment in R&D as well as a lack of co-ordination between academia and industry in research activities (Dulaimi et all, 2002).
Poor rates of investment in R&D may be explained by the fact construction R&D requires a particularly substantial front-end investment that may be only recouped by long-term volume: uniqueness of most projects, temporary supplier alliance, industry fragmentation and opacity jeopardize firms' ability to achieve a volume high enough to make many innovations economically desirable, not to mention the notorious low profit margin prevent construction firms from having a bit of leeway to invest in new technologies.

Lack of coordination between academia and industry is due to fragmentation, as it is a bit easier to communicate and coordinate with a few big-players than a myriad of small firms, and opacity, limiting the diffusion potential of any academic-developed innovation. The lack of standardization and informality of current construction processes makes it difficult as well for academic-developed technology to be adaptable and applicable to a main part of the industry.
CHAPTER 2: PRODUCTIVITY DRIVERS

The previous chapter exposed the reasons explaining the difficult diffusion of innovation in the construction industry, and the resulting productivity stagnation. It also exposed why the supply side of the industry may lack incentives to invest to boost productivity, and why the demand side may be poorly equipped to exert pressure for more quality at a lower price. In this context, it may seem like construction is totally stuck, and current situation will never improve. Fortunately, there is no fatality, and currently there are disruptions at work that may very well break the deadlock and upset construction’s balance in the near future.

2.1. Supply Side: Labor Scarcity and Technology Availability

One constraint supply is facing and that may influence innovation, is the labor availability. Lack of digitization, craftsmanship culture, and physically demanding conditions shy young people away from this career path. The sector’s share of employees aged 45 years or older increased from 32 to a whopping 50 percent between 1985 and 2010 (McKinsey, 2017). In addition, many construction workers take demand downfall-inducing financial crises as good reasons to exit the industry and never come back. In this context, it should be no surprise that construction current workforce is dangerously shrinking. In addition, the remaining workforce is relatively expensive, especially taking into account the high proportion of low-skilled workers compared to other industries: depending on the continents, construction wages increased more than in manufacturing or services, or declined by less than their related productivity (McKinsey, 2017).

At the same time, recent years fortunately have also seen a surge in investment into construction technology start-up companies aiming namely at improving the industry productivity. Collaborative tools aiming at improving project/task management and field reporting probably constitute the largest category among those ventures, but digital marketplaces, VR/AR, drones and automation also represent almost ready-to-go alternatives to the lack of available and cheap workforce.

Such appetite by private equity firms for construction technology comes at the right moment as current labor scarcity may encourage construction companies to adopt those more efficient processes than they would intuitively under different circumstances.

2.2. Demand Side: Rising Requirements

On the demand side, there is currently an increased awareness that high construction costs have substantial societal impacts that go beyond owners and developers’ profitability. In the past, frequent cost and schedule overruns were almost considered part of business. Nowadays, the costs
have become too high for the entire society and the expectations of a productivity revolution in the biggest of all yet-to-be-disrupted industries are higher than ever.

First, there are pressing needs for affordable urban housing. Demographic trends indicate that the percentage of people living in urbanized areas will keep on increasing, hence amplifying the need for affordable housing in urban areas. The issue is that construction in urban areas is very complex and typically more expensive (especially with poor project management) due to space constraints and the fact most urban construction projects are brownfield. In some cities like Boston, the construction costs in many areas are way higher than what can be afforded by the 100% Average Median Income, which is creating a housing crisis.

Second, such urbanization as well as development of emerging countries will also require increased infrastructure spending: it is estimated that $57 trillion worth of infrastructure investments will be required by 2030 just to keep up with the requirements of the global economy (McKinsey, 2013). Infrastructure mega-projects are very complex by their scale and can be plagued by poor-to-average project management with potentially catastrophic consequences on a city’s or even a country’s finances (cost overruns) and their citizens (schedule overruns): 98 percent of megaprojects suffer cost overruns of more than 30 percent, and 77 percent are at least 40 percent late (McKinsey, 2015). As an example, infamous Boston’s Big Dig was originally scheduled to be completed in 1998 at an estimated cost of $2.8 billion. However, the project was completed only in December 2007, at a cost of over $14.6 billion, not even to mention suboptimal quality and design flaws.

Third, sustainability is becoming a requirement rather than just a desirable characteristic, which has consequences for the construction process as well as the built asset. In particular, inefficiently managed construction processes can produce an enormous amount of unnecessary waste. In addition, built products have almost always a very inflexible design that makes them immutable in their current form, which obliges to scrap them rather than to modify them in case their useful life is shorter than their physical life. Finally, the systematic use of materials with a high-embodied energy content (concrete, steel) also contributes to make construction one of the most unsustainable industry at the moment.

2.3. Competition: Disruptive New Entrants

A few researches on innovation theory purport that radical innovations, defined as “breakthroughs in science or technology that often change the character and nature of an industry”, “often appear from outside an existing industry” and “often involve the entrance of new companies and organizations into an industry” (Slaughter, 2000). Indeed, new entrants are the best placed to introduce radical innovations meant at making current processes obsolete, as they have no vested interests in the current industry setup. And this is precisely what may be going on.

First, the internet allows for more market transparency and makes potential new entrants better known to owners and developers. Blogs popularize the latest trends in technology and online platforms provide more information about relative costs and track records of different suppliers,
which will enable developers/owners to better understand new technology/processes advantages and the trade-offs that they are making when they procure projects.

Second, the expected increase in global competition will encourage companies to develop internationalization strategies. In the past, construction firms rather focused on their home regions/countries, as construction is a local business in which local relationships, assets and resources are extremely important, but those constraints may be overcome by cooperating with local firms when entering a market, whether by alliance, joint venture, or outright acquisition. This strategy shift may cause an increase in the average construction firm scale, which may profit Asian firms in particular, as they may leverage on the size of their market and on their cost advantage at the detriment of firms from developed countries where the construction industry is more fragmentized, to become new Toyotas.

Third, those larger scale foreign firms may invade new markets with disruptive technology as their lack of vested interests will not encourage them to preserve target markets current setup. This combination of larger scale, eagerness to show their competitiveness, and availability of disruptive efficient technology could prove a lethal cocktail for local firms that may lack the tools to match those new competitors.

All this is becoming a reality: for instance, Chinese firm Broad Sustainable Buildings, the prefab builder that hit the news with its building systems allowing it to build skyscrapers in days (the Youtube video showing the erection of a 30 story hotel in 15 days received millions of hits), is now planning to penetrate foreign markets with a franchising system. In Chicago, leading European prefab builders and developers WElink Group and Barcelona Housing Systems (BHS) are planning a sustainable prefab mixed-use development that may provide up to 20,000 dwelling units (ConstructionDIVE, 2017).
Large emerging market competitors, especially Chinese firms, are capturing an increasing share of construction revenue.

Global contractors with $1 billion+ international revenue by type of economy in award year:

<table>
<thead>
<tr>
<th></th>
<th>2005</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed</td>
<td>33</td>
<td>15</td>
</tr>
<tr>
<td>Emerging</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>China</td>
<td>2</td>
<td>66</td>
</tr>
</tbody>
</table>

100% = 36 companies in 2005, 100% = 89 companies in 2015.

1 Developed or emerging, as classified by IMF.

SOURCE: ENR Sourcebooks, McKinsey Global Institute analysis

Image 18: Proportion of emerging countries' major contractors ($1 billion revenue and more)
"If I had asked people what they wanted, They would have said faster horses"
Henry Ford (allegedly)

It is sometimes perceived that innovation is a rare occurrence in the construction industry, but such perception may be unfounded. As a matter of fact, innovation occurs constantly and consistently throughout the sectors in the industry (Dibner and Lerner 1992; Johnson and Tatum 1993; Slaughter 1993). The last decades have seen the emergence of new materials, more efficient processes and technologies, and ultimately better quality built products. Academia in particular, have recently developed exciting automated tools and technologies, such as brick-laying drones (Gramazio Kohler, 2012) or advanced 3D-printing arms (MIT – Keating et al, 2017).

Yet the industry productivity is still struggling, at least if variation in built products quality is not taken into account. First, current industry setup is highly inefficient. As described in Chapter 1, construction is highly fragmentized, and suffers from a lack of competitiveness. Fragmentation slows down and sometimes prevents wide diffusion of the above mentioned innovations, and lack of competitiveness does not encourage contractors to make the necessary upfront investments required to adopt those innovations.

Second, it appears that many of the few innovations that have been widely adopted in construction in recent decades, are actually incremental by nature (Ozorhon et al., 2010). Incremental innovation is defined as “small improvement in current practice that has minimal impacts on other components or systems” (Slaughter, 2000). Such predominance of successful incremental innovations within the construction industry can be explained by the fact that construction is composed by many interrelated systems. The industry fragmentation and the fact that those systems are often under the control of different unrelated parties make the adoption of architectural innovation (defined as small improvement as well, but requiring significant modifications in other components and systems – Slaughter, 2000) or systemic innovation (defined as a combination of different innovations that are integrated, involving a higher degree of interface complexity – Slaughter, 2000) much more complicated than for other industries.

Here, the analogy with Henry Ford’s presumed quote becomes obvious. One just needs to replace the words “faster horses” with “stronger concrete” or “higher-strength steel” to see the parallels: the industry has spent the last couple of centuries trying to perfect faster horses (Mullett, 2017). The old systems have been upgraded, but they are still there, archaic and embedded in craftsmanship. Although innovation is critical to renewal of industries, the problem is that not all innovations are equal: incremental innovations produce the smallest productivity gains, whereas systemic innovations produce the largest productivity gains (Shabanesfahani and Faraj Tabrizi, 2012).
By overlooking the adoption and diffusion of systemic innovations, construction deprives itself from the largest foreseeable productivity gains. Studies have shown that different examples of systemic innovations in other industries often involve “advances in supply chain management, increasing use of enterprise resource planning and prefabrication component systems” (Taylor & Levitt, 2004). Such systemic innovations could be implemented in case there is a major change in the industry current paradigm – in particular, a change from a project-driven approach to a production-driven approach like in manufacturing, would create a fertile ground for the development, adoption and diffusion of systemic innovations.

This chapter will be structured as follows. Subchapter 3.1 examines different ideas to improve the industry’s current setup, in particular its competitiveness. Subchapter 3.2 analyzes the most desirable characteristics construction’s new production-driven system should have to allow for systemic innovation and revolutionize the industry. Subchapter 3.3 examines various innovations that could be adopted to cope with the heterogeneity of the locations on which the built products are installed (demolition, digging, foundations) that will inevitably fall out of the scope of the projected production-driven approach. Those subchapters are also designed as the direct answers to the three main causes for lagging productivity in the construction industry as detailed in Subchapter 1.2.

3.1. **Improvement of the Industry’s Current Setup**

This subchapter is aimed at listing a few points of consideration that could serve as a basis to improve the industry’s setup. It should be noted however that such analysis is based on the current setup. As will be described in subchapter 3.2, the introduction of a new paradigm/construction system may influence such setup as it could give birth to a new industry eco-system. In this context, some of the current setup’s flaws could be “naturally” resolved by such new eco-system introduction, as the industry’s setup evolves with the production process: industry’s setup and production process are closely linked and interact with each other.

3.1.1. **Encourage Disruptive Innovation**

Industry’s superstructure (as defined in chapter 4) should absolutely work both to encourage innovation, and at the very least to stop restraining such innovation’s adoption and diffusion, depending on the case and the party.

First, regulation of the construction industry needs to be more flexible. At the moment, such regulation is highly prescriptive about the choice of processes, equipment, materials, and designs that construction companies use. The problem is that it is realistically impossible for regulators to keep themselves up-to-date about the most recent cutting-edge innovations in the construction industry, not even to mention making informed decisions. This situation has resulted over the years in a fossilization of authorized practices (Gann et al, 1998), as understanding and acceptance of new processes/materials/etc. by officials is way slower than pace of innovation.
Switching from a prescription-based to a performance-based system of regulations, on the other side, would be highly beneficial to construction innovation. Focus would not be on what the construction companies are allowed to do, but on the outcomes they need to achieve, with more leeway on the methods or materials to reach those outcomes. Adoption and diffusion of innovations would hence be facilitated should they meet the required regulatory outcomes. In addition, it would a good opportunity to help solving the lack of regulatory harmonization at the same time, as result obligations would be easier to cope with for construction companies. For instance, current US regulations forbid the use of Cross-Laminated Timber (CLT) for high-rise buildings, whereas research on this material has advanced a lot. Performance-based regulations would allow the use of CLT in case it meets public authorities’ standards of performance.

Second, industry’s superstructure may need to go beyond than merely restraining itself from restraining innovation in the industry. As discussed in subchapter 1.1.2.1, innovation is risky and often unsuccessful for single firms, which may make innovation economically irrational for those firms. In this context, industry’s superstructure should act in order to stimulate and encourage innovation that risks not to take place otherwise. Regulators assistance may take the forms of direct government funding, tax credits or reduced fees for investment in R&D: for instance, the European Union launched the “Horizon 2020” innovation program: such fund plans to grant not less than EUR 80 billion from 2014 and 2020 in order to embrace innovation in the EU. Recognizing the issues described above, it aims at removing barriers to innovation and making it easier for the public and private sectors to work together in delivering innovation. Public authorities may further favor the adoption and diffusion of such innovations by mandating their use on public-procurement projects: for instance, this is what the UK authorities did to promote BIM. Owners and developers may want to create professional organizations to centralize and structure innovation priorities and diffusion strategies.

3.1.2. Demand Predictability and Scale

As most disruptive innovations require very substantial upfront investments, construction may be somewhat ill-structured (compared to other industries) to adopt such innovations as it is notoriously fragmentized and composed mainly of small and resource-scarce low-profitability companies. In this context, demand predictability and scale are absolute prerequisites for those companies to take the risk and invest in disruptive innovations as this would provide them with the necessary long-term pipeline to guarantee they will recoup the cost of their initial investment.
A plant to produce pre-cast building components can break even at 5,000 to 8,000 housing units annually

Break-even scale for 3,000- to 30,000-unit pre-cast plants

<table>
<thead>
<tr>
<th>Plant capacity</th>
<th>3,000 units</th>
<th>6,000 units</th>
<th>15,000 units</th>
<th>30,000 units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Break-even scale (units)</td>
<td>Utilization (% of capacity)</td>
<td>2,600</td>
<td>5,000</td>
<td>8,000</td>
</tr>
<tr>
<td>5</td>
<td>2,600</td>
<td>5,000</td>
<td>8,000</td>
<td>13,500</td>
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<td>85</td>
<td>85</td>
<td>80</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>500</td>
<td>1,500</td>
<td>4,500</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>300</td>
<td>1,000</td>
<td>3,000</td>
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<td>20</td>
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<td>200</td>
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<td>2,000</td>
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<td>100</td>
<td>350</td>
<td>1,000</td>
</tr>
<tr>
<td>30</td>
<td>30</td>
<td>0</td>
<td>150</td>
<td>500</td>
</tr>
</tbody>
</table>

Startup capital expenditure

$ thousand

1 Assumptions: Average cost of capital, 10%; unit price, $19,500; EBITDA margin, 10%; structure share of revenue, -30%; depreciation/lifetime of plant, 10 years; maintenance, 0.5% of revenue; corporate tax rate, 25%; debt share of capital expense, 70%; interest rate, 5%; standard unit size, 50 square meters.

2 Based on manufacturer business plans. Capital expenditure figures based on assumption of low labor cost.

SOURCE: Scaling-up affordable housing supply in Brazil: The My House My Life programme, UN-Habitat, 2013; KPMG; Turner and Townsend; expert interviews; publicly available information of manufacturers; McKinsey Global Institute analysis

Image 19: Estimation of the number of housing units needed to be produced to reach breakeven for an investment in prefabricated construction

The best-placed actors to provide such pipeline through demand scale are probably public authorities: in the United States, government procurement represented over 20% of total construction demand between 1993 and 2004 (US Census Bureau, 2004). For instance, it has been noted that mandatory use of BIM for UK government procurement has boosted this technology. Although most private owners lack such market power, they should at least try and plan their projects as pipelines for construction companies. In particular, non-real estate industry related owners may possibly join forces to create professional organizations that would try to gather the needs in real estate of various client industries.

Regulators may also improve demand predictability by facilitating and streamlining the permitting and approval processes that need to be successful in order to initiate construction projects. First, risk related to project impact could be taken into account to draft more flexible regulation to accelerate low-risk projects' approval that account for the majority of construction output, whereas higher-risk structures like industrial projects would keep on being scrutinized. Second, current permitting and approval processes' archaism may give a glimpse at how much room there is for efficiency improvement, especially through digitization: for instance, land-use registrations may be digitized and online automated application and approval (in case of total compliance) may be made available to skip time-consuming manual decision-making by local authorities as well as typical...
informality and possible corruption. Third, historical land fragmentation should be tackled with by assembling (when possible) individual parcels into a bigger site, and creating more development plans focused on areas of urban growth and infrastructure expansion.

3.1.3. Reduce Information Asymmetry

As described in subchapter 1.3.1.1, one of the biggest challenges facing inexperienced owners and small developers is the gap that exists between what they know about the cost and specifics of a project and what their contractors know (McKinsey, 2017). Such gap has a devastating influence on construction true cost, resulting competitiveness and impact on the Society.

Information asymmetry may be tackled in three different ways. First, as will be detailed in subchapter 3.2, the creation of a new paradigm focusing on a production-driven approach would substantially decrease the level of informality in the industry, and construction transactions would switch from the acquisition of services and goods, to the acquisition of goods only, which would lower the required owner/developer sophistication to make informed choices. At the exception of final assemblage, prefabricated construction in particular allows owners/developers to focus on the final products characteristics, and not how such products is built.

Second, professional associations and public authorities may work to develop industry benchmarks to provide owners and developers with data on average project costs and performance of contractors. This would allow owners that build infrequently in particular to mark offers to market, make an informed choice and ultimately elect the best firm for their needs, instead of being obliged to settle with an obscure local firm that would be tempted to use its informational advantage for its profit. An example of such initiative is the International Construction Measurement Standards coalition (McKinsey, 2017).

Third, many other industries (legal services, finance, insurance, etc.) have solved informational unbalance between supply and demand with the help of intermediaries. Intermediaries reduce such balance against remuneration: informationally disadvantaged clients pay them to reduce the informational gap with their suppliers. Intermediaries’ access to aggregate information gained by dealing with many owners and contractors over time (Simchi-Levy, 2004) is especially invaluable for owners with infrequent projects. In the past, such function was fulfilled by “master-builders” architects but they were part of an era long gone. Nowadays, such function is usually fulfilled by construction managers: if they become the hired contractors, they cannot finger point at other parties such as architects as they were paid to cooperate with them beforehand, which theoretically removes the risk of non-owner induced change orders. Another solution, overlooked until now, would be to expand the role of bonding companies (LePatner, 2007). Those companies traditionally protects owners and subcontractors against contractors’ insolvency. They could push their guarantee further and guarantee a maximum execution price by protecting owners if contractors’ attempt to renegotiate construction budgets through change orders not initiated by their clients, accompanied with implicit or explicit threats of not completing their project, would be requalified.
as contractors’ “soft default”. In addition the election of bonding companies would not involve any principal-agent issue as frequently appears with construction managers (LePatner, 2007).

### 3.1.4. Design Completion and Constructability

Changes in design strategy may have major impacts on the industry: tending towards design completeness would improve construction competitiveness, whereas design constructability may improve both industry competitiveness and efficiency.

More often than not, architects submit incomplete drawings to owners and contractors. Sometimes this is done on purpose: recent decades have seen a tendency in favor of “fast track projects”: this project delivery method consists of starting construction before design is finalized – the idea is to improve developers’ rate of return by shortening the exit horizon as much as possible (LePatner, 2007). Some other times, it is not done on purpose, and simply reflects nowadays industry practice, or possibly a flaw in architects’ training. The impact of design completeness on the industry competitiveness is obvious though: an incomplete design provides contractors with opportunities to submit change orders in a non-competitive environment, and those change orders’ potential costs and resulting budget uncertainty largely outweigh savings from shorter completion timeline. In this context, it is critical that owners/developers give up using fast track methods and require complete designs from their architects (LePatner, 2007). Also, owners may want to self-discipline and to restrain themselves from unnecessary specification changes after work has started, as the resulting change orders will have the same consequences.

In addition to completeness, extra attention and care needs to be addressed to design constructability. A design’s level of constructability also has an impact on change orders, similar to design completeness. In addition, keeping the actual construction process in mind already at design stage can bring major savings, whereas issues created by a poorly constructible design can truly plague a project (McKinsey, 2017). For this to happen, different paths may be examined.

First, architects may want to try and become more knowledgeable about cutting-edge construction techniques, which would allow them to participate more in the constructability review. Architecture schools may also want to re-orient their cursus and recognize that design is only a part of what is expected from nowadays architects. Second, an alternative to architects’ training would be to improve the collaboration and knowledge transfer between architects, contractors and suppliers. Most of the time, design is a relative non-collaborative process: architects create a front-end design that is simply handed to contractors. Most contractors do not have the opportunity to raise points about design, which results in on-site complexities and constructability issues (McKinsey, 2017). Until architects develop the skills allowing them to perform a constructability review alone, a solution would be to integrate contractors early in the design phase (an ECI - early contractor involvement – model, warmly recommended by the World Economic Forum), and use tools as BIM to communicate, so that each contractor bid may be integrated in the system (McKinsey, 2017).
The idea, and what should be one of the owners/developers’ main objectives, would be to force architects to cooperate with contractors during planning and hence avoid the difficulties caused by a separation between the design and construction stages, instead of focusing only on design and outsourcing constructability down the chain at the detriment of their clients’ interests. Also, a change in the design strategy could be considered: instead of starting from a purely abstract design and modify it to improve constructability, an alternative strategy may consist of finding the most straightforward design possible (in terms of constructability) while meeting at the same time clients’ minimum requirements (McKinsey, 2017).

3.1.5. Contracts Aligning Interests and Improving Accountability

Conservative contracts/delivery methods that are traditionally used in construction, such as lump-sum contracts, have been reported as involving high cost risk for contractors, high incidence of adversarial relationships (as contractors try to impact such costs on their clients), low levels of integration across the supply chain and as being detrimental to innovation, as risks are typically not shared and rather pushed down the supply chain (Kumaraswamy and Dulaimi, 2001). In this context, recent years have seen the emergence of the Integrated Project Delivery (IPD) method.

Inspired namely by production concepts developed by Toyota, IPD promotes contractual collaboration and risk sharing through the life of the project: it involves the owner, architect, contractor and other stakeholders into a single contract to determine collective project goals, costs, risk-sharing and compensation. In addition to solving many of the issues embedded in conservative traditional methods, it also forces all parties to consider the implications of their part of construction on other parties’ parts (McKinsey, 2017).

IPD works best with owners with a pipeline or portfolio of projects that have the necessary scale to make large up-front investments for each project phase, be proactive in driving productivity improvements and in managing all involved parties, and benefit from knowledge transfer between projects. Similarly, contractors must be willing to put their profit at risk and accept to cooperate (McKinsey, 2017).
3.1.5.1. **Collaboration**

The first proposed concept is to move away from the traditionally hostile contracting environment to switch to a cooperative mindset. Contractors and owners' interests are antithetical: the industry would welcome contractual structures that encourage them to partner and cooperate efficiently. Likewise, many architects prefer to use templates drafted by their local architect association (AIA in the US): most of the time, those templates aim at isolating the architects from any potential liability associated with construction, to the point that some renowned architects like Frank Gehry took the ethical decision to refuse to use those templates (LePatner, 1999). In the US for instance, private owners have no professional association of their own to oppose to the American Institute of Architects or the Associated General Contractors. In this context, they have no vested interests in templates drafted by those associations as they aim at lobbying for their respective corporations: owners’ best interest is in new form of cooperative contractual structures.

Such structures would target the improvement of performance at project-level as this is where added-value accrues to the owner, instead of focusing shortsightedly on trade or package level. Also, such structures would aim at taking into account the impact of various parties' interactions with each other, which is impossible in a sequential trade-type contractual structures.

Besides project management and cross-organizational cooperation, those contractual structures would also promote knowledge sharing among project participants and hence favor innovation diffusion. For instance, bringing contractors at early design stage to cooperate with architects would not only improve design constructability as discussed before, but would also allow contractors to provide their input about what technologies could be used. Contractors could provide valuable insights about potential upsides and risks of different techniques in order to allow the owner to make informed decisions: research has shown that the presence of a well-integrated team is key in driving innovation (Walker et al., 2003).

Of course, such cooperation and team integration would require a lot of pro-activity and involvement by the owner or its representative, as cooperation between third parties with potentially divergent vested interests can represent a managerial challenge. Fortunately, recent emergence of modern digital collaboration platform can help owners to set a “single source of truth” as well as spot potential conflicts more easily, provided that the use of a common platform (5D BIM as a minimum, preferably) is made mandatory for all project participants.

3.1.5.2. **Risk Sharing**

A second concept would be to favor systematic risk-based contract structures in which project risks, defined as expected variability compared to common outcome expectations regarding dates, budget and quality, would first be identified and prioritized by their potential impact and probability of occurrence, then shared among project interested parties. Weights would not be
set equal though, as such risk allocation is more efficient if each risk is assigned to its “natural owner”, i.e. the party that is the best placed to manage such risk. For instance, owners would typically be responsible for scope changes and site conditions. Also, contractors will probably bear a substantial part of construction risk as they are best positioned to do so, and intermediaries such as architects and guarantors will probably be required to bear more risk than they currently do under traditional delivery methods.

At the difference of traditional delivery method, tendering would not be based on cost only, but on parties’ ability to manage risks assigned to them, i.e. their efficiency and management cooperative skills. Consequently, it would require owners to perform thorough contractor due diligence and examine “their past performance, competence, risk exposure, project-management systems and other IT tools, and compliance with health, safety, and environmental regulations” (McKinsey, 2017). This would favor the constant selection and consequent development of efficient contractors at the detriment of non-efficient ones, which will improve the industry productivity.

3.1.5.3. Accountability

The above mentioned collaboration mandated by a single contract involving all interested parties, and subsequent risk distribution among best placed parties, would create a sound basis to improve each project supplier accountability.

For instance, contractual structure may include that the architect agrees to provide a 100% complete design, and the contractors agree to confirm that they had had the opportunity to review the drawings’ completeness and constructability and that no extra budget will be required unless the owner requests a change of scope. In this context, as contractors would be required to identify any omission during the bidding process, any information that could have been easily provided by the architect at this stage will not be accepted as a basis for a later change order, or the contractor would be considered in soft default. On the other hand, those arising from the owner requesting a scope change would obviously still be allowed, but the contract would provide a context so that such change order would not be skewed by monopoly and superior information. This setup would drastically reduce the number of requested change orders and budgets would move closer to true cost: initial bids may be higher than otherwise, but owners would enjoy less price volatility.

Owners may also want contractual structures to include quick and efficient dispute resolution mechanisms. Such mechanisms would identify the best resolution per type of issue, who is responsible for the issue, who should bear the related cost and the acceptable delay for arbitrating. Such mechanism should at all cost include a “no-hostage” provision in order to prevent any conflicted party to blackmail other parties by causing a project to stop: no dispute-related delay may be tolerated, and the conflicted party must keep on working on the project while applying to arbitration mechanisms provided by the contract.
3.1.5.4. **Fair Compensation for Risks Borne**

The detailed analysis of critical risks mentioned in 1.5.2 would also allow to apply the most important financial concept of trade-off between risk and return in order to design fair compensation structures that favor parties that deserve it, i.e. parties that effectively bear risks. Such risks should be appropriately valued, and all interested parties should receive a fair compensation for the risks borne.

Contractual structure may also include incentives in order to align the interests of the owner and contractors. Such incentives would be designed and negotiated with contractors at the contract inception so that all parties agree in advance as to what is included: they should be attractive enough to ensure that the contractors has a stake in improving the project’s outcome, but without compromising the project’s profitability.

Incentives may be related to the achievement of targets of cost and/or early finish, but their design should ensure they are not abused: contractors should not try and reach those targets at the detriment of quality, or with adverse consequences for other parts of the project as the project-level outcome is what matters to the owner: incentives should be earned by all parties only if there was a positive outcome as project-level, hence encouraging all parties to cooperate. Some practitioners go so far as to recommend that whereas contractors should be reimbursed their costs related to the project, their entire profit should depend on the project’s success.

In addition to shortening construction time and keeping cost low, incentives could also be used to reduce innovation risk aversion if parties in a position to innovate are rewarded for taking such risks as well: they would be encouraged to adopt new ideas and propose better ways of doing things to the owner. Large-scale owners with project pipelines may also co-invest in technology pilots (before deployment on larger projects) with contractors and share costs and rewards proportionally.

If risk takers may need to receive a fair compensation, certain industry particularities, on the other side, may be worth being challenged. Owners may want to scrap budget allocated to contingency, or at least have total control and subject them to a case-by-case owner review, instead of the current industry practice of seeing them as automatic profit for contractors. Under traditional delivery methods, contractors typically charge the entire contingency budget, but never reimburse when conditions are better than expected. Furthermore, financial theory related to risk remuneration provides that diversifiable risk should not be remunerated. Likewise, general condition costs should be very narrowly defined, include a cap, and preferably be mandatorily included in the bid to provide owners with more visibility about true cost.
3.1.5.5. **True Fixed Cost and Competitiveness**

Productivity is comparatively high for industries with typically fixed prices like aviation, automobiles, computers, etc. and low for industries involving "mutable cost", like education, healthcare, law and construction (LePatner, 2007). This is precisely why one of the main objectives of the paths described in subchapters 3.1.4 and 3.1.5 in particular, is to create an industry set up in which contractors' bids reflect true cost ultimately borne by owners/developers. True cost is a necessary input in improving an industry competitiveness: true cost will allow owners to switch their focus onto contractors' productivity as a selection criteria and to make informed choices in selecting the most efficient contractors, which would remove inefficient contractors from the industry as they will run out of business. True cost will also encourage industry consolidation as contractors will be encouraged to improve productivity, namely by growing bigger and realizing scale economies.

3.1.6. **Vertical Integration and Horizontal Consolidation**

3.1.6.1. **Horizontal Consolidation**

As discussed in subchapter 3.1.5.5, allowing owners/developers to tender on the basis of bids' true cost and contractors' efficiency will promote the industry's competitiveness. If productivity becomes the main factor for contractors to be hired, such contractors will be encouraged to become more efficient. Then the construction eco-system may start evolving as, according to Barry LePatner's provocative prediction, "construction firms will resemble modern automobile factories more than pre-industrial artisanal playgrounds" (LePatner, 2007).
This contemplated race for productivity would theoretically encourage contractors to improve, smoother, and standardize their processes, which may take the form of creating, or adhering to, new construction paradigms as one will be presented in subchapter 3.2. Besides those radical changes, construction supply may also apply old recipes already tried and tested by other industries. The most obvious recipe would be for contractors to increase their scale and grow bigger: construction's notorious fragmentation shows there is plenty of room for improvement in the average contractors' ideal scale to maximize productivity.

Horizontal consolidation would allow construction firms to profit from scale economies, to dedicate more resources to invest in R&D and to manage the risks related to innovation diffusion with bigger and more stable pipeline.

It would also allow them to increase their negotiation power with workforce suppliers like unions: labor unions have a long tradition of strength in construction "because they often outsize and outwit" small contractors with little expertise in labor matters (LePatner, 2007). Unions' tactics sometimes involve preventing introduction of technology to protect workforce's rights (Mandelstamm, 1965, LePatner, 2007): larger-scale contractors would have more negotiation power to limit the effects of such tactics.

Last, larger, consolidated contractors would probably be in a better position to assume full managerial responsibility on their projects, which would substantially decrease the industry practice of subcontracting, as it would negate scale economies' positive effects. It would also increase transparency and promote efficiency by avoiding the finger-pointing games between subcontractors when an issue arises.
3.1.6.2. **Vertical Integration**

There is also plenty of room for improvement in terms of vertical integration as some research purpose that the lack of stable supply chain or long-term strategic relationships constitute major differences between construction and other industries (Brandon, Betts and Wamelink, 1998). This can be explained within projects by construction's traditional contracting methods: separation of tasks into discrete packages and sequential involvement of contractors contribute to the fragmentation of the industry. It can also be explained by construction current project-driven approach: each project is treated as a unique event with little that can be carried forward in terms of techniques, procedures or strategic relationships. Also, lack of competitiveness in the tendering process makes the selection process almost random, which prevents long-term relationships. Finally, construction's embedded informality and lack of process standards prevent integration of contractors with suppliers. Again, the solutions examined in this subchapter are related to the industry's current setup. Any new setup that would provide with construction process standards allowing for an extensive standardization of the materials, parts and processes would have a huge positive impact on contractor/supplier integration.

Since the 1970s, different concepts have been proposed to solve the various problems related to fragmentation. Such efforts have been unsuccessful until recently, when three areas of innovation may successfully team up to promote process integration in the industry.

- **Integrated project delivery**

  First, issues related to the traditional delivery methods may be overcome by the increasing use of integrated project delivery methods. As described in subchapter 3.1.5, such methods would allow and encourage project participants to communicate and cooperate, as their success and profit would be tied to the success of the project.

  Those kinds of cooperation would be even more beneficial if they could be turned into long-term strategic relationships, because the perspective of further future cooperation would act as an incentive for contractors to deliver better service/product levels, and each lesson learnt during a project could be put into fruition for the next projects. For those cooperation to last more than one project, owners obviously need to have a pipeline of project, which limits this setup to large-scale owners/developers. Also, owners must choose to keep on working with the same group of contractors, which requires an analysis of the trade-off between synergies brought by this long-term strategic relationships, and punctual non-competitive bids by participants in this relationships.

- **Building information modelling (BIM)**

  Such cooperation with contractors and interested parties is only made possible by the development of IT tools that allow cooperation and communication optimization. In this context, owners may want to mandate the use of 5D BIM by all participants. Such technology provides invaluable structured information that can directly link design to detailed procurement, which favors communication between contractors/owners and
suppliers, and allows the creation of new supply chain management tools. For instance, unicorn Katerra says its building information modeling tools and computational design are directly linked to its enterprise resource planning global supply chain infrastructure for ease of material ordering, manufacturing, tracking, and delivery (Robotics and Automation News, 2017).

**Supply chain management**

Whereas integrated project delivery improves the integration of different types of contractors within a project, supply chain management tools help integrating contractors and suppliers as well as improving and strengthening relationships between owners and suppliers. Here as well, there is plenty of room for improvement as construction is one of the least sophisticated sectors in procurement and supply-chain practices. In addition, construction consumes an incredible volume or raw materials the procurement of which can be a brain teaser, hence supply chain proper management is of paramount importance in construction. Heavy and bulky materials need to arrive on-site in the correct amount and sequence, so that they do not cause on-site warehousing issues due to overstocking, or stop production in case of understocking.

First, procurement workflows could be entirely digitized in order to maximize the usefulness of relevant data on supply availability, lead times, service and quality metrics, and cost structures in order to ensure more sophisticated logistics management and best value for money.

Second, contractors may invest to optimize their procurement processes: in technical optimization, such as mandating the use of standardized specifications, and process optimization, such as standardized payment terms or templates for clean sheeting.

Third, contractors may want to coordinate with their suppliers to adopt an optimal approach for all their projects. If such cooperation would allow suppliers to batch their orders together for instance (assuming a minimum of standardization in the supplied goods), scale economies due to logistics and transportation costs minimization may be shared along the supply chain.

Last, strengthening relationships between suppliers and owners are critical for innovation and productivity of the industry. Indeed, suppliers are often the main initiators of innovation, and owners are the ones ultimately deciding on which production technology, whereas contractors are mere intermediaries. In this context, owners and suppliers could work jointly on industry standards for new materials and processes.

### 3.2. Development of a New Construction Paradigm

To revert to our previous analogy, Henry Ford did not invent automobile; he did not invent assembly line, standardization, or continuous improvement either. His genius rather lays in the fact
he “adapted the moving assembly line process for the manufacture of automobiles” (Mullett, 2017). Or should we rather say he adapted the automotive products to standardization and mass production? It goes probably both ways, and the most important is that such adaptation led to a virtuous circle that allowed superior quality and significantly lower price than its hand-made competition, enabling the creation of a new and rapidly growing market. Of course, customers have changed, and require now customization that Henry Ford could not offer at the time (“any color provided it is black”).

Yet, automotive industry provides many interesting similarities with construction: it fulfills (quasi) vital needs (especially in most of the US cities), deals with the assembly of very complicated products (design and tuning of a modern thermal engine is probably even more complicated than isolation and ventilation of buildings, arguably one of the most complicated parts of construction), consumes a lot of raw materials and has a huge impact on environment. Yet, automobile production has reached efficiency levels of production akin to manufacturing, and authorizes for substantial customization. This is clearly one of the models construction should inspire from.

Modularization, product specifications and proven routines are universal recipes for all industries to make complexity manageable. If applied to construction, it would lead to the creation of a totally new paradigm, from the current informal setup embedded in craftsmanship. Such paradigm main outlines will be developed further below and may include a greater use of repeatable design (while still allowing for design originality), modularization of components to promote upgradability and customization, as well as off-site prefabrication of as many components as possible, limiting on-site work to assembly and finishing in order to enjoy factory environment production: in a nutshell, this new paradigm would consist of switching from a project-driven model to a formal production-driven model.

The development and application of such new paradigm may lead to a complete reshaping of the industry. As described in subchapter 3.1, standardization and competitiveness would encourage vertical integration. Furthermore, prefabrication pushed to the extreme could make involvement of third party contractors redundant, with manufacturers hence transforming themselves into turnkey solution providers. Removing contracting layers would improve transparency and lower prices in the industry, and final assemblage would be performed either by manufacturers, or by owners’ internal teams.

One step beyond such industry reshaping would be the adoption and diffusion of building modules standards that would recommend free-access and free-use building systems, that otherwise would be patent protected by market practice. This would prevent turnkey solution manufacturers from abusing newly-established situations of monopoly by the exclusivity of patented building systems. The resulting process formalization and market transparency would allow the creation of efficient markets, where owners could buy from a “palette of products that largely already exist and carry clear prices” (McKinsey, 2017). This new construction ecosystem would profit owners/developers and the society in general, and would paradoxically profit turnkey manufacturers as well, as removing any monopoly risk (i.e. risk of having a dispute half-way of a project with a manufacturer
using a patent-protected building system, weakening the position of the owner/developer) would convince owners/developers to adopt such systems and hence to sustain their growth.

Some practitioners estimate that this shift towards a transparent and formal manufacturing-like system of mass customization, modularization and prefabrication, together forming a production system, would provide gains of a way greater magnitude to the industry than the less-disruptive solutions detailed in subchapter 3.1, some even citing a “potential to boost productivity by five to ten times, depending on the sector” (McKinsey, 2017).

Nevertheless, the industry diversity, due to different landscape and weather conditions (including earthquake and hurricane risks), raw material and workforce availability, scale and use of the built products, current situation (brownfield vs greenfield), as well as cultural preferences and regulatory obligations, would probably require more than one single production system. In this context, one could imagine that the ideal setup would consist of a matrix of systems, or a matrix of different variants of a basis system, with the above described characteristics acting as dimensions of such matrix, providing one or several system variant(s) for each given situation of scale, use, location, workforce and raw material availability, etc.

Also, a radical shift to a production system will not be possible for the entire industry. Construction covers a “broad spectrum in size and complexity, and change of different forms is possible along the breadth of that spectrum” (McKinsey, 2017). On both ends of the spectrum, projects will need to stick with a project-driven process and rely only on the recipes detailed in subchapter 3.1 to improve productivity. At one end, heavy infrastructure construction projects that tend to be unique, bespoke and non-repeatable (although highways for instance, may be divided into repeating sections) by nature, do not marry well with a production-driven model: nuclear plants are a perfect example. At the other end, fragmented trades, for instance for renovation projects where only parts of the buildings need to be upgraded, will always include an irreducible level of informality due to the overwhelming dominance of brownfield existing conditions. In the middle of the spectrum though, there is potential to move toward a production system.
Construction in the middle of the project-scale spectrum can be dramatically different in a production system.

### Transparency across small trades

- **Small trades**
  - Digital marketplace provides transparency and comparison for owners across different trades, reducing the information asymmetry.

### Construction production system

- **Single-family home**
  - Designs customized off a standardized base built in factories and assembled on-site in less than a week.

### Better projects

- **Airport**
  - Components, including fully modular units, assembled off-site and tracked through fully digitized supply chain.

- **Nuclear power station**
  - Built on-site but using a radically improved project model with a collaborative, long-term owner and contractor relationship and technology throughout the process.

**SOURCE:** McKinsey Global Institute analysis

Image 23: A production-driven system will apply to specific kinds of projects

### 3.2.1. Pre-requisite: Digitization

Many of the proposed improvements to the industry proposed so far, and the setup of a production-driven system in particular, require, as pre-requisites, advanced construction modelling and enhanced communication among all participants in a project. Those could be provided by recently developed digital tools.

**Image 24:** Link between digitization and productivity.

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1 Based on a set of metrics to assess digitization of assets (8 metrics), usage (11 metrics), and labor (8 metrics); see technical appendix for full list of metrics and explanation of methodology.

**SOURCE:** B.E.A, B.L.S, US Census; IDC, Gartner; McKinsey social technology survey; McKinsey Payments Map; LiveChat customer satisfaction report, Appbrain; US contact center decision-makers guide, iMarketer; Bluwolf; Computer Economics, industry expert interviews; McKinsey Global Institute analysis
Building Information Modelling (BIM) may prove an invaluable tool to improve front-loaded design and planning: BIM allows architects to build an entire project digitally, from start to finish, before construction actually starts. BIM makes it now possible for construction what was never possible before, due to products’ size: the utilization of prototypes. BIM fulfills the same role as prototypes in manufacturing: the resulting 3D digital representation of a building includes many of the building characteristics (including structure, envelope, MEP, etc.), is complete with details on every last component, and allows the minimization of errors, omissions and rework beforehand. Its completeness and precision should allow contractors to bid on complete designs and confirm that no change order (besides scope change by owner) would be required later, which confirms prices are reflective of the project’s true cost. Paired with virtual reality, it also allows owners to visualize the final result and confirm the proposed layout fulfills their needs, or alternatively propose upgrades and take design decisions before they are turned into costly change orders.

From a project management perspective, BIM also improves communication as it can be used as a library of information for the design, construction and ongoing maintenance/management of the asset as well as provide a “single source of truth” to all stakeholders. Paired with augmented reality technology, it can also improve interaction between the work site and the office and facilitate live discussions among different parties. Using BIM as a foundation, a large number of apps, which can be loaded on handheld and mobile devices, have been developed to create digital workflows and enable real-time collaboration, document management, material logistics, productivity tracking and on-site reporting. Surveying and geolocation tools using optical laser technology can simplify and enhance the accuracy of site reporting, updating BIM models automatically with handheld devices or drones requiring minimum human supervision. Last, captors and Near Field Communication (NFC) technology can be integrated to put the Internet of Things to work on construction sites: advanced data analytics would allow real-time productivity tracking and facilitate day-to-day decision making, allowing contractors/manufacturers to come up with better front-end estimates of a project’s cost and to minimize risk.

3.2.2. Making Bespoke an Option

We could make another analogy, now with the garment industry. A century ago, all men’s suits were hand-made and hence bespoke. Then, alternative production systems started being developed, like “ready-to-wear” and “made-to-order”, in order to offer customers to choose between a cheap but generic ready-to wear suit on the one hand, and a personalized, hand-made but expensive bespoke suit on the other hand. Nowadays, ready-to-wear suits are the norm, even for weddings, but a few aficionados prefer bespoke suits that are still available for the ones willing to add a zero on the check. Both processes exist: at least, consumers are given the choice. Not so in the construction industry. Only bespoke projects exist, and of course on the higher end of the budget range: there is no ready-to-wear or made-to-order available, hence bespoke is the mandatory choice, not a customer’s choice.
Part of the explanation obviously lays with the informality of the current construction process. Another part has to do with the design process. Recent research report asserts that the current architectural design approach “follows directly in the Beaux-Arts tradition, with the goal that each building is essentially designed as a unique work of art” (Luo et al., 2017). In this context, such heterogeneity of design and project specifications makes it very difficult for the construction industry to formalize its processes and increase its productivity. Yet, the architecture profession, especially star architects, continue to lobby their clients for originality of design at any cost, as it is nowadays a standard measure by which to judge architects’ work.

The point is that real estate development projects’ main clients (outside of corporate real estate) are actually not architects, but real estate developers and the society in general. Those latter parties’ interests are more aligned than one may think: real estate developers participate in projects for profit, but such profits only materialize if their projects are successful, i.e. if they get the approval of the target market they were designed for. Likewise, the public needs developers to create, maintain and renovate quality areas to work, live and play. Compared to those clients, architects are a part of the supply chain that need to adapt to their clients’ needs and wishes, and there is no logical reason that their interests be prioritized at the detriment of their clients’.

A switch of paradigm in construction such as the one that is described in this chapter would probably be very beneficial to owners and developers. The impact of the required process formalization and standardization on design originality is not exactly clear at this stage. Nevertheless, as construction is a pretty risk-adverse industry, and the setup of a new production system would inevitably requires a learning curve, it is safe to imagine that the application of this new system would first require the avoidance of any unnecessary “overdesign”, before it gradually allows for more customization. It is no different from the car industry if we revert to our Henry Ford’s analogy: Henry Ford first froze cars’ design in order to refine the moving assembly line process. Decades later, digitization, automation and big data now allow the car industry to produce totally different cars going down the same assembly line, while still sharing common design parts: a difficult balance needs to be found in all industries between standardization (which lowers costs) and configuration (that fits better clients’ needs).

In this context, a switch to a production-driven system would initially require architects to adopt new strategies to adapt to this new system: in order to be efficient, offsite modular construction processes require up-front planning to take their specificities into account. This is frequent in other industries: consumer electronics, for instance, uses “design for manufacturability”, i.e. the configuring of a device’s shape and function to make it cheaper to build. A similar strategy adapted to offsite modular construction would consist of dividing a project into repeatable design elements whose size allows easy transportation (and hence prefabrication off-site). In addition, the new system off-site automation would require architects to ban design ambiguity from their drawings and use a “building product” mode of design, where documents are designed to inform an industrial product supply chain.
Once the industry masters this strategy, the next step would be to reach mass customization: different strategies may be adopted in that respect. Building systems themselves may be designed with a mindset allowing for customization: for instance, unicorn Katerra claims that it does not have "pre-existing models that clients can choose from. Rather, it has developed a standard kit of parts that can be deployed in different ways for each project, depending upon the context and client preferences (McKnight, 2017)."

Another strategy, called "site adaptation", would consist of using replicable design where it is possible and to implement limited parts of customized design around those modules: this strategy is fairly in line with the essence of mass customization which is described by some practitioners as a method of "effectively postponing the task of differentiating a product for a specific customer until the latest possible point in the supply network" (Jacobs et all, 2004). It is also in line with most clients' needs, as not all parts of a building necessarily need to be customized: for instance, only front facades are customized for Las Vegas casinos, the side walls are just painted concrete.

Again – there is nothing wrong with bespoke. And bespoke will need to continue to exist in construction, either because some types of project (small scale renovation of existing buildings, etc.) do not lend themselves to Modern Methods of Construction (MMC), or because clients/end users value design originality more than cost efficiency. The point is that clients should have the option to opt for bespoke or not, and alternative construction systems should be proposed to clients for which cost minimization is a high priority. Likewise, developers, as top of the decision-making tree in charge of project initiation, planning/programming and overall budget, should keep themselves informed of MMC benefits, limitations and latest developments. On this basis, they should ensure the scope of their project is well-defined and unambiguous, consider the use of MMC from the project inception stage and, if appropriate, hire architects that are fluent with MMC and have experience designing such type of project.

The above may prove a challenge for numerous architects, as their knowledge and educational background are often limited to traditional design (in priority) and construction approaches. One solution would be to integrate MMC and building product mode of design in architect cursus of schools of architecture: it would simply reverse a previous educational trend in architecture schools favoring design over construction methods, and revert closer to the pre-existing condition of architects as master builders, when they were in charge of design and construction altogether. This evolution may be necessary over the long-term for architects to avoid losing market shares. Some of their colleagues, such as Boston-based Turkel Design and New York-based Resolution 4 Architecture, are already specializing in customized prefabricated home design (Berg, 2017). In addition, wide adoption of MMC may trigger vertical integration in the industry, which could encourage manufacturers to take over design phase: Katerra, for instance, proposes a turnkey solution that integrates design, prefabrication and assembly. Nevertheless, such setup does not provide any independent party opinion to counter-balance the power of manufacturers/contractors: this is a role that architects could play if they become knowledgeable in MMC.
3.2.3. Formalization, Standardization and Mass Production

One of the main features of the proposed paradigm is the formalization of construction processes and standardization of built products' main components: the idea is to switch from a project-driven informal system to a production-driven system. The use of a formal production model would help managing production process' inherent complexity. By making complexity more manageable, this system would minimize cost and time variability by bringing production under tight control (Shewhart, 1931; Shewhart et all, 1939). Those concepts are the basis of modern production optimization methods such as Lean Construction, Last Planner and Just in Time theories (Alarcon, 1997; Ballard et all, 2002). Such standardization would provide numerous advantages.

First, it would improve construction process' efficiency by allowing repetitive manufacturing, task separation and ultimately continuous improvement. Repetitive manufacturing is the production of discrete units in a high volume using fixed routings: just the opposite of construction at the moment. Nevertheless, a discrete construction project may be broken into several units, creating an artificial repeatability. For instance, the installation of windows on the World Trade Center One is unique and not repeatable. But if the installation of a single window on this building is considered a process itself, and the Freedom Tower's 21,900 windows are all standardized, the installation process can be viewed as repetitive, creating opportunities for process improvement as lessons are learned while installing the first windows (World Economic Forum, 2016).

Such process formalization and repetitiveness would also allow the implementation of task separation: instead of construction workers performing very different tasks with varying degrees of success, those workers would be allocated a specific task on the basis of their intrinsic qualities, and would become even more skilled at their specific tasks as repetitiveness allow for many iterations of performing the same task. If structurally managed, this could provide a basis for a continuous improvement system.

Second, standardization would improve quality of the built products. Formality and complexity management would lead to lower rework rates since initial product and process design would be more precise and less ambiguous. In addition, formality and repetitiveness would also allow for more quality checks than conventional construction, and their potential for automation could also reduce human error. Such quality improvement could help solving tolerance problems, which could boost prefabrication.

Third, standardization may substantially reduce construction costs, as it would improve construction efficiency as explained above, and would also improve the transparency and competitiveness of the industry, especially if such standardization is coupled with free-access and free-use widely-adopted standards.

3.2.4. Modularization/Componentization

Another main feature of the proposed production-based system is the modularization or componentization of built products, as overviewed briefly in section 2.2. This thesis will rather use the more generic term “componentization”, as “modularization” (which is probably the most
intuitive term) is already widely used in the industry to define one specific form of building componentization. Componentization can be loosely defined as the breaking down of built products into a discrete and finite number of interchangeable components: the concept is to regard buildings as complex modular objects rather than single, indivisible and monolithic permanent sculptures.

Componentization of buildings can take several forms that are relatively well defined in the industry. A form of classification uses the scale of componentization. First, entirely prefabricated assets, very rare as they must be very small to allow for transportation. Next, modular or volumetric structures, where components are built as box-like 3D modules (often reflecting complete rooms or sections of a building, such as bathrooms or hotel rooms) that are transported to the site for final assembly. Next, panelized components (often representing walls, slabs and roofs), easier to transport and 2D-equivalent of modular components. Finally, smaller Lego-like components that can be combined into bigger structures that compose buildings: those components may allow for easier transportation and flexibility (to modify or upgrade the structure), but require more work on-site (World Economic Forum, 2016; Ozorhon et all, 2014).

In addition to allowing repetitive manufacturing as discussed in 2.2, componentization is also an absolute prerequisite for off-site prefabrication, as one of construction’s main peculiarity, compared to other industries, is the size of built products, which makes transportation of finished products impossible (at the exception of very small buildings): in this context, MMC involve both product innovation (componentization, to make prefabrication possible) and process innovation (off-site prefabrication, discussed in 2.4). On top of allowing repetitive manufacturing and off-site prefabrication, componentization offers many other advantages, as described below.

3.2.4.1. **Non-Permanent Buildings: the End of Immutability**

Componentization makes possible a major change in the current view that buildings are permanent and immutable (at least in Western culture). Buildings are actually never permanent, but such cultural mental construct leads to the building of monolithic, non-upgradable buildings, which creates various issues (Novikov, 2016).

First, even traditionally-built buildings are complex products whose components have very different service lives, from the structure (actually close to be permanent) to the MEP (around 20 years) and now captors and wiring required by the Internet of Things (around 5 years). Traditionally-built buildings are often not designed with future renovation in mind, with wires, plumbing and electronics buried inside walls or floors: renovation hence requires partial demolition without a possibility of fully recycle these materials, with makes renovation time-consuming, expensive and messy.
Second, buildings themselves have a useful lives that may differ from their service lives. As urban economic cycles and cultural/sociological trends are much shorter than buildings' service lives, a majority of buildings can become functionally obsolete before their physical end-of-life, either during downturns when neighborhoods of abandoned permanent buildings create additional burden on public infrastructure, or during booming periods, when functionally obsolete permanent buildings constrain and slow down the pace of redevelopment.

Componentization may be the answer to those issues, by designing buildings, from the planning stage, as upgradable and reconfigurable assembly of interchangeable components. Such components should be assembled, and not glued together (concrete), to allow for future maintenance, replacement or disassembly.

To cope with heterogeneous service lives, components with shorter service life such as captors or MEP, should be made more accessible and separated from components with a longer service life. This is not different from the automotive industry, where cars are designed to ensure easy access to consumable spare parts such as bulbs, battery or filters. It allows for an efficient building maintenance: companies like Sekisui House offer to keep track of all components' service lives and proactively conduct maintenance, similar to the way cars are serviced (Novikov, 2016).

Componentization could also provide limited improvement to buildings' configurability, which could help reducing the gap between physical and functional life span. This would be mostly
limited to intra-use configuration updates though, but could be a solution for specific types of tenants, such as office and retail, that require from time to time reconfigurations which are problematic with traditionally-built buildings, mostly due to load-bearing interior walls. For instance, DIRT Environmental Solutions propose an innovative version of modular prefabrication with walls and rooms that can be reconfigured in hours (Moore, 2017). Also Google plan to move its headquarters under a canopy structure (intended to provide light and create an interior microclimate) where robot-crane hybrids called “crabots” would automatically configure and re-configure on-demand the interior landscape to suit the company’s ever-changing needs, by using a clip-on system of steel columns and monocoque floor plates weighing up to 10 tons (Hanley, 2015).

3.2.4.2. Disassembly vs Destruction

As discussed, componentization can help reconfiguring buildings at the end of their functional life (at least when considered ahead), but it represents more of an ad-hoc solution when limited same-use reconfiguration is required, and may have little interest if a building’s entire high and best use changes. For instance, if an entire office building needs to be transformed into a residential or retail one, sometimes the most efficient solution may be to simply scrap the building, as too many characteristics such as floor plates, height between floors, etc. need to be upgraded.

Fortunately, those radical reconfiguration needs are probably less frequent than physical obsolescence or ad-hoc reconfiguration needs. In addition, componentization can actually facilitate the scrapping of a building as well, as it is way easier to disassemble componentized buildings than to demolish traditional buildings. In this context, closed-loop circular economy regenerative concepts may be adapted and integrated into construction: Circular Business Models, taking the entire lifecycle of a product into account, may be used to design reusable buildings in order to plan for future disassembly, re-use and/or recycling of building components (Stocking, 2017).
Reusable buildings may help improving construction’s sustainability: the industry consumes a lot of raw materials, and such materials risk becoming scarce and therefore more expensive, not even mentioning the pollution relative to those materials’ carbon print. Instead of throwing components to waste, they could be resold for use in other buildings if construction systems standards exist and are widely used: requirement for fresh, raw materials as well as pollution related to demolition waste would be substantially reduced. A prefabricated house builder like Sekisui House goes so far as to provide trade-in programs for used buildings in exchange for newer constructions (Novikov, 2016).

3.2.5. Off-site Prefabrication

At the heart of many of the advantages promised by the switch to a production-driven system, is off-site prefabrication. Off-site construction consists of the “planning, designing, fabricating, and assembling of building components at a location other than their final installation point, or outside of the construction field”. Prefabrication and modular/componentized construction both fall under the offsite construction umbrella: prefabrication refers to the “creation of building components at a factory or manufacturing site, before they are assembled onsite” (CB Insights, 2017). Hybrid systems also exist: for instance, Skanska has developed a new concept called “Flying Factories”, which are temporary factories that are set up close to construction sites in order to profit from both on-site (minimized transportation costs) and off-site advantages (World Economic Forum, 2016).

Although this setup has been around for decades, off-site prefabrication has gained a lot of traction lately: in particular, Chinese company Broad Sustainable Buildings has developed a “construction process in which 90 percent of work is carried out in its factories, with the balance being on-site assembly. Repeatable designs and elements are used to simplify the structure and increase scale. Using these techniques, the company has built namely a 30-story hotel in 15 days. It estimates that costs were 10 to 30 percent lower than for a similar building constructed with traditional methods” (McKinsey, 2017). Off-site prefabrication also impacts the way different parties interact and communicate: this is why different tools have recently been developed, such as cloud-based collaborative software platform ManufactOn, which manages prefab production materials and the related prefabricated construction supply chain (Molitch-Hou, 2017).
There are still a few challenges for off-site prefabrication to overcome in order to attain wide diffusion, which explains its global adoption is rather heterogeneous (some of prefab hot spots are Japan, Germany and Scandinavia). Prefab suffers in some markets from a poor image about quality, price and potential for customization (it is sometimes confused with manufactured or mobile homes in the US). Many customers are also reluctant to commit to particular off-site suppliers, as many systems are patent-protected and no free-use standard exists, which makes it difficult to find an alternative in case of dispute. Next, transportation costs and related practical complications can be an issue and undermine prefab economic rationale. Last, manufacturers themselves are reluctant to invest in such system: prefab requires a very substantial upfront investment, and notorious construction demand unpredictability makes recoupment uncertain. Yet, as mentioned, off-site prefabrication has also many advantages.

First, one of prefab’s most obvious advantages is to shorten construction period, as off-site construction of prefabricated components can take start before or at the same time as site work and foundation, whereas construction can only start after site work and foundations are finished in traditional construction. The more fabrication that can be accomplished off site, the more time can be saved on site: optimized project management would ensure that prefabricated components are built, shipped and be ready for assembly at or around the end of foundation works. Saving time may have major effects on the economics of a project: earlier completion would allow to put the building to work and turn the project into a stabilized property more quickly. In addition, profit made by developers is typically derived from performance-based promote that is calculated from the project’s Internal Rate or Return (IRR) and hence is very sensitive to timing: shortening construction period can maximize a project’s IRR and magnify developer’s performance fees.

Second, off-site prefabrication can allow construction companies to cope with several site-specific complexities. As less work is performed on-site, project suffers less from inclement weather and safety procedures required by population proximity are limited (Antunes and Gonzales, 2015). Prefabrication also simplifies procedures to be performed on-site as they are mostly limited to assembly: such procedures require less workforce and may be performed by unskilled workers, which avoids the need for skilled workers that are not available in all areas. Next, procurement management is made easier as well, as prefabricated components can be brought to the site in a “just-in-time” fashion compared to traditional construction’s bulky raw materials that are difficult to store and process in space-constrained sites. Impact on transportation is more uncertain though: on the one side, delivery of raw materials is probably easier and cheaper to off-site factories (whose location has been determined namely by materials accessibility in the first place) than to randomly located construction sites that may be far from any materials supply and even lack proper transportation routes. On the other side, prefabricated components must also be ultimately transported to the site, and transportation restrictions may apply, depending on the scale of componentization.

Third, off-site prefabrication would improve project management and process efficiency as productivity is higher in a controlled environment such as a factory than it is on-site. In addition, stable and controlled environments are more automation-prone as they are more adapted to the
use of industrial robots like in manufacturing. In this context, prefabrication could experience substantial growth as robotics and automation develop and become more practical and affordable: it is no coincidence that countries with large prefabricated construction markets, such as Japan and Germany, are also leading manufacturers of industrial robotics and automation systems (Francis, 2017). Prefabrication also improves safety as common job site dangers are minimized in a controlled and well-supervised environment: as most assembly chains take place on the ground floor, there are fewer risks or employees falling off scaffolding for instance. Next, prefabrication is more sustainable, as production in a factory allows a drastic reduction in wasted materials (that may be recycled for other projects fabricated in the same factory), consumes less energy, and reduce pollution (Laher, 2017). Last, off-site construction may solve many of construction’s current workforce issues: prefabrication facilities can be located on purpose in areas with available skilled workers and require fewer personnel due to formalized processes and efficiency related to repetitive manufacturing and task separation.

3.2.6. Industry standards

New production-driven construction system will need to overcome a critical obstacle inherent to any innovation in order to attain wide diffusion: system interchangeability among suppliers. If a supplier's system is patent-protected and incompatible with systems proposed by other manufacturers/contractors, committing to such supplier for a large-scale project would be very risky for a developer as such system exclusivity would put the supplier in a monopolistic situation in case of a dispute (over a budget increase for instance): this undermines the concept of true cost we have tried to develop previously, and weakens construction’s competitiveness.

Various mitigation strategies exist: strong wording may be inserted in the contractual agreements, but this may not change the fact that, at the end of the day, developers would probably still be the entity with the highest value at risk (in case the project is delayed), especially as elaborate corporate structuring such as Special Purpose Vehicles may limit manufacturers/contractors exposure. An alternative structural solution would be to develop industry-wide standards that would ensure most of the various manufacturers’ construction systems are interchangeable. Such standards may be sponsored and/or mandated by public authorities, or alternatively system patent holders could waive or rent their rights and make such systems free-access and free-use, maybe through compensation such as franchise fees, in order to ensure wider diffusion of their systems if the economics make sense. System developers may also develop BIM add-ons for designers to model virtual construction using their systems should they wish to, in order to help integrating such systems all along the supply chain.

Such standards may focus on components, connections, or preferably both. An example of standardizable connection would be the “Vector Bloc” developed by Vector Praxis. This approach is similar to consumer electronics with common standards such as USB ports that remain unchanged through generations of products.
VectorBloks are connected vertically with high-strength bolts and horizontally with a “Gusset Plate” sandwiched between machined faces. The resulting 12-way connection delivers vertical tension capacity, good fixity and diaphragm action attributable to the module floors.

Image 28: Vector Bloks connection system

An example of standardizable component could be the double-Y-shaped beams and slab floors developed by Chinese firm Broad Sustainable Building. This design has achieved 9.0-magnitude earthquake tests thanks to this unique column design, with diagonal bracing at each end and tabs that bolt into the floors above and below. The efficiency of the system allowed the company to build a 30 story building in 15 days (Hilgers, 2012).

Even transportation truckloads are standardized: each load carries two modules to the site, with the necessary columns, bolts, tools, and other peripherals to connect them stacked on top of each (Hilgers, 2012).
3.3. Procedures to be Performed On-site

As efficient as a production-driven system may be, construction sites will have always heterogeneous conditions (existing buildings if brownfield, slope, etc.) that need to be coped with: efficient processes need to be developed in order to prepare sites for the assembly of prefabricated components. In this context, recent innovations may be of a great help, namely for demolition of existing structures, excavation and foundations. In addition, some procedures may be more efficient when performed on-site, like envelope systems. Last, the use of robots for on-site assembly of prefabricated components is still science-fiction at the moment, but spectacular advances in automation (especially drones) could make it possible in a near future.

First, automation can be used to help demolishing existing structures that need to be torn down to build a new project. Several companies such as Brokk or Husqvarna have developed demolition robots that are capable of powerful blows in very space-constrained environments (O’Malley, 2015). Some of these robots, namely the ERO robot developed by Omer Haciomeroglu, can even break concrete into pieces small enough to be recycled for other projects, without dust or waste of water (Grozdanic, 2014).

Image 31: ERO “concrete-eating” demolition robot
Second, there are major developments at the moment in the automation of excavation equipment. For instance, Komatsu is developing automated bulldozers integrating physical and digital systems. "Drones, 3D scanners and stereo cameras gather terrain data, which is then transmitted to the bulldozers; these are equipped with intelligent machine-control systems", i.e. autonomous decision-making systems based on Artificial Intelligence concepts that enable them to carry out excavation work autonomously. This allows for higher equipment utilization ratios, reduction of manual errors and speed-up of excavation work on construction sites: on mining sites, autonomous haul trucks are already in common use (World Economic Forum, 2016).

Third, 3D printing has gained a lot of traction in the media, to the point that some practitioners consider it to be the future of construction. 3D printing has not been covered intensively in this thesis as, by essence, it operates within the legacy mindset of permanent buildings and may provide limited upgradability and configurability. In addition, 3D printing in the construction industry is still at an early stage of development: it still suffers from resolution problems, speed, scale (in case of gantry system), high costs, and materials inefficiency. Nevertheless, concrete 3D printing could be an interesting solution for foundation work where optimization of materials, overall appearance and flexibility regarding future uses are less of a problem.

Last, clients' expectations about energy efficiency are getting higher by the day, and some European countries now require proof of a particularly high energy performance in order to grant building permits. Such performance depends namely on a building's airtightness, thermal bridge-free construction and thermal insulation. Airtightness in particular, is somewhat problematic with prefabricated construction: prefabrication accuracy is getting better and better namely with automation, and can offer lower and lower tolerances, but is not perfect. In addition, compression of lower-floor modules (due to the weight of modules above them) can be problematic on high structures. In this context, on-site cladding is often preferable. Brick cladding in particular is interesting, as brick is a small enough module that it can cover a multiple of defects (Alter, 2017). There have been a few initiatives that recently lead to commercialized brick-laying robots: as an example, New York-based firm Construction Robotics has developed a robot called SAM (Semi-Automated Mason). Such robot can lay around 3,000 bricks a day, compared to an average of 500 bricks for most human masons (Dormehl, 2017).

![Image 32: SAM, the bricklaying robot](image-url)
CHAPTER 4: INNOVATION ENABLERS

Research studies are in agreement to document that innovation is critical to survival and renewal of industries in general (Shabanesfahani and Faraj Tabrizi, 2012). Nevertheless, as discussed in subchapter 1.1.2.1, innovation is risky and very often unsuccessful for individual companies: some go as far as comparing investing in innovation to gambling or buying a lottery ticket (Orstavik et al, 2015). In many cases, innovation is so risky that it makes total economic sense to avoid investing in it on a micro level.

This situation is even more acute in construction, partly due to its fragmentation, preventing innovation investment on a macro level as well: various studies purport that, compared to other industries, construction is particularly slow to take-up innovations in the absence of specific driver or motivator (Nam and Tatum, 1997; Wamelink and Pries, 2007; Whyte and Sexton, 2011), regardless of the “process undertaken and the nature of the adopters” (Gambatese and Hallowell, 2011b).

In this context, it is not expected that most construction innovations will diffuse rapidly until a particular demand is created for it: quick adoption hence depends considerably on the existence of factors known as “motivators, enablers or drivers” (Nam and Tatum, 1997; Winch, 1998; and Bossink, 2004). To find out who those enablers are, we will refer to the Winch’s Model (Winch, 1998), initially developed on the basis of research on flight simulators and extrapolated to complex products systems (Miller, 1995). Such complex products systems are defined as having the following characteristics, which are found in construction as well: “first, they are composed by many interconnected and customized elements organized in an hierarchical way; second, they show nonlinear and continuously emerging properties where small changes to one element of the system can lead to large changes elsewhere in the system; and third, there is a high degree of user involvement in the innovation process” (Winch, 1998).

Winch’s Model is composed of a three-layer system that is composed of an innovation superstructure (consisting of clients, regulators and professional bodies) and an innovation infrastructure (consisting of specialized trade contractors, consultants and component suppliers): the interface between the two is represented by system integrators (principal architects, engineers and general contractors).

Image 33: Winch’s innovation structure (Winch, 1998)
The innovation superstructure governs the innovation environment, specifying demand (clients and public authorities), regulating performance (regulators) and supplying knowledge processes and tools (professional bodies) to the system integrators. Those system integrators create the link between construction infrastructure and superstructure and ultimately assemble complex systems products (as defined by Miller et al., 1995), using components and subsystems supplied by the innovation infrastructure.

Extensive research that has been carried out on such innovation structure and innovation diffusion consistently propose that adoption of innovation in construction occurs only if the superstructure plays a sufficiently strong role. Some of those studies even mention that the superstructure must actually take the initiative and assume a leading role by formulating clear demands for the industry to take steps in adopting innovations (Orstavik et al., 2015): clients, in particular, are in the best position to take such lead, at least if they are big enough to generate a significant demand and impact the market.

On the infrastructure side, manufacturing firms are key source for construction innovation. They are in a better position than contractors and consultants to provide innovative building products buildings as they tend to operate in more stable and standardized markets, which allow them to adopt a longer term vision, maintain R&D programs and knowledge bases, and engage in virtuous circles of learning as their activities are not project-based (Blayse and Manley, 2004).

Many manufacturing firms do their best to promote their products and diffuse their innovations themselves. Nevertheless, recent studies purpose that even though those “technology-push” strategies are indispensable (along with manufacturing firms’ efforts to develop new products), they are generally not sufficient to ensure wide diffusion on their own. Such studies took BIM as an example: such technology had been around since the 1990s, but its diffusion accelerated only when public sector commissioning bodies started mandating it for new projects: wide diffusion was only achieved when a “market pull” was added to the “technology push” driver (Orstavik et al., 2015).

Things may change though, as recent investments in construction tech have truly gone through the roof in recent years. In particular, Katerra has become one of the few Unicorns (i.e. private company valued at more than $1 billion) in the sector; defining itself as a technology company, it is trying to revolutionize the way buildings are developed, designed and built. It remains to be seen if such “technology push” triggered by Katerra and others will be successful this time (and independently of any “market pull”).

In this context, and as this thesis is primarily addressed to developers, our analysis of innovation enablers in the construction industry will focus on its superstructure and will be meant as a wrap-up of this thesis (namely Chapter 3), as well as a check-list that may be used by owners and developers when planning a project and selecting stakeholders and suppliers.

4.1. **Clients (including public sector)**

As mentioned before, clients are commonly considered to have “enormous capacity to exert influence on firms and individuals involved in construction in a way that fosters innovation” (Blayse and Manley, 2004; Barlow, 2000; Gann and Salter, 2000; Kumaraswamy and Dulaimi, 2001; Nam and Tatum, 1997). Their commercial power (provided they have a sufficient scale) may allow them to simply mandate processes or products, but it appears that the leadership they may bring to a project is truly one of the main enablers of innovation in the construction literature (Ozorhon et al. 2010). Previous research shows that leaders can “play a critical role in shaping project spirit” (Aronson et al. 2010, 2013), “resulting in the project team committing to the project objectives” (Aronson et al. 2006).

Unfortunately, not all clients may be able or willing to act as innovation leaders: some already act as innovation leaders for other industries, and are more concerned with innovation in relation to their own core business than with construction innovation. Some others are too risk-adverse and prefer to stick to “traditional” setup, or may not be sophisticated enough to make a difference. For those reasons, several national guidelines on exercising the role of a construction client have been developed in some countries (Orstavik et al., 2015). Indeed, clients may foster innovation in the construction industry in many ways.

First, clients may want to try and forecast their construction needs in order to group them into pipelines to build up scale. Not only it will give them more negotiation power with projects’ shareholders and cost savings from scale economies, but it will provide more visibility to such shareholders to the future demand for their services, which may make them more willing to invest in innovation.

Second, clients may want to develop their construction technical knowledge in order to allow them to take over a leadership role and share such knowledge with project participants. In addition, clients should keep themselves up to date with recent innovations and future trends within the industry. For instance, this may evolve creating and maintaining internal construction management and innovation groups. Large-scale clients may also invest in their own internal R&D. Clients may also create brainstorming groups to shape corporate-level views of the future paradigmatic evolutions within the construction industry, and develop their own specifications based on such views: for instance, mandating the use of modular construction and off-site prefabrication when possible, and setting configurability and upgradability objectives to facilitate asset management.

Third, once they have attained a certain scale and level of technical sophistication, they can put their commercial power at play and exert pressure on project participants (Ozorhon et al., 2014) for higher standards of work leading to improved performance, flexibility, cost and budget, as the
more “demanding and experienced the client, the more likely it is to stimulate innovation in projects it commissions” (Barlow, 2000; Shabanesfahani and Tabrizi, 2012).

Fourth, more stringent standards of work requirements may need to be compensated by some flexibility. Clients may need to accept to avoid overdesign and communicate with their architects accordingly in order to favor production processes formality: clients should try and define the right mix between standardization (to minimize costs) and customization (to fit their needs) as well as verify if elements of design are not too difficult to build or exaggeratedly increase costs. Clients may also want to promote and sponsor the use of risk-sharing, fair and collaborative delivery systems in order to avoid any adversarial mindset that would be detrimental to innovation.

Fifth – when hiring or contracting, clients may want to favor long-term relationships with project participants, or maybe even combinations/alliances of participants ideally, in order to enjoy synergies, cooperation processes, communication channels, and innovative ideas that may have been developed in past projects. In this context, selection process may include other metrics than only cost: professionalism, track record and efficiency should also be examined, and any additional cost may be compensated by a lower project risk. At the same time, owners should stand for their rights, and use their industry knowledge to ensure the rigorous competitiveness of the bidding process: owners need to require final drawings from architects, require confirmation by contractors that such drawings are complete and may not lead to change orders, ensure bids reflect the project’s true cost, and anticipate any dispute by inserting strong wording in the contract and verifying the chosen construction system is compatible with market alternatives in order to avoid any supplier monopoly.

Last, clients may want to interact with the regulator to discuss the impact of current regulations, explore the needs for new regulations, and ensure good relations. As already discussed in subchapters 3.1.1 and 4.2 below as well, a regulator has a tremendous impact on innovation diffusion, as least as important as clients themselves. In this context, clients may want to assemble in professional organizations (gathering real estate developers, asset managers and corporate owners) in order to set up an as efficient advocacy strategy as possible: there is no theoretical reason such strategy would be unsuccessful as taking the industry forward should be a common goal for both parties.

In summary, clients may take the following initiatives in order to foster innovation and improve productivity in the construction industry:

1. Build up scale by grouping projects into pipelines and assemble in professional organizations;
2. Develop their construction technical knowledge and keep themselves updated with the most recent innovations and future trends;
3. Invest in their own R&D and share their knowledge with project partners;
4. Develop their own specifications for future projects to promote products configurability, upgradability and disassemblibility;
5. Avoid overdesign and arbitrate between customization and standardization;
6. Encourage design constructability and manufacturability as well as industrialized production systems such as prefabrication;
7. Promote and sponsor the use of risk-sharing, fair and collaborative delivery systems to ensure a collaborative mindset among all project participants;
8. Require higher standards of work regarding performance, flexibility, cost and budget;
9. Require drawings completeness and restrain from fast track delivery methods;
10. Require contractors to confirm the drawings are complete and will not lead to change orders;
11. Impose true cost bidding;
12. When hiring, take efficiency into account besides cost;
13. When hiring, favor long-term relationships and alliances to keep synergies;
14. Include fast dispute resolution paths in agreements preventing project stoppage;
15. Ensure construction systems do not put any market participant into a situation of monopoly;

4.2. Public authorities

Many of the initiatives that may be taken by regulators in order to incentive innovation and boost productivity within the construction industry have already been discussed in subchapter 1.1.2.1 as well as in subchapters 3.1.1 and 3.1.2. Regulators may have an influence both on the “technology push” and the “market pull”.

Regarding the “technology push”, regulators may first want to ensure building codes do not constitute an obstacle to construction innovation. Such codes should be harmonized from a geographical and administrative perspective in order to favor mass production. In order to cope with the innovation pace, building codes should also be updated regularly to reflect technological changes and drafted in a way that makes them more adaptable: the best solution would be to implement outcome-oriented regulations when possible, leaving the developers/contractors the choice of the building system and the opportunity to adopt new technology as long as minimum health and safety requirements are attained. The main drawback with this strategy is that it may require substantial efforts by public authorities to ensure their requirements are met, but this is something that may be outsourced to reliable third parties.

Second, public authorities may want to simulate innovation by construction's supply. They may choose to impact supply indirectly: for instance, they may favor market openness to international firms in order to simulate movement of capital, technology and skills as well as opportunities for economies of scale. It would also promote competitiveness which would oblige supply to invest in technology to maintain or acquire a competitive advantage; competitiveness could be further strengthened by publishing performance data on contractors. They may also choose to impact supply directly, by creating a more fertile environment for innovation and sponsoring R&D by the private sector and academia, and by developing labor skills through training and apprenticeship programs in order to favor practical adoption of construction innovation.

Regarding the “market pull”, public authorities may obviously want to leverage their position of biggest construction client (at a consolidated level) to apply the recipes listed in subchapter 4.1: in
particular, governments should skip existing lowest bid approach and review their bidding processes and asset specifications in order to include total-life-cycle cost, sustainability and technology.

Second, public authorities may indirectly favor demand predictability by harmonizing the approvals/permits processes. Instead of requiring the participation of many different agencies, such processes should be streamlined: bottlenecks should be eased, bureaucracy should be reduced and the whole process should be digitized, allowing almost immediate approvals for compliant projects. Processes should also differentiate projects by the risk of impact on their environment, with simple or lower risk projects requiring lighter processes than industrial projects.

In summary, public authorities may take the following initiatives in order to foster innovation and improve productivity in the construction industry:

1. Harmonize building codes from a geographical and administrative perspective;
2. Upgrade building codes as regularly as possible to keep up with innovation pace;
3. Favor flexible outcome-oriented building codes;
4. Differentiate projects on the basis of the risks for their environment;
5. Digitize the review process and reduce bureaucracy;
6. Outsource technical review of projects to third parties to quicken the process and boost demand;
7. Favor market openness to international firms in order to simulate movement of capital, technology and skills;
8. Sponsor R&D by private sector and academia;
9. Develop labor skills through training and apprenticeship programs;
10. Leverage their position of biggest construction client to apply the recommendations addressed to clients in subchapter 4.1.

4.3. Professional Bodies

If innovation is critical to renewal of industries, not all innovations are equal: various studies show that systemic innovations produce the largest productivity gains (Shabanesfahani and Faraj Tabrizi, 2012), which is good as those are precisely the most adapted to construction. Indeed, as discussed in Chapter 3, construction is composed by many systems interacting with each other: a change in one system will impact all other systems, which makes non-disruptive innovations not adapted to the complex construction systems. In this context, incentives for innovation are weak and risky unless the innovation has properties that improve performance of the entire system as systemic innovations do.

Nevertheless, systemic innovations imply that many organizations innovate at the same time, which require effective cooperation, coordination, and working relationships between the different parties composing construction infrastructure and system integrators (Ozorhon, 2013). Such inter-organizational cooperation would be very difficult to put in place in the absence of intermediaries, namely due to construction fragmentation.
In this context, all parties interested in promoting construction innovation may want to regroup and form organizations representing all stakeholders along the value chain as well as relevant experts and academia in order to fully truly represent the interests of the sector as a whole. Such organizations could namely play the role of innovation brokers (Davidson, 2001), consisting of orchestrating co-operation and knowledge growth across the industry as well as acting as an unofficial global meeting places to evaluate the merits of competing technologies (Winch, 1998).

Such professional bodies could first work on developing standards across the industry. The resulting harmonization of products’ technical specifications would have the potential to allow processes industrialization and digitization as well as improve intra- and inter-organizational cooperation. Such standards may be related to software systems (allowing cooperation, communication and digitization), components interfaces (allowing system compatibility and economies of scale, thus improving productivity), costs (allowing fair comparison among competitors and promoting construction competitiveness), and legal agreements (such as alliances and IPD, reducing initial legal costs and ensuring the industry legal stability).

Professional bodies may as well act as information intermediaries. In the past, the tendency within the industry was rather to develop and protect proprietary knowledge in order to have a competitive edge. Now the tendency is rather to share knowledge and join forces to cope with an increasingly complex and challenging environment: it is totally in line with the theoretical concept according to which innovation at micro level can be overly risky and even irrational for a single entity. In construction as in other industries, “first movers are at risk, yet if nobody dares to move, the industry as a whole will be the loser” (World Economic Forum, 2016). To break this vicious circle and avoid stagnation, industry-wide joint efforts may be brokered by professional bodies, acting as producers, repositories and disseminators of knowledge (Winch, 1998; Manseau, 2003).

Such role of a neutral, respected information intermediary would help firms to become aware of cutting-edge technologies and competencies: such increased knowledge sharing would also help closing the gap between technological development (plenty at the moment in the construction industry) and diffusion (way more tricky). Finally, professional bodies could leverage on their position to gather data and publish benchmarking studies to improve the transparency within the industry.

It should be noted as well that such cooperation should take place not only among peers, but between companies of different types along the value chain as well. In the past, the tendency within the industry was to try and “push risk down the value chain instead of pulling innovations out of it” (World Economic Forum, 2016). Nowadays, the tendency is rather to erase industry boundaries and encourage cross-industry collaboration in order to favor the pulling of innovations, with the expansion of integrated project delivery methods as an example.

In summary, the various constituents of the construction sector may want to assemble in professional bodies that would take the following initiatives in order to foster innovation and improve productivity in the construction industry:
1. Develop standards across the industry, particularly in relation with software systems, components interfaces, costs, and legal agreements;
2. Act as producers, repositories and disseminators of knowledge;
3. Gather data and publish benchmarking studies to improve industry transparency;
4. Act as a unofficial global meeting places to evaluate the merits of competing technologies;
5. Represent the interests of the sector as a whole.
CHAPTER 5: CONCLUSION

There has been a recent boom in construction tech due to substantial investments by industry outsiders like private equity firms, and recent developments in digitization and automation. Nevertheless, such initiatives seem uncoordinated: as a consequence, the adoption of those innovations by clients is slow. In this context, the ultimate goal is to provide a vision for the future of the industry under the form of a new construction paradigm. Such guidance may be implemented by clients and other members of the industry superstructure through a list of recommendations developed in this thesis.

Construction demand may use those recommendations to define their specifications and orient their tendering processes in such a way those will favor the adoption of a production-driven system by pressurizing industry supply into adhering to this strategy. Such demand requirements consolidation and preferences communication will provide directions to industry supply as to how orient their technology developments, and will ensure the meeting of “technology push” and “market pull” to favor the diffusion of construction tech innovations.

In this thesis, I employed Ozorhon’s innovation structural framework. To implement this framework, I have first examined barriers preventing innovation in the construction industry. My analysis revealed that the three main causes are a lack of competitiveness, industry fragmentation and informality of the construction processes. Digging deeper to analyze interactions with other factors, I found that such issues are in turn due to other root causes, which are numerous across the industry. Namely, a lack of competitiveness is due to non-repeat-client culture, information asymmetry, poor specifications and mutable cost. Moreover, fragmentation is due to demand unpredictability, built products uniqueness and lack of competitiveness. Lastly, processes informality is due to building products uniqueness, complexity and size, as well as lack of building code harmonization. Combined, these factors lead to significant barriers in the adoption and diffusion of innovation.

Second, I discussed the main drivers that may be pressuring the industry into improving its productivity. The industry itself is confronted with societal challenges that make it more and more difficult to recruit a skilled workforce. Industry demand can no longer accept the gap between increase in construction costs and inflation, which leads to housing crises, infrastructure underinvestment, and threatens the well-being of society. Last, industry is confronted with disruptive new entrants, whether large-scale construction companies from overseas (for example, Broad Sustainable Buildings) or construction tech start-up companies sponsored by the private equity industry, which may upset some construction markets.
Third, I examined the possible solutions that could be put in place to improve construction efficiency. As disruptive technology exists in the sector but struggles to get adopted by the industry, I theorized that organizational innovations were the most needed as the current construction paradigms and the industry structure may prevent the diffusion of such technologies. Accordingly, short-term solutions regarding current setup have been proposed in order to solve two of three main causes, namely lack of consolidation and fragmentation. Now, a more ambitious and longer-term solution may also be considered as current construction paradigms are the primary source of many of the issues listed before. A change in paradigm may solve those issues as it may generate a structurally sound new ecosystem free of many of the current issues plaguing the industry.

Fourth, I concluded by considering the actions that industry demand may take in order to meet industry supply efforts in modernizing the industry. In this context, the construction stakeholders need to assemble to build up-scale in order to have a significant impact on the market: clients may want to gather in associations to build up pipelines and exchange knowledge, public authorities may want to administratively and geographically harmonize their policies and requirements, and suppliers may create professional bodies to agree on standards and test ideas.

As a summary, construction clients may have now the opportunity to modernize the industry and enjoy better deals by lobbying and pressuring the industry towards the development of interchangeable industry standards and the maturing of modular construction systems. Those initiatives will complement disruptive innovations that have been boosted in recent years. Moreover, these initiatives have been mainly sponsored by private equity firms which are generally
recognized as centers of excellence for strategy. In this way, private equity firms have the opportunity to enhance operations. Once the private equity industry gets interested in a sector, as it is now in construction, it is generally a good sign, as they are in business to reach Internal Rates of Return north of 20%, and are competitive to do so. In this context, clients and developers that decide to engage private equity firms will be involved in revolutionizing the construction industry and may end up being very successful.
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Chapter 4


