Safety and Health in Prefabricated Construction: A New Framework for Analysis

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Abstract

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Given the promise of productivity gains, cost-effectiveness and environmental efficiency, contemporary prefabrication strategies continue to shape not only the means of production and assembly for buildings, but also the extended population of workers and their accompanying job conditions. While the widespread belief is that the impacts from prefabrication will yield healthier and safer conditions when compared to traditional methods, there is little evidence, often contradictory, to support this claim. This study aims to provide a foundation of knowledge on prefabrication in the context of health and safety, and to reexamine the problems associated with occupational risk using a balanced framework.

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INTRODUCTION

In 2018 the construction industry was valued at $1.3 trillion[1] (US Census Bureau, 2018), and market projections anticipate a stable growing trend. Such an outlook presents great economic opportunities for builders and will pressure the industry to deliver at a faster pace. At the same time, The Associated General Contractors of America (AGC) reports that 70% of contractors are struggling to find skilled laborers to fill the current demand (2017). Under this scenario, new reasons arise to use prefabrication, and even more so as quality requirements and expectations for Return on Investment (ROI) rise.

In the latest discourse on high-performing and sustainable built environments, prefabrication promises benefits that hit on all the sector's major concerns: costs, time, waste, and workforce shortage. For every dollar spent on prefabrication, the average benefit-to-cost ratio on a complex building project is estimated to be 1.30 (Mortenson 2015). A McGraw-Hill survey from 2014 reported as much as four or more weeks in schedule reduction, peaks of 6% and higher budget savings, and up to 5% or more in site waste decreases when using off-site technologies (2014).

Productivity gains and competitive advantage are the main drivers to the adoption of prefabrication, while safety is frequently leveraged as one of the benefits to promote its use. The claim that prefabrication is, by default, safer than traditional construction is widespread in the industry, and it is usually explained as a direct by-product of compressed schedules and the need for less human labor on the job site. In risk terms, this rationale is expressed as an impact/frequency trade-off: "the main thing that happens to on-site risks by using pre-assembly

[1] Adjusted value of "Construction Put in Place", or of construction spending.

is that the many, common-place, high-likelihood, low consequence risks are largely replaced by fewer, higher potential consequence risks, which are much less likely to occur as they tend to be easier to identify and control." (Gibb 2004) (Figure 1).

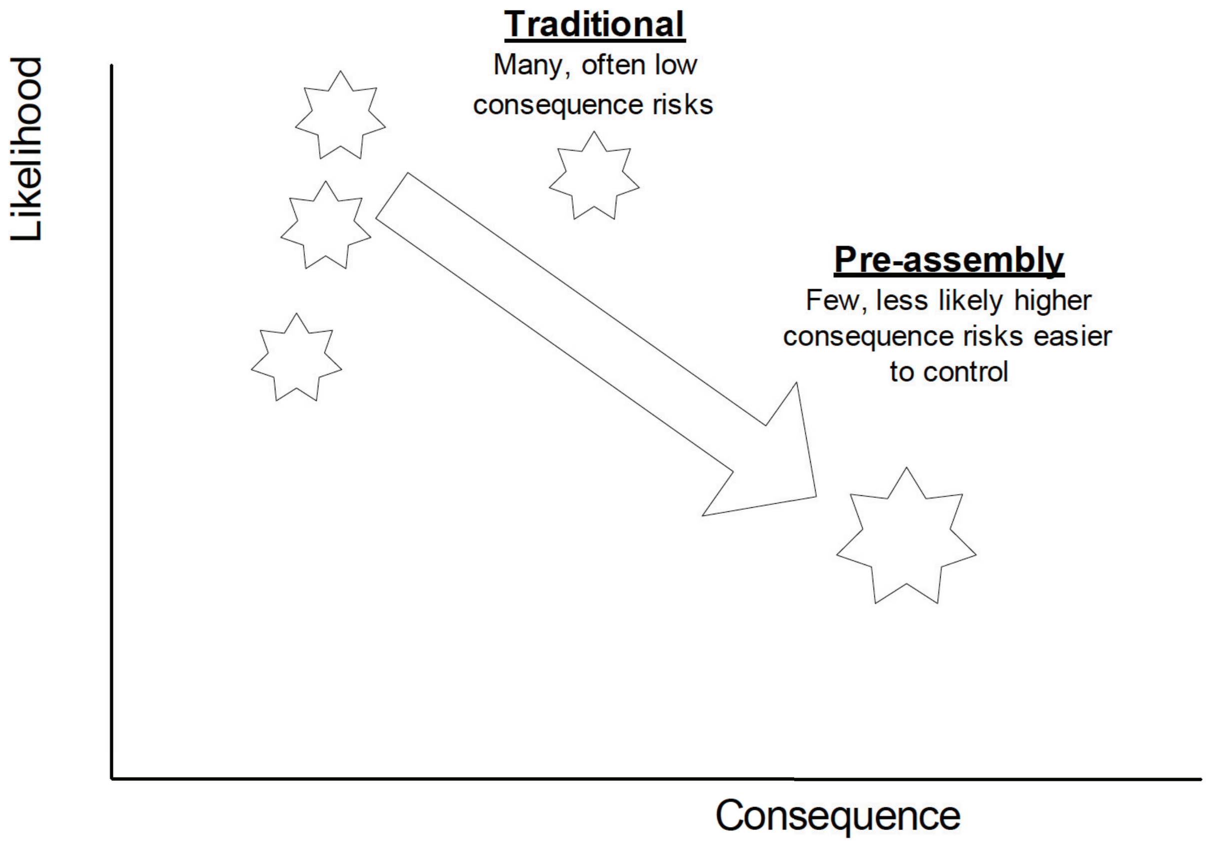

Figure 1. Safety risk comparison between traditional and off-site construction methods. Source: Gibb 2004.

However intuitive, the comparative argument has been inferred, and presented in absolute terms, with no factual evidence to support it. Instead, just as a technology, a contract term, or a single construction delivery method do not fit all projects, the benefits of prefabrication are conditional. This conditionality is particularly true for prefabrication benefits related to safety and health (Figure 2).

Figure 2. What could go wrong: sequence of a construction accident in Austin TX, involving a precast wall component. Retrieved from: https://youtu.be/Mn6PYOG6sWw.

As prefabrication regains currency in the construction industry, it is critical to discern between its different forms and applications, while investigating the implications on workers' welfare, lest unrecognized hazards become a hidden statistic. Only then, once the types and sources of risk are acknowledged by those involved in their design and execution, can off-site processes and techniques offer opportunities for improving work conditions.

This study aims to consolidate the body of knowledge on safety in the context of prefabricated construction practices, and to provide a clear framework of the phenomenon. It will integrate viewpoints from different professions of the built environment to provide a cross-disciplinary research perspective. Lastly, this study will consider, and attempt to overcome, the widespread disregard for considerations of long term occupational health over "in favor of the more immediate, high impact occupational safety." (Gibb 2006).

The target audience of this study necessarily includes those built-environment stakeholders with the ability to prioritize the safety impacts of prefabrication methods –those that design, produce, install and stimulate demand for pre-manufactured products. However, it is hoped that it will also stimulate the interest of professionals and organizations that divulge emerging safety issues, develop training tools, and provide information and consultation services to employers and employees to promote safe workplaces.

This thesis is organized as follows:

Chapter 1 provides a conceptual framework for the research objectives. After introducing the context of prefabrication (definitions, evolution, and ranges of applications in the built environment), it will look at both the present-day drivers for use along with Research and Development (R&D) themes prompted in the design and construction sectors. An overview of safety in prefabricated techniques and processes will preface the literature review in Chapter 2.

Chapter 2 constitutes the first step into the core of the study, and presents a systematic review and discussion of the existing literature.

Chapter 3 outlines the research design, and the methods used to address the research problem at hand.

Chapter 4 presents a descriptive statistical analysis of data gathered from occupational accident records in the US during the decade of 2007-2017.

Chapter 5 triangulates the preceding paths of examination with a hazard and risk analysis applied to four different methods (two traditional, and two prefabricated) of producing, delivering, and assembling a concrete wall system.

Chapter 6 synthesizes the conclusions and the limitations of the study, offering ideas for future research and debate.

Chapter 1. RESHAPING THE CONTEXT FOR PREFABRICATION

1.1 Defining Prefabrication

The practice of manufacturing and pre-assembling building components prior to installing them in their final location is ubiquitous and a core trait of construction. Early examples of such go as far back in time as the Neolithic Period[2].

In its modern connotation, 'prefabrication' originated with the industrial revolution, which allowed the diffusion of cast iron elements and the mass production of raw materials, giving new impetus to the building sector (Knaack at al 2012). The European architectural production of the time reflects the excitement for the possibilities introduced by prefabrication, ranging from the archetypal Crystal Palace to social housing programs (Figure 3, and 4). In the US, the availability of supplies (nails, nominally dimensioned lumber), paired with the extreme standardization of the balloon frame technique, allowed the mail-order catalogue housing boom of the early 1920s and 30s (2012) (Figure 5).

[2] A notorious example is the "Sweet Track" roadway, built in England in 3800BC, which was made of pre-fabricated wood planks, pegs, and log rails (Prasher 2016).

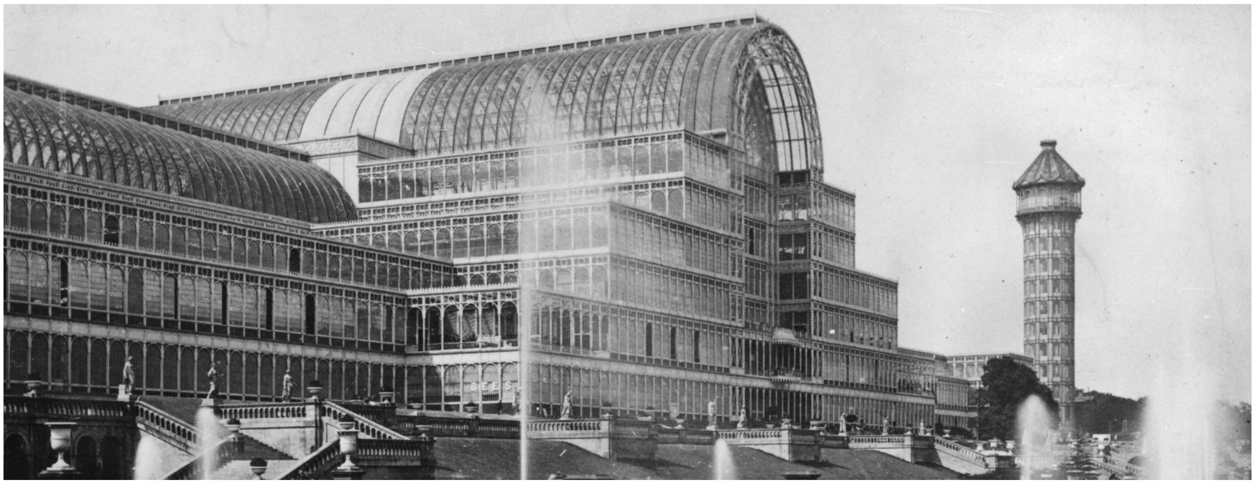

Figure 3. Crystal Palace, by Joseph Paxton (1851). Source: Plimmer G. (2015, October 21) Chinese dream to build replica Crystal Palace shattered. *The Financial Times*. Retrieved from: https://www.ft.com/content/160b03c8-77d2-11e5-a95a-27d368e1ddf7.

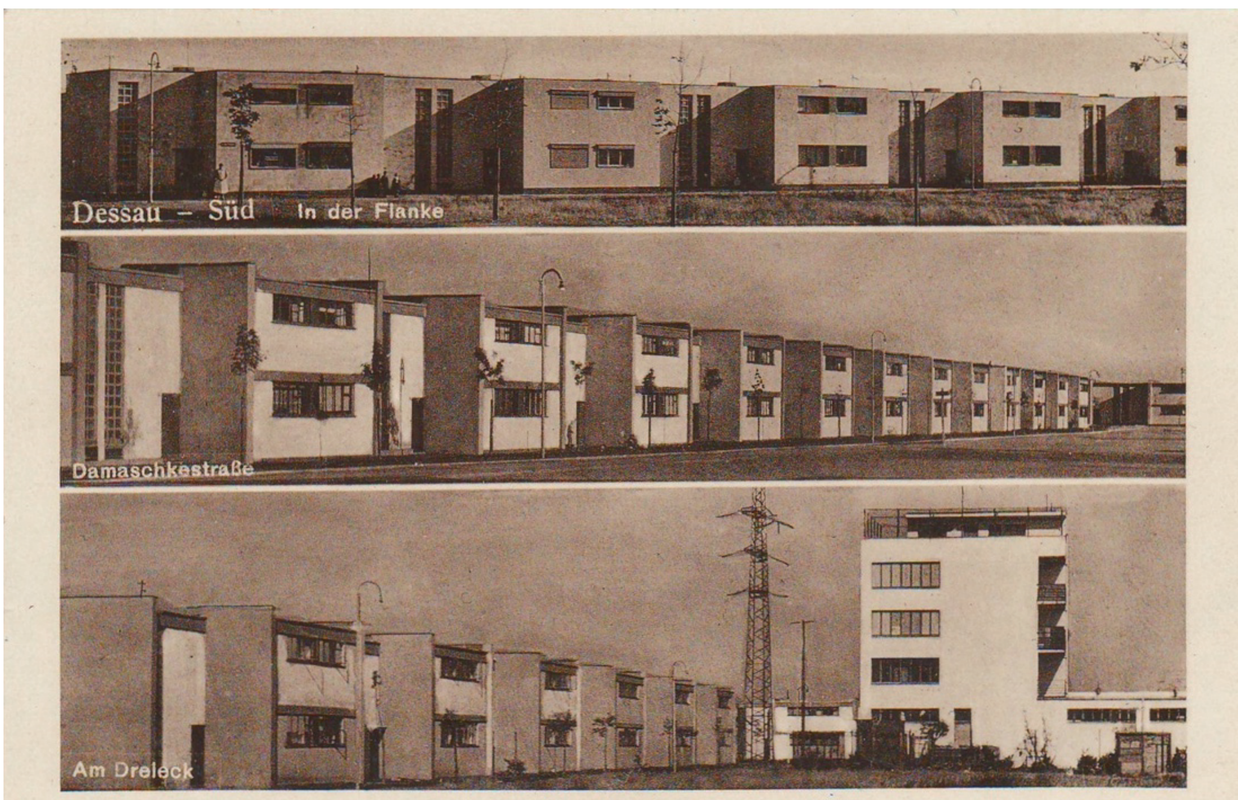

Figure 4. Dessau-Törten Housing Estate, by Walter Gropius (1926-28). Retrieved from: https://www.fostinum.org/bauhaus.html.

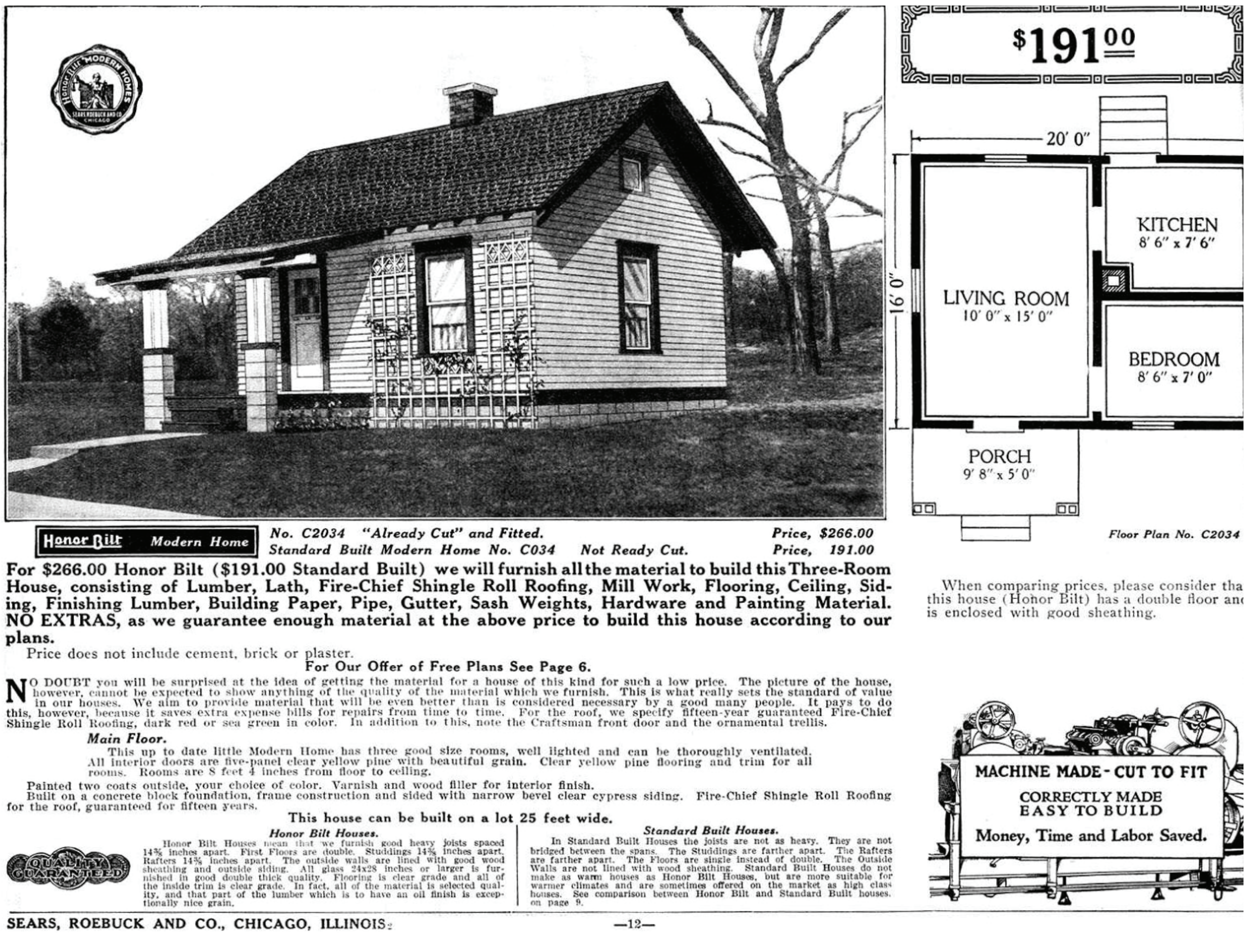

Figure 5. Example of pre-fabricated catalog mail-order home, available at Sears. Model No. 2034, "The Natoma". Retrieved from: http://quonset-hut.blogspot.com/.

Ever since, prefabrication has cyclically re-emerged as a phoenix-like, progressive movement, in the professional and academic arenas. It continues to evolve in significance and scope, alongside technological advancements and the rise of Building Information Technology (BIM) methods, Lean processes, and Green building trends (Figures 6, 7).

Figure 6. Le Haut du Lièvre, Nancy, France, by Bernard Zehrfuss (1960). Retrieved from: http://www.enattendantmieux.org.

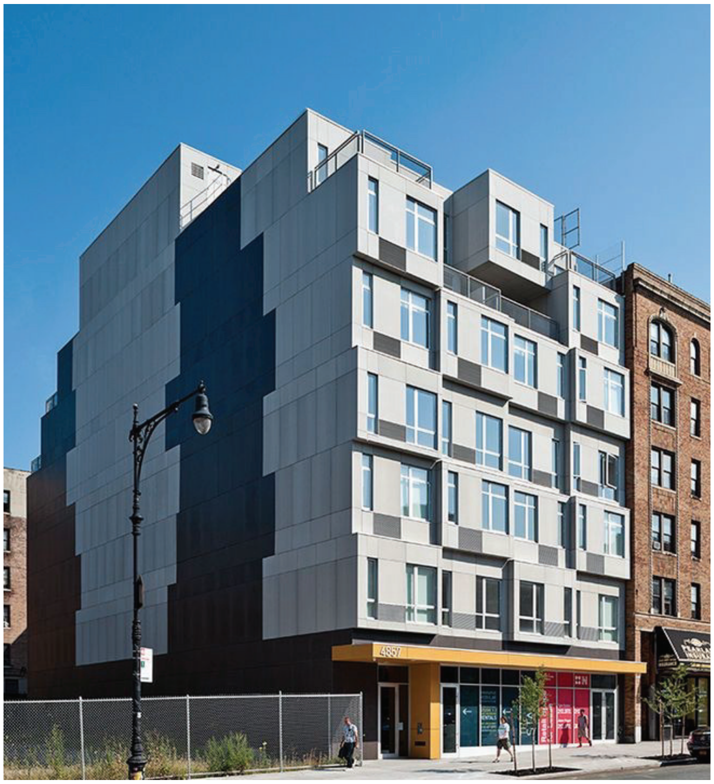

Figure 7. “The Stack”: twenty-eight affordable housing units in New York, by Gluck+ (2014). Retrieved from: https://gluckplus.com/.

Over time, the collective imagery of the post-industrialization age has harbored a notion of prefabrication that draws on stereotypical arguments offered in favor of or against mass production. These arguments often contrast the loss of quality and aesthetics with the gains in production growth, time savings, and economic value. Moreover, prefabrication is often mistakenly considered a synonymous of standardization, even though they are distinct phenomena, and one is not a condition for the other (Gibb 1999).

This deep-rooted perception seems outdated under the present-day advanced conditions of manufacturing, where "mass customization has taken over from mass production (…). With high powered computer-aided design and digitally controlled manufacturing machinery there is no longer the necessity for 'identical' standardization" (Gibb 1999). In fact, the new wave of industrialization has partly developed in response to the increasing demand for Engineered to Order (ETO), in turn urged by Lean management practices.

In the last decade, the mission of sustainable development also allowed prefabrication to shed some of its negative connotations. And yet, much of the old stigma remains, affecting the way users, builders, and designers think and talk about it. Architects —formerly enthusiastic experimenters—still lead the skepticism, likely remembering the dystopian, post-war productions: "the touted benefits of offsite prefabrication have been exaggerated not only by those looking for a story to tell the media, but also by those in the construction sector looking to capitalize on society's fascination with seemingly Lego-like construction that is promoted as an inherently faster, greener, smarter delivery method." (Smith and Quale 2009).

As effectively summed up by Smith (2011), prefabrication is essentially "a tale of necessity and desires". Paradoxically, and to an extent that has not yet been precisely established, it is naturally and inevitably ingrained in all acts of design and construction; the discriminating factor is just where we draw the line on what we consider an assembly or sub-assembly within the entirety of a built object. On one end of the range, there are single components manufactured off-site such as steel beams or interlocking bricks; at the opposite extreme, there are finished room modules, or—as recently experimented in China (Hager et al. 2016)—3D-printed buildings. The spectrum includes many other products that may or may not be generally thought of as prefabricated or standardized, even though they satisfy the technical definition for both.

Glass windows are a telling example of early off-site systems for construction. Until the very end of the 19th Century, they were glazed and framed on site. But today, window systems built off-site are not recognized or counted towards prefabrication, because they are considered part of the conventional, 'stick-built' way of doing. This suggests that *in the contemporary imagery, the notion of prefabrication is as much entrenched in the mechanization of the production process as it is in the ideas of novelty and mass production*.

Gibb (1999) provides a taxonomy that describes this dichotomy by organizing all forms of off-site construction in four levels. His categorization is bookended by single assembly materials at level 0, and fully pre-manufactured buildings (100% modularized) at level 4 (Figure 8*)*.

Level	Description	Definition
Level 0	Base material	Basic materials with no pre-assembly
Level 1	Component sub-assembly	Relatively small scale items that are invariably assembled offsite – not really part of the true offsite spectrum. e.g. light fittings, windows, door furniture.
Level 2	Non-volumetric pre-assembly	A large category covering items where the designer has chosen to assemble in a factory prior to installation. Units do not enclose usable space. Applications may be skeletal, planar or complex. e.g. cladding panels; above ceiling service modules.
Level 3	Volumetric pre-assembly	Units that enclose usable space and are then installed within or onto a building or structure. Typically fully finished internally. e.g. toilet/bathroom pods; plantrooms.
Level 4	Modular 'whole building'	A colloquial term commonly used to describe units that enclose usable space and actually form part of the completed building or structure. Typically fully factory finished internally (and possibly also externally). e.g. edge of town or restaurant facilities, multi – residence housing.

Figure 8 . Classification of off-site construction technologies. Source: (Gibb 1999).

Prefabrication, as generally inferred from today's literature, spans Gibb's levels 2 through 4. Items under levels 0 and 1, while effectively fabricated or pre-assembled off site, would not register as such. As a matter of fact, the current notion of off-site construction transcends the idea of mass production, since innovations (e.g. 3D printing, concrete smart cast, BIM, Lean) are making dramatic changes in the way we build, increasing the value of —and demand for—pre-engineered products.

We can use three broad groups borrowed by Richard (2017) to describe the degrees of prefabrication of a project (Figure 9), even though this study will not investigate this relationship (i.e. "quantity" of prefabrication-ness) to health and safety.

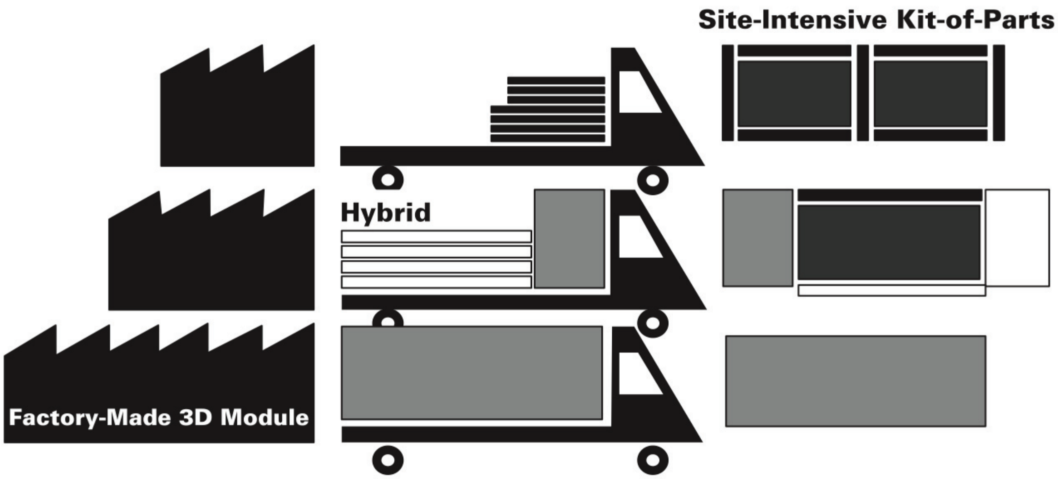

Figure 9. “The three categories of industrialized building systems”. Source: (Richard 2017).

- “As a building is bound to be tied to its foundations, the site-intensive kit of-parts concentrates at the site the final assembly of components or sub-systems delivered from different manufacturers. (…)
- The factory-made 3D module divides a building into volumetric modules completely finished at the plant and easily connected to the infrastructure once at the site. (…)
- The hybrid involves manufacturing the complex parts at the plant and leaving the heavy or large-scale tasks to the site.” (Richard 2017)

Based on this general grouping, the Hybrid and Factory-Made 3D Module systems would gain a project the label of ‘prefabricated’.

Different degrees of prefabrication, the size or technological newness of the pre-assembled components, and even the educational background of the project players have informed the very definition of the concept. Presently, the terms 'prefabricated', 'modular', and 'off-site construction' are used interchangeably—yet with somewhat variable connotations—by architects, engineers, contractors, developers, and owners. Below, a sample of respected industry-derived definitions:

> **Off-site construction:** "The process of planning, designing, fabricating, transporting and assembling building elements for rapid site assembly to a greater degree of finish than in traditional piecemeal on-site construction."
>
> **Prefabrication:** "The manufacture or fabrication of sections of a building at an off-site location which are delivered to and assembled at the building site"
>
> –National Institute of Building Sciences (NIBS)
> Off-Site Construction Council (OSCC). Glossary of off-site construction terms.
>
> **Modular construction:** "A process in which a building is constructed off-site, under controlled plant conditions, using the same materials and designing to the same codes and standards as conventionally built facilities – but in about half the time."
>
> –Modular Building Institute (MBI)
>
> **Modularization/Modular Construction:** "The manufacture and remote assembly of major interior or exterior sections of a building (e.g., wall, floor, roof) of one or multiple

material types which may include portions of a system (e.g., electrical, plumbing). Examples include curtain wall, structural insulated panels and entire building modules."

Off-Site Fabrication: "The fabrication or assembly of components (no manufacturing processes) off-site or on the construction site but at a location other than the point of installation. The process is usually completed by specialty contractors (e.g., finish carpentry)."

Permanent Modular Construction (PMC): "A design and construction process per formed in a manufacturing facility, which produces building components or modules that are constructed to be transported to a permanent building site."

Prefabrication: "Manufacturing processes generally taking place at a specialized facility, in which various materials are joined to form a component part of a final installation. Examples include trusses, joists, structural steel and precast concrete."

–McGraw-Hill Construction

These are general, or nuanced, enough to allow for a wide range of interpretations. Establishing a common vocabulary is not just a matter of accuracy. Inadequate conceptualization poses methodological problems that become evident when looking at the few scientific sources currently available. Without a unified way of talking or thinking about prefabrication and what it encompasses, it's difficult to interpret survey statistics.

For example, if a pool of industry representatives is asked whether their experience has shown that safety is a benefit of off-site construction, it is vital to know what application their response is based upon. Are their answers evoked by the thought of a bridge girder or a stair, a utility rack, a wood wall panel, or something else entirely? Unless we know the scope of discussion for prefabrication, it will be very difficult to gain meaningful insight from the answers. Similarly, term ambiguity makes it challenging to run comparisons against *in-situ* methods. This can be particularly impactful for risk analysis purposes, as well as for making claims of greater ROIs.

While the words ‘prefabrication’ and ‘modularization’ are descriptive of a certain domain of practice, their meaning is not prescriptive enough to be shared cohesively across disciplines, where definitions can perpetrate misunderstanding and harbor skepticism. This problem is felt all too well in the architectural community, where so many terms are needed to distinguish among a plethora of products and accentuate their qualities: ‘flexible’, ‘modular’, ‘pre-manufactured’, ‘kit’, ‘portable’, ‘mass-produced’. Yet, ‘prefab’ ends up supplanting them as a catch-all term that fails at both representing the essence of the concept effectively, and at conveying the underpinnings of its ramified lexicon (Aitchison and Macarthur 2017).

In the context of this study we will take a middle-of-the-road stance and simplify the use of terminology while settling on definitions the respect the different sensitivities towards vocabulary insofar as possible[3]. The definitions are de-stigmatized, and intuitively understandable by all disciplines. While it may seem that a more generalist approach is in contradiction with the need for greater clarity, we argue that the blanket term for the category

[3] This does not apply to verbatim citations, which might not be exactly aligned to such definitions.

should not attempt to be definitive. Despite the extensive glossaries of terms used by professionals to capture technical and conceptual nuances, the qualitative data gathered through surveys is unable to incorporate all the distinctions in word variety. And, as we will see in the coming chapters, it should not try to do so: naming the specific types of pre-manufacturing technologies can be more useful for interpreting safety-related responses than broad categorizations. For the scope of this research:

- **Off-site Construction** will be an umbrella concept for all construction technologies fabricated, pre-assembled, or manufactured outside of the project site, later assembled on site, following the definition offered by NIBS.
- **Prefabrication, prefabricated, or industrialized** will refer only to components produced in a manufacturing facility, regardless of dimensions, purpose, yield (mass produced vs. engineered to order) and complexity.
- **Modular/Modularized** contains the concept of standardization, and should not be confused with prefabrication itself. In this study, it is a subset of prefabrication that comes in volumetric elements (e.g. a bathroom pod, tilt-up roofs, whole-house unit), represented in Gibb's taxonomy under levels 3 and 4 (see Figure 8).

1.2 Present-day Drivers and Common Applications

The prime factors behind the new wave of enthusiasm towards prefabrication are productivity, competitive advantage, and ROI (McGraw Hill 2011). The latter two are particularly important for design-builders, while productivity is a priority for trade contractors. Future demand is expected to be incentivized by the prospect of saving money and time, as well as in response to the growing demand from owner and developers, already a critical motivator for architects (2011).

Surprisingly, higher education in the built environment does not seem to share the corporate sector's interest in this topic. Off-site construction is not only taught in less than 40% of the architectural and construction management programs (Figure 10), but it is also researched very little in US universities (Smith et al. 2017). When addressed in classroom settings, "Off-site Construction Product Types" differ between disciplines. Architectural programs prioritize—in this order—prefabricated exterior walls, curtain wall assemblies, and precast concrete, whereas construction management programs focus mainly on precast concrete, followed by HVAC, plumbing, electrical, and steel assemblies (Figure 11). Education programs lag behind the use of and interest in prefabrication of the industry, where challenges around transportation, logistics and scheduling have already surpassed the questions of its definition or utility. In other words, the industry is already trying to solve the questions "how do we do it?", rather than "what is it?" or "is it worth it?" (2017). Lastly, safety does not appear in Smith's list of most frequently taught or sought-after off-site topics related to prefabrication for either academia or the industry. Interestingly, however, McGraw-Hill (2011) reported that safety is the third reason, after schedule and cost, for demand-driving owners to consider using prefabrication.

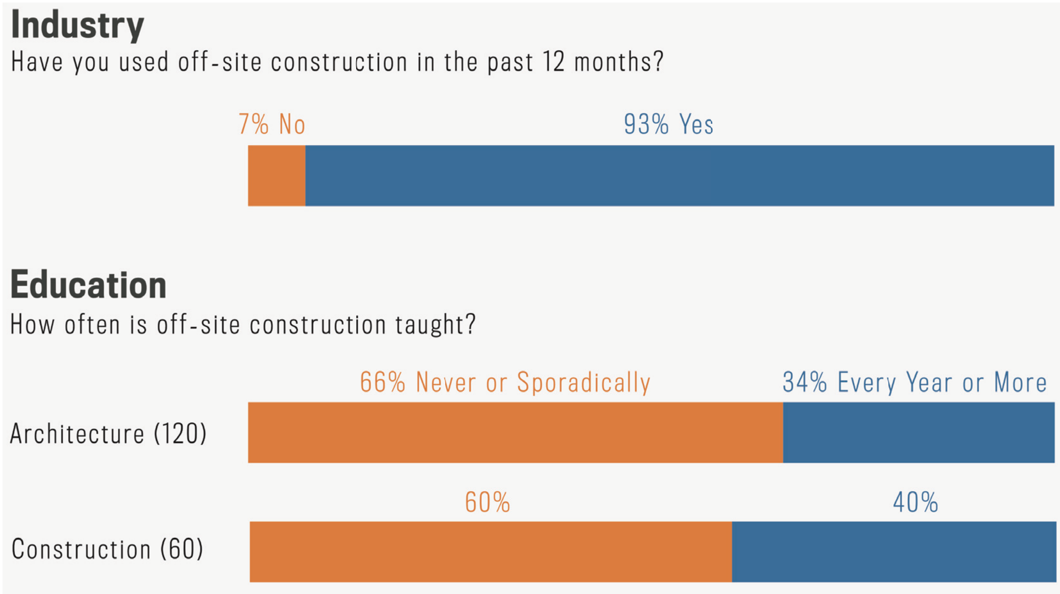

Figure 10. "Off-site Construction is More Common in Industry". Source: (Smith et al. 2017).

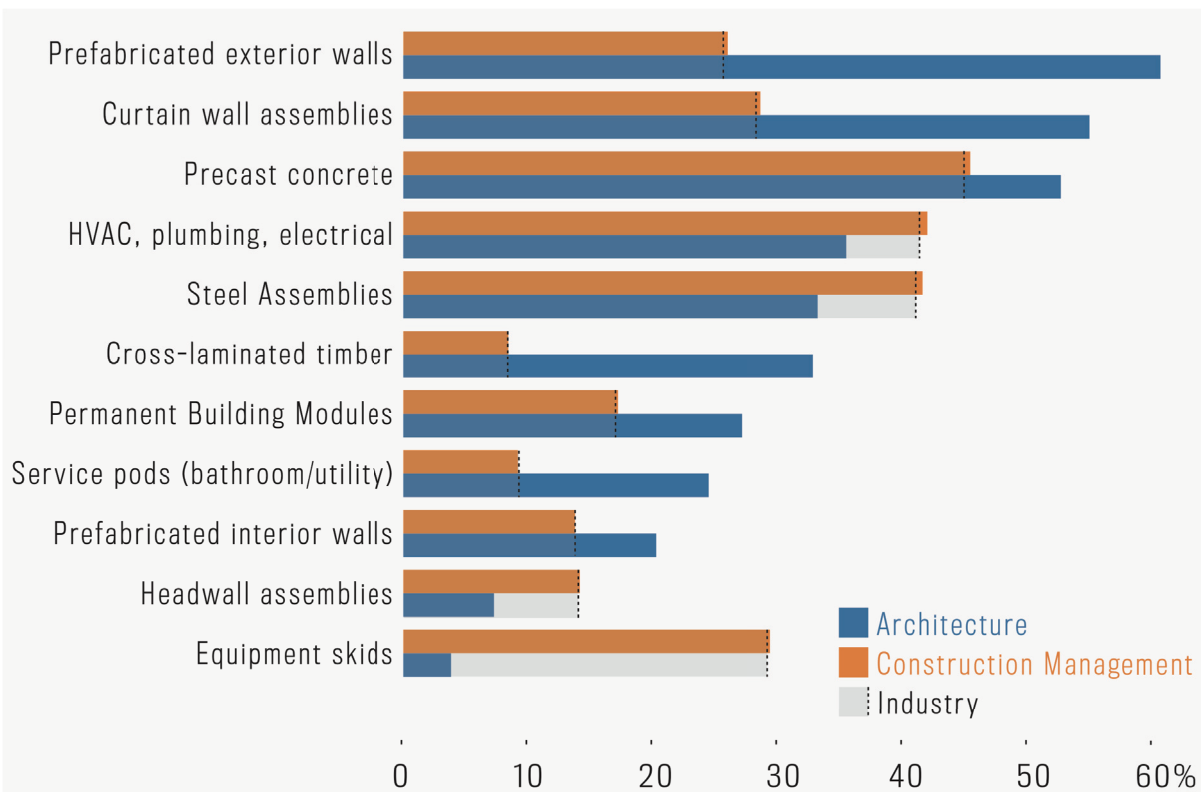

Figure 11. "Most Addressed Construction Product Types". Source: (Smith et al. 2017).

In Europe, prefabrication has both fascinated and frustrated the architectural community, capturing its attention and stirring creative experimentation and debates, particularly on housing design. Northern countries (Denmark, the Netherlands, Sweden, and Germany) were already the greatest users of precast technologies in the late 1990s (Jaillon and Poon 2009). Struggles with balancing rapid demographic growth and density have long fueled the use of prefabrication for high-rise residential buildings in Japan (Buntrock 2017), China (Zhang et al. 2014), and Hong-Kong (Jaillon and Poon 2009). Domestic construction has evenly adopted prefabrication in healthcare, higher education, manufacturing, low-rise office, and public projects (McGraw-Hill 2011), but the involvement across sectors is uneven between contractors, engineers, and architects.

The United States' receptiveness towards prefabrication, and the uptick in use over the last decade can be in part attributed to the progresses in automation, new products, and technologies for construction, but also to the establishment of progressive and highly collaborative delivery tools such as BIM and Lean, and the rising standards for sustainable performance in highly complex buildings. Social demand, such as the pressures to create affordable housing or achieve urban density, are also behind the push for prefabrication. The shortage of skilled labor may also be a new driver, though the contention that prefabrication reduces the number of workers on the job has been called out as a myth (Gibb 1999).

The Sustainability agenda makes a powerful case for the use of prefabrication, even when not immediately detectable as particularly 'green' (McGraw-Hill 2013). As a matter of fact, Leadership in Energy and Environmental Design (LEED) certified projects have been associated with a high safety risk due to their greater incidence of injuries when compared to non-LEED buildings (Dewlaney and Hallowell, 2011). And yet prefabrication is a frequently proposed strategy to meet those same certification requirements, and practice prevention through design (2011).

Lean principles, which in progressive practices go hand in hand with BIM tools, also have a strong alliance with prefabrication, because they contribute to eliminating on-site waste (Gambatese et al. 2017). In addition to the implication of 'greener' construction, the Lean philosophy of waste reduction (Ikuma 2009) further promotes safety, and so there could be a positive, compound effect of prefabrication and Lean on safety in projects that adopt both.

Lastly, BIM can more easily identify hazards before construction operations start, partially due to its "Clash Detection"[4] feature (McGraw-Hill 2013), but largely because it activates extended cooperation between the many professions involved in the project, and highly collaborative delivery processes are known to foster a climate of health and safety (CII 2003). Given that prefabrication and BIM are often leveraged concurrently, the positive effects of mutual interaction should not be ignored.

Prefabrication is expected to eventually become a prevailing project method –its use growing hand-in-hand with future progresses in automation. Even so, prefabrication cannot be considered better *a priori*, nor the universal solution for all projects. It is worth remembering that what guides the decision on method is still a combination of "needs (program) and resources (the four "Ms": materials, machinery, manpower and money)" (Richard 2017). Designers also agree that there must be a balance between the use of conventional, standardized, and off-site components.

[4] "Clash detection helps in effective identification, inspection and reporting of interferences in a project model." The BIM Institute. Retrieved: http://www.thebimcenter.com/2016/03/what-is-clash-detection-how-does-bim-help.html.

Successful project-specific approaches will never call for total prefabrication, as “maximised prefabrication does not always equal optimisation either from an architectural or from an economic point of view.” (Vibæk 2017). The same lack of equal optimization can be thus assumed for safety and health, and therefore its interactions with prefabrication are worth exploring.

1.3 Safety and Health in Prefabrication

The latest Bureau of Labor Statistics (BLS) census of Fatal Occupational Injuries (BLS 2017) reported that 2016 marked three years of progressive increase in workplace fatalities in the US, with 5,190 deaths. The construction industry still accounts for 21.1% of the total, and these counts do not include non-fatal occupational injuries or illnesses. With such figures in mind, any construction practice that eliminates the exposure to one of the Fatal Four[5] can translate into a considerable number of lives saved.

The accepted rationale for explaining why prefabrication is automatically safer for construction is that it lessens the amount of work done on-site, with less work hours equaling to fewer chances of accidents (Haas and Fagerlund, 2002). This reasoning further supposes that the reduced on-site hours involve alternate activities where former hazards have been removed or substituted for.

[5] The “Fatal Four” are the four leading causes of fatality identified by OSHA: Falls, Struck-By, Caught-In/Between, and Electrocution.

For example, “by taking the work”:

- “(...) from a high elevation to the ground, where fall injuries are much less likely.”
- “(...) from inside an excavation to grade, where there is no risk of soil cave-in”.
- “(...) from the field to a factory, which allows the use of safer, automated equipment in improved environments” (Toole and Gambatese 2008)

Factories, in turn, are considered safer than project sites (Gibb 1999), and the project site would then benefit from greater on-site organization (1999). The recurring argument in support of moving assembly operations to the manufacturing environment is that:

“[*In manufacturing plants*]

- Risks are less as they are easier to control
- Training is easier to achieve
- There is less trade overlap
- There is a much lower workforce turnover
- People ‘look out’ for one another
- The adverse weather factor is removed” (Gibb 2003, cited in McKay and Gibb 2011)

Figure 12. Prefabrication of plumbing racks at Consigli's Prefab Lab. Source: (Teichloyz, Sarma et al. 2017).

The recognized pitfalls of prefabrication are twofold. The first is usually associated with bulkiness of the components: oversize elements require adequate training for handlers (rigging and hoisting), extreme coordination on the field, and planned sequencing. The second comes from poor processes and communication: "If the installation programme or sequence is not very clear or realistic, workers cannot generally understand it very well. When the components are installed, accidents are therefore more likely to occur, especially collisions with other components and occasionally even with workers" (Li, Guo et al. 2010).

Figure 13. Delivery of a prefabricated utility rack. Source: (Teichloyz, Sarma et al. 2017).

Whitepapers and market reports such as those from Mortenson (2014) and McGraw-Hill (2011 2013) are, so far, the main data-driven sources of safety-related knowledge on prefabrication. However, they do not seem to corroborate the mainstream perception that safety is the logical consequence of reducing the workers' time on the job, thereby pushing assembly tasks and associated risks into the more controllable manufacturing facilities. As we will see in the literature review, the information is extremely limited, generally positive, yet at odds with prefabrication's supposed contributions to safety once the data is stratified by trade (McGraw-Hill 2013).

Blismas et al. (2006) argue that safety is usually not used as a selling point for prefabrication, even though it is one of its most significant benefits. They further point out how a "multi-dimensional value-based system" focused on "soft" qualities such as "health, safety, quality, human and environmental factors", rather than cost, would better guide the decision to adopt one construction method over another (2006).

One of the hypotheses of this study argues that the implicit conclusion around improved safety is a fallacy that feeds on the idea that the conventional and prefabricated construction changes only in the collocation of the hazards, as it ostensibly shifts them from on-site to off-site, like a moving parts game. This conclusion does not account for any health and safety threats that may be introduced by the prefabricated method of choice during both the production, transportation, and on-site installation phases. By doing so, this line of thinking overlooks or discounts a whole set of tasks and installation sequences that make the prefabricated process very different from the conventional one. For the purpose of occupational health and safety, we can think more critically about these common, flawed safety conceptions if we evaluate individual off-site construction through a comprehensive Job Hazard Analysis (JHA)[6].

Another mistake would be to treat the traditional and off-site processes as identical for the purposes of hazard exposure assessment, to consider any safety benefits equally applicable to all prefabricated solutions. This is also true within construction: safety protocols and practices in commercial and industrial projects are more stringent than in housing projects. Residential projects have their own distinct hazards (Grant and Hinze 2013), and tend to prefer prefabricated technologies not as frequently used in the commercial sectors.

As to the merits of more carefully considering the safety aspects, should it be possible to conclude that it is essentially equally safe or safer to use prefabrication —which is just as arduous to prove as the contrary— why does it matter? The answer is awareness.

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[6] "A job hazard analysis is a technique that focuses on job tasks as a way to identify hazards before they occur. It focuses on the relationship between the worker, the task, the tools, and the work environment." (OSHA 2002).

Awareness is the fundamental for accident and injury prevention in all work environments of the supply chain. If a job comes with any (real or false) guarantee of safety attached, the attitude towards it will be laxer and less critical, and hazards will be more likely overlooked, underestimated, or miscalculated. *Risk can be mitigated only when correctly recognized, and anticipated. Additionally, by accepting the default conclusion of improved safety, the industry is also potentially missing opportunities to leverage prefabrication towards prevention.*

Prefabrication holds more occupational health and safety complexity than commonly presented. The nature and shape of the problem at stake are somewhat reminiscent of "The Blind Men and the Elephant" metaphor, where fractional understanding and the inability to grasp the entirety of a phenomenon lead to its mischaracterization. The problem carries enough relevance to warrant the attention of the research community while leaving ample room for exploration. What specifically emerges from this preliminary critique is the lack of organized knowledge around the topic and a comprehensive interdisciplinary perspective; the absence of an expert occupational safety and health (OSH) angle; missing quantitative data and incomplete qualitative data on the manner and magnitude of the impact of prefabrication on worker health and safety.

Chapter 2. LITERATURE REVIEW

2.1 OVERVIEW AND SELECTION

Four main questions guided the literature search:

- What do we know about the occupational risks associated to prefabrication?
- What are the health and safety concerns?
- What are the health and safety advantages?
- …for whom?

The analysis started with a compilation of publications gathered through library search engines such as WorldCat, UW Libraries, and Google Scholar, the examination of citations (referral sampling), as well as other online sources. The database queries were done by keyword, using several combinations of paired terms: one term interchangeable for safety (e.g. hazard, accidents, injuries, health), the other term swapped for prefabrication (e.g., off-site, industrialized construction, modular construction, pre-assembly). Title screening, followed by abstract reviews, yielded 49 results. A full-length reading filtered out most of the collected works, and the final selection included 11 publications, which comprise of 4 journal articles, 4 research/market reports, 1 doctoral dissertation, and 2 conference papers. The flow diagram in Figure 14 outlines the screening process.

The protocol for selection set the boundaries for the systematic review, and observed the following principles:

Eligibility criteria

- The publication must be aimed directly at health and/or safety concerns or benefits as a consequence to the use of off-site construction methods.

- Any scale and type of off-site methods under levels 2 to 4 defined by Gibb (1999) are accepted (e.g. pre-cast structures, housing modules, mechanical components).

- The publication focuses on occupational health or safety in any job phase and environment, off-site and on-site alike.

Exclusion criteria

- The publication predates the 2000s[7].

- The safety focus is in relation to the quality and performance of the prefabricated component in itself (e.g. "stability of precast systems").

- Safety is a secondary proposition, not proven but deduced from the primary object of study.

- The study presents research bias.

[7] The notion of prefabrication is tied as much to its technical definition as it is to its level of novelty. A component that satisfies the definition of 'prefabrication' but is commonly used in what currently constitutes traditional/conventional construction is no longer considered prefabricated in the contemporary discourse (e.g. mass-produced window systems).

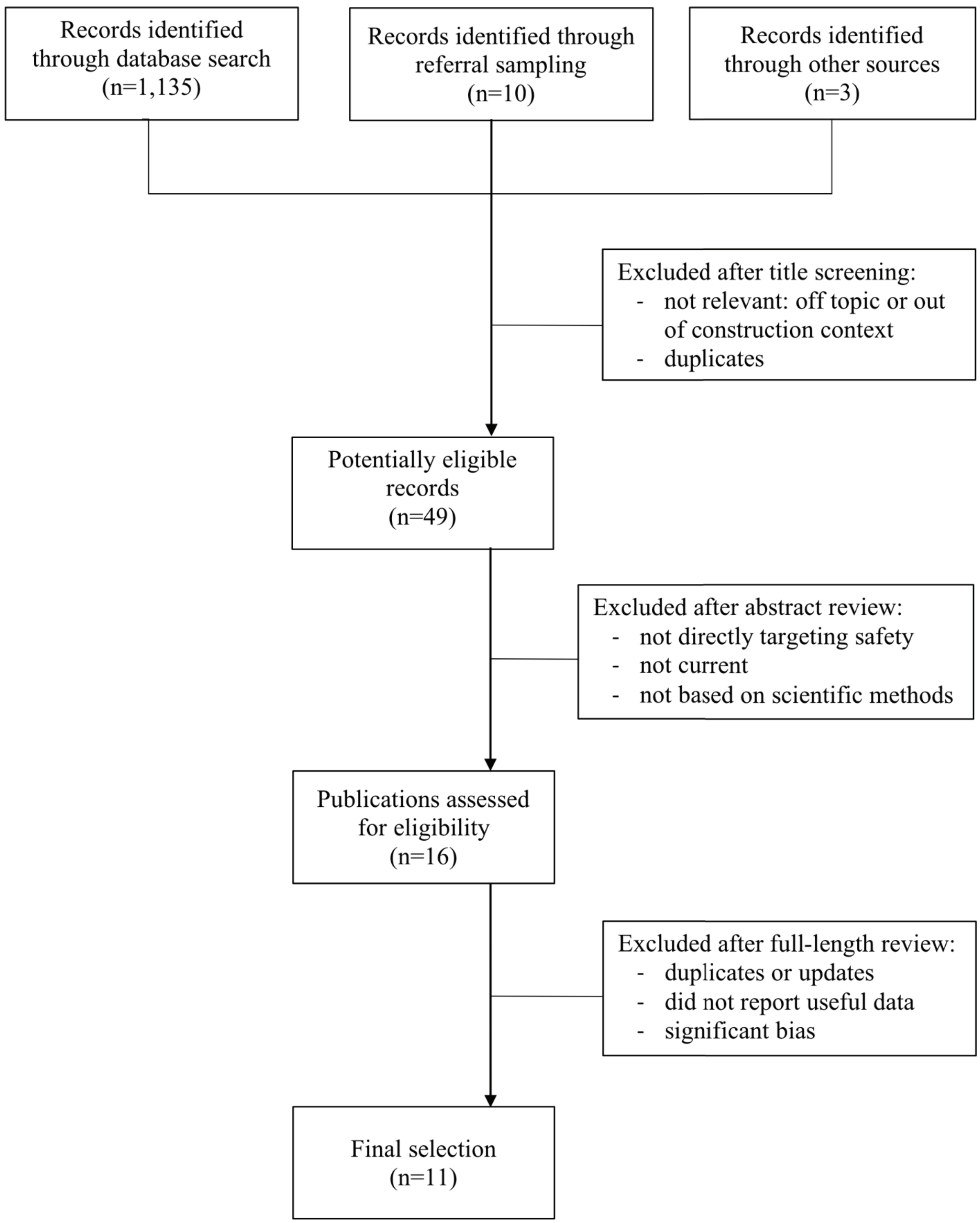


Figure 14. Publication Screening and Selection Process.

Table 1 lists the final selection, consisting of studies published in the last 15 years. The majority were conducted in the US, two in the UK, and one in Sweden. Even though standards and regulations may differ, the contexts and issues examined in the European countries are still applicable to the American industry. For the purpose of the systematic analysis, in-text references will use the ID # assigned in Table 1.

Table 1. Descriptive Summary of Selected Literature.

ID	Title	Author(s)	Year	Type	Con text	Prefab Type	Concern	Methods	Tools	Sector	Work Env.
1	Safety Hazards to Workers in Modular Home Construction	Becker, Fullen et al.	2003	Research Report	US	Modules, tilt-up roofs	Any	Quest./ interview + task analysis	Job Safety Analysis: observation/ videos	residential	on-site
2	Risk assessment and analysis of workload in an industrialised construction process.	Rwamamara	2007	Article	SE	Wall panels	Ergonomic	Case study	ErgoSAM (sequence-based assessment), QEC (Quick Exposure Check)	residential	on-site
3	Knowledge and opinions of designers of industrialized wall panels regarding incorporating ergonomics in design.	Kim, Seol et al.	2008	Article	US	Wall panels	Ergonomic	Survey		residential	on-site
4	The effect of offsite construction on occupational health and safety.	McKay	2010	Doctoral thesis	UK	Various	Ergonomic	Quest./ interview + ergonomic analysis	ABA ergonomic assessment	mixed	Factory + on-site

5	Health and Safety Management of Offsite Construction, how close are we to production manufacturing?	McKay, Gibb et al.	2011	Conf. Paper	UK	Various	Ergonomic	Quest./ interview + ergonomic analysis	RULA (Rapid Upper Limb Assessment)	mixed	Factory
6	Low back injury risks during construction with prefabricated (panelized) walls: effects of task and design factors.	Kim, Nussbaum et al.	2011	Article	US	Wall panels	Ergonomic	Experiment	Wearable sensors	residential	on-site
7	Prefabrication and Modularization.	McGraw-Hill	2011	Market Report	US	Various	Any	Survey		mixed	on-site
8	Safety Management in the Construction Industry.	McGraw-Hill	2013	Market Report	US	Various	Any	Survey		mixed	on-site
9	2014 Off-Site Construction Industry Survey.	NIBS	2014	Market Report	US	Various	Any	Survey		mixed	on-site
10	Safety concerns related to modular/prefabricated building construction.	Fard, Terouhid et al.	2017	Article	US	Various	Any	Indirect data analysis	OSHA accident records	mixed	Factory + on-site
11	Consequences of industrialized construction methods on the working environment.	Simonsson and Rwamamara	2007	Conf. Paper	SE	Reinforced steel system	Ergonomic	Case study	ErgoSAM (sequence-based assessment)	heavy civil	On-site

Multiple off-site methods were addressed by each study, with extensive overlap but no single type common to all. More than half of the publications lacked specificity when describing the technologies of choice, therefore only broad categorizations were possible (Table 2); implicit inclusions of additional typologies, if any, were not captured. A few studies did not identify the nature of the off-site products enough to link them to any category.

Table 2. Types of Off-site Technologies Addressed by The Literature Selection

Type of Off-site Technology	**Publication**
Cross-laminated timber	(1) (9)
Headwalls	(9)
Interior wall panels	(2) (3) (4) (6)
MEP	(4) (7) (9)
Modular components (pods)	(1) (4) (5) (9)
Precast concrete cladding	(3) (4) (5) (6) (7) (9)
Steel assemblies	(4) (9) (11)
Structural precast concrete	(5) (9)
Partly or fully unspecified	(7) (8) (10)

2.2 Perception of Prefabrication and Safety: Off-site

On a purely theoretic level, the general speculation around off-site work environments is that they are safer than construction sites, and subject to higher standards to begin with. This may explain the relative lack of research interest in production and transportation (off-site) with respect to installation (on-site). Only one publication (5) is focused exclusively on off-site occupational hazards, while two studies (4) (10) address the health and safety concerns for both factory and construction workers; of these three, one is based in the US, two in the UK.

McKay, Gibb et al. (5) investigated eight facilities that produce prefabricated elements with the intent to understand how their approach to safety compares against the automated industrial sector (e.g. automotive, aluminum production). Observations, interviews and ergonomic assessments resulted in the conclusion that off-site employers have room for improvement when it comes to safety. At the same time, there is great potential, provided that they embrace a manufacturer's mindset and run the factory floors more like a production line and less like an "'under cover' construction site" (5). The parallel is extremely important, because manufacturing processes and layouts, even for the same products, can be very different, depending on the employer's background[8]. Health and safety in controlled spaces are thus neither a given nor naturally superior. However, the industrial sector provides many opportunities to improve conditions in manufacturing plants, something that cannot be as easily said of construction sites.

Off-site and on-site research tend to differ in scope: the first is focused on health effects (illnesses, and effects of long term exposure to a hazard); the latter is aimed at safety (traumatic injuries and fatalities). In the context of construction components, ergonomic problems are somewhat easier to audit in off-site scenarios, and those that stand out the most upon direct observation (4) (5), however, they are not necessarily the major risks in factory settings. As seen in the UK-based studies (4) (5), both finished product type and dimension, manufacturing

[8] In this particular study, only two of the eight companies examined came from the manufacturing industry, and all of them were also installers.

protocols, and level of mechanization have a way of determining the predictability of accidents or the degree of exposure: on one end of the spectrum they may result in quasi on-site conditions, and on the other end remotely-operated assembly lineS.

The US-based study (10) stands out for being the only one approaching the matter quantitatively, by means of a comparative analysis of off-site and on-site accidents formulated around a set of OSHA incident reports covering the years 2002 to 2013. The data indicated that the top three causes of accident in factories were, in this order: fall, struck-by, and caught-in; *these are also the top-three reason of death on construction sites*. Non-deadly, accidents in manufacturing environments resulted more often in amputation and fracture (both 27.3%), whereas the most common on-site injury was fracture (46.8%). Of a total of 125 relevant cases, 62% occurred on-site, 18% in manufacturing plants, and 20% remained unspecified. Although incomplete[9], these figures suggest the great hazards that off-site construction claims to remove are the same that re-emerge with its use, both on and away from project sites.

This holds true also in the UK, where "[*modular*] manufacturing and installation, combined (…) were among the top 10 high-risk industries, industries, as measured by BLS annual surveys of occupational injuries and illnesses" (1), and reinforces the fact that reducing the number of people and work-hours spent *in-situ* should not justify a false sense of security. Correspondingly, it should alert us to the health and safety risks for off-site workers, because prefabricated items are new products in the manufacturing industry as much as they are in the construction sector, and pre-assembly is far from the collective imagery of automated assembly lines rolling out mass

[9] The limitations of the OSHA Fatality and Catastrophe Investigation Summaries search engine will be discussed in Chapter 4.2.

produced components. The assimilation of prefabricated production into industrial processes is still in progress, and does not yet have a level of mechanization that would result in relatively safer work conditions for the employees (4) (5). Manufacturers or fabricators operating in indoor versions of a construction site (rather than a mature industrial assembly line) are more controlled or safer only with respect to weather conditions.

Lastly, transportation is an essential factor in off-site construction, and normally perceived as a deterrent barrier to using larger prefabricated components, although usually for logistic reasons alone. One publication (4) tangentially broached the safety implications in transportation (which maintains the highest work-fatality rate in the country) and warehousing of large pre-assemblies that require oversize trucking and hauling. While it's been observed that delivery operations tend to be more organized, with fewer shipments, and likely to be mechanically handled, it remains that there is yet insufficient literature to discuss the broader effects of the long and short-distance transportation demands, should prefabrication become the norm. Conversely, there is abundant research on cost-benefits and environmental impact on this same topic.

2.3 Perception of Prefabrication and Safety: On-site

Perception is an important indicator when grounded in common or specialized knowledge and supported by experience, even though the sensitivity to and awareness of risk are highly subjective. In the absence of dependable metrics to evaluate safety benefits, assessments of traditional and prefabricated construction are difficult to make (Pasquire and Gibb 2002), but qualitative data can be used to direct future approaches, while offering multifaceted insight on a yet unmapped area of knowledge.

Eight out of eleven publications focus exclusively on construction-worker safety, which is consistent with the general impression that the manufacturing portion of the prefabricated process is not a leading concern. Of these, only three (7) (8) (9) collected the opinion of industry practitioners in various roles on projects that used modular or prefabricated construction. The sample size was large: 809 (7), 263 (8), and 312 (9) respondents, respectively. Participants were a mix of project professionals: general contractors, specialty contractors, architects, and engineers; owners and developers were typically approached individually for in-depth interviews.

In the first market report (7) 34% percent of the surveyed pool noticed that prefabrication is safer, owing to the fewer workers on scaffolding or ladders, and to not having as many people close to each other in tight spaces. Ten percent considered prefabrication to be less safe than 'stick-built'. This belief was not elucidated, though it was speculated that it derives from the challenges of handling large prefabricated components, the need to involve heavy equipment, and to increase coordination efforts. The stance of the remaining majority (56%), was neutral: prefabrication was not considered to have any positive or negative impact on on-site operations, safety wise (Figure 15). The role of the respondents seemed predictive of the attitude towards risk: more general contractors (GCs) than subcontractors thought it was less safe to work with off-site methods, whereas mechanical contractors and fabricators found that it improved their work conditions. A higher or lower sensitivity to legal and financial liabilities may have impressed on the answers, as 12% of the GCs thought it has a negative impact on safety, an outlook shared by only 3% of the architects and 6% of the engineers. However stratified, the majority ultimately held that prefabrication is safety-neutral, but the sustainers of the positive effects are a share large enough—and those against small enough—to justify a closer look at benefits and trade-offs.

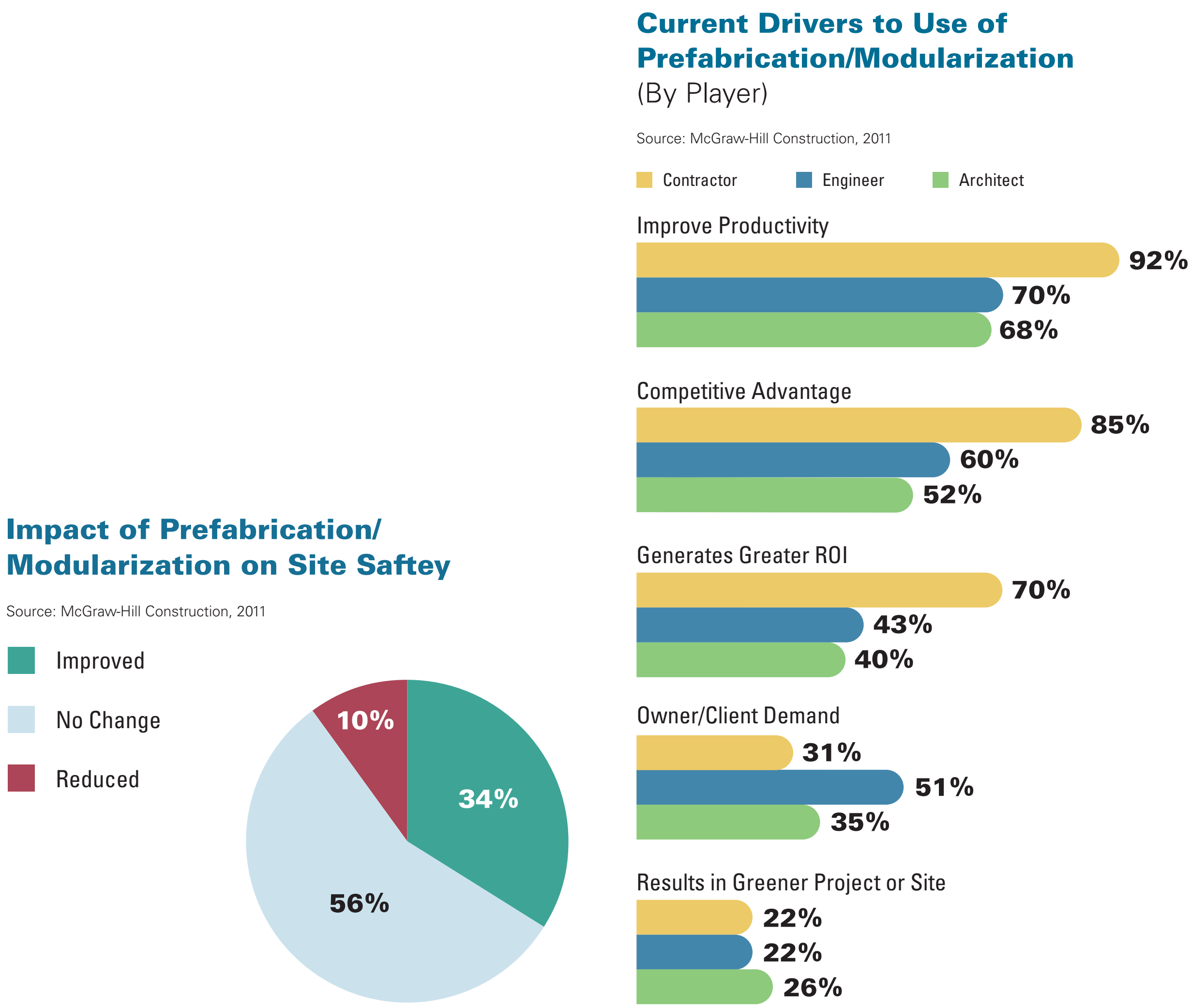


Figure 15. Excerpts from the industry survey on the benefits of off-site construction conducted by McGraw-Hill. Source: (McGraw-Hill 2011).

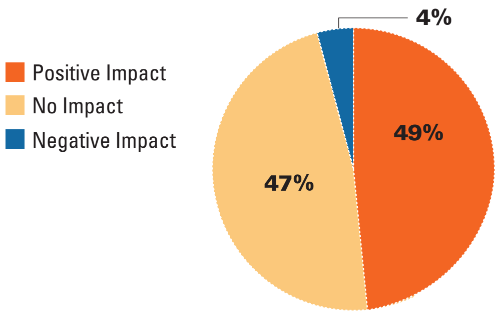
This study (7) was the first of its kind for scope and scale. Motivated by the wish to divulge and promote the benefits of using prefabrication, it placed the emphasis on budget and schedule savings, just to find they are neither easily quantifiable nor clear cut[10]. For this reason, the conclusions argue that the industry should learn more about the impact of other advantageous factors that may tip the scale towards a wider spread adoption of prefabrication, when piled onto others. Safety, sustainability and quality are the most obvious, and in the queue (according to anecdotal accounts) for becoming the future drivers to the use of prefabrication (7).

A survey (8) conducted a few years later, again by McGraw-Hill, focused on "Identifying Risks and Reducing Accidents to Improve Site Productivity and Project ROI", showing that of the construction firms that adopt "prefabrication/modularization (*sic*)" 49% believe that it improves site safety (Figure 16). The remaining were neutral, and just a small fraction (4% in both groups) thought that it is detrimental. After differentiating by role, it emerged that a significant percentage of GCs (54%), and more than specialty contractors (43%), thought that it definitely contributed to safety. The main reasons given to explain the positive rating were that i) most of the assembly is done either at ground level or elsewhere, ii) there are less workers on site and working on the same thing at the same time, iii) that there is less need to work from heights.

[10] The reason may be the same that makes it difficult to discern the safety value of prefabrication in this and subsequent McGraw-Hill reports, and has to do with the fact that the questions are not related to context/project type and to the prefabricated method.

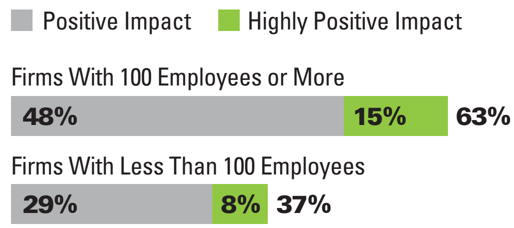
Impact of Prefabrication/Modularization on Site Safety (According to Respondents That Use Prefabrication/Modularization)

Source: McGraw Hill Construction, 2013



Firms That Find That Prefabrication/ Modularization Has a Positive Impact on Safety
(by Size of Firm)

Source: McGraw Hill Construction, 2013



Aspects of the Use of Prefabrication/ Modularization That Contribute to Project Safety

Source: McGraw Hill Construction, 2013

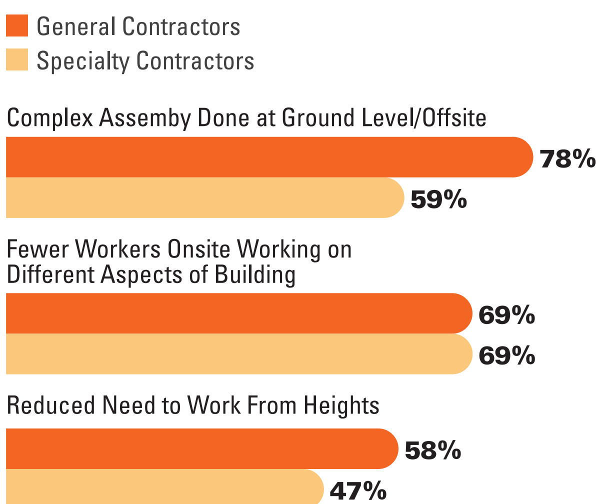


Figure 16. Excerpts from the industry survey “Safety Management in the Construction Industry” conducted by McGraw-Hill. Source: (McGraw-Hill 2013).

This last outcome seems in contrast with the 2011 survey, where GCs were warier towards prefabrication. Once again, based on this feedback alone it is difficult to discern the reason for the change of attitude. The report doesn't specify the types of off-site construction used by the responding subjects (pods, precast cladding, MEP systems, interior panels?), and thus we are unable to speculate on a possible link between typology and perceived risk. Additionally, 73% of the users report having both a fully inclusive and widely observed safety program in place, and valuing highly site-specific safety plans. Both attitudes suggest that companies that invest in advanced organization-wide measures towards prevention often use prefabrication, but not necessarily that prefabrication contributes to their safety culture.

Lastly, most builders using prefabrication are also adopting BIM (8). So, it is also possible that the project types, delivery methods, and management processes correlated with BIM have higher level of collaboration and pre-planning activities, and these are the real boost to safety, rather than prefabrication alone. This seems to be somewhat confirmed by the shared belief, among contractors, that preemptive hazard recognition plays a key role in prevention, and BIM supports early collaborative efforts toward problem identification and solving.

In 2014, a subsequent research report by NIBS (9) on the "perceived and realized benefits" of off-site construction, showed a turn towards skepticism: only 38.5% of 312 nation-wide participants, when asked about their most successful prefabricated projects, included safety as a resulting benefit (Figure 17). We don't know what remaining proportions were neutral and/or negative, nor what share of the 'success' of the project was owed to using off-site construction, if at all.

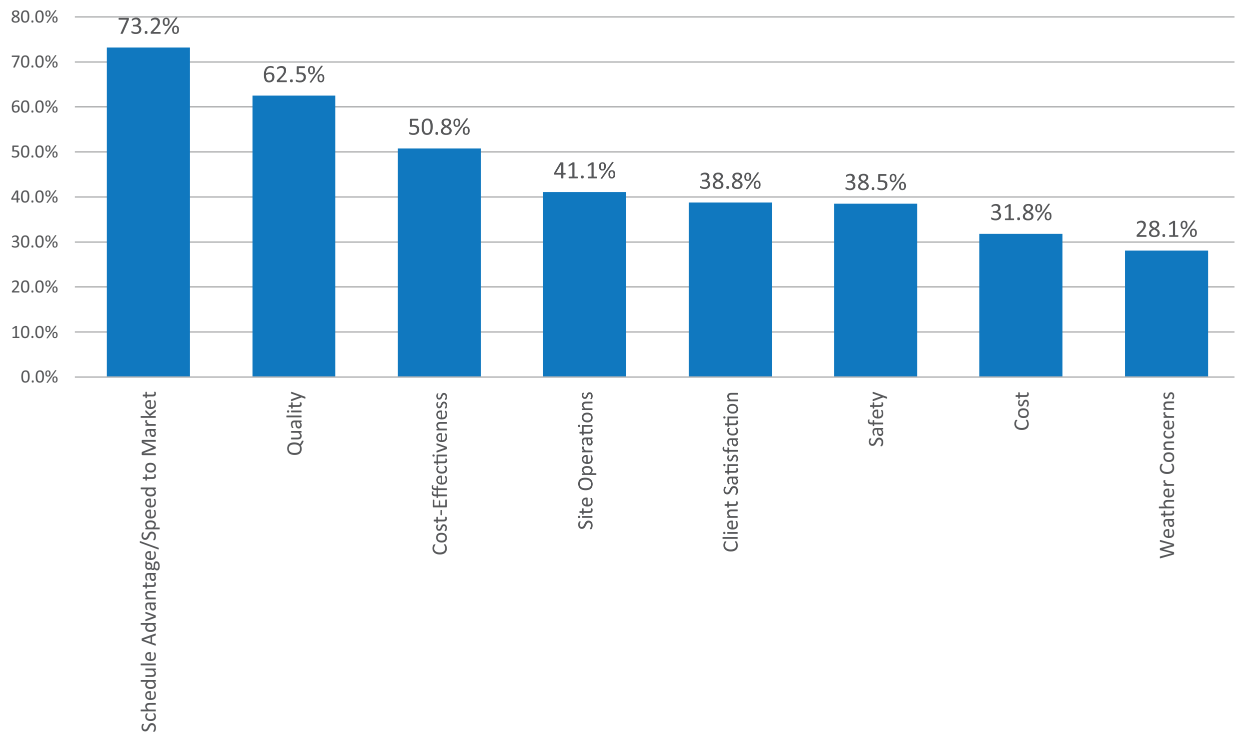


Figure 17. Excerpts from the industry survey conducted by NIBS in 2014, showing the responses to the question: "For this [*most successful experience with off-site construction*] project, what were the actual benefits realized by using off-site construction?". Source: (NIBS 2015).

It can be assumed that part of the reason for the inconsistent responses (as well as the overall neutrality) lays in the research design. In this (9) survey, the questions were meant to take the pulse on the state of the prefabricated market, without expressly soliciting attitudes towards safety. Additionally, "precast concrete structures" were reported to be the most commonly applied prefabricated typology, without further description, but they did not appear—or were not categorized as such—in any of the preceding studies. It is then possible that the type of product used (or intended) by the surveyed, in addition to firm size and maturity, may have acted as an effect modifier in the preceding surveys (7) (8). Because vague classifications and semantics hinder the interpretation of otherwise valuable data, future research should account for these and similarly possible discriminants for perceived risk associated to off-site construction methods.

2.4 Product and Process Design

We have seen the importance of defining and identifying the prefabricated technology to recognize and weigh the safety risks or benefits that come with it; the nature and size of the components determine the *in-situ* logistics and sequencing, while its design features affect the ease of execution.

Relatively small two-dimensional prefabricated elements can accelerate the construction process and still introduce notable health hazards that are largely due to design choices. Research focused on inner prefabricated walls (2) (6) corroborated the role of design in the health and safety of the installers. On-site observations as well as experimental trials found that their ergonomic exposure is intensified by the sequence and repetition of actions (lifting, carrying, moving) in combination with the physical features of the component (dimensions, weight, gripping points).

Even so, factory-built panels are currently the most adopted prefabricated component in the US. According to product designers (3), the housing sector has become increasingly interested in them because they are fast to install, they make for more precise assemblies, they are guaranteed to be code-compliant, and are less subject to jobsite theft.

A 2008 survey (3) gauged the knowledge and perspectives of a group of panel designers towards the inclusion of safety considerations in product development. Panel designers are product designers. As such, they are not part of the core group of traditional project stakeholders, even though they indirectly influence the construction process, since height, length, mass, layout and stacking order determine how much time and how many people and/or equipment are needed to move and set them in place. When asked where ergonomic factors ranked in their design process, if at all part of it, they explained that the leading input parameters for design purposes are transportation (shipping cargo dimensions, pallet stacking), and floorplan information, and both efficiency-oriented, whereas crew size and weight are of least importance.

Within a pool of participants that had 3 to 30 years of experience in construction and 1.5 to 30 years of experience in panel design, most claimed to have 'moderate' ergonomic competence. In-depth interviews also revealed limited awareness of potential sources of hazard for the crews, and little to no familiarity with the installation procedures and related ergonomic issues (3). However, such knowledge was not deemed necessary in their capacity: 50% didn't consider ergonomics their responsibility, and others thought they were already including it (i.e. "splitting single long panels in two"). The majority concurred that on-site workers and their direct supervisors are fully responsible for any job-related injuries.

Panel designers were also found to have a mindset comparable to that of architects towards the inclusion of safety principles in project design (3). Even though new drafting software and ergonomic assessment tools can assist in the development of improvements, the neutral, when not resistant, attitude towards making ergonomic-driven corrections is colored by the belief that it would come at the expense of the product's flexibility and cost, and likely require more work on their part (3).

Product and process design are inter-reliant in affecting off-site construction operations. The main disadvantages are typically identified with transportation, craning, and handling of large components. This raises the importance of designing processes purposely for prefabrication, since most of the safety benefits are—or anecdotally believed to be—a function of size. A study (11) that ran a one-on-one comparative JHA on a large prefabricated system for a bridge project, reversed the ergonomic concerns posed by wall panels, showing how the use of pre-assembled steel reinforcement eliminated hours of repetitive work done in bent posture. However, in focusing on a specific stage of installation, it did not capture the full breadth of the prefabricated activities, offering a piecemeal evaluation of its safety. *This brings to the attention the limits of making task-by-task comparisons between traditional and off-site construction*.

A pilot study sponsored by the Center to Protect Workers' Rights (CPWR) (1) addressed this matter, finding that the problem lays in the question, as it's asking to compare oranges to apples. In this study, researchers examined the safety of on-site workers against modular housing systems, specifically, 3D pods and tilt-up truss roofs. Direct observations and questionnaires across four different companies aimed at identifying the procedures and the exposures of each method (traditional vs. modular), and at assessing their value in safety terms. After running a Job Safety Analysis[11], it became apparent that there is a combination of hazards unique to modular assembly, and from a safety standpoint, *the installation of all the individual parts that make a prefabricated system is not comparable to the installation of the latter*. In other words, the prefabricated on-site process is so different from the conventional on-site process that treating (and managing) them as equivalent only increases the likelihood of accidents (1).

[11] Job Safety Analysis is often used interchangeably with Job Hazard Analysis (JHA).

It is worth reporting the researchers' observations to support this statement, to admit that, while the assembly is faster (thus reducing the total working hours on the site), and requires less laborers, it still includes highly risky activities:

> "Compared to traditional residential housing, modular home installation has these major job tasks (and potential hazards):
>
> - Flagging traffic while positioning the home for hoisting (struck by)
> - Hoisting of large, heavy modules, or "boxes," by an inexperienced workforce on a site having uneven terrain and other less-than-desirable conditions. (struck by, caught between)
> - Working under a heavy load that is being hoisted into place (struck by, caught between), which happens less often in other residential work
> - Aligning the house to the foundation (caught between)
> - Accessing the foundation wall with a ladder that does not exceed the top edge of the wall, as required by OSHA, to allow clearance for the house to set (fall)
> - Accessing the roof with an extension ladder (fall) (also a problem in traditional residential construction)
> - Riding the tilt-up roof into place/riding the load (fall)
> - Accessing the attic area from the roof top (fall)
> - Working under the roof while it is suspended by the crane (caught between, crushed by, fall)." (1).

Further, lack of specific training (on rigging, for example) increases risk, as seemingly confirmed by the fact that, despite the relatively small sample size, 29% of the workers disclosed that they had, at some point, been hurt on a modular house project –injuries included strains, sprains, fractures, amputations, and electric shock. This statistic is not easily generalizable, and it is also representative of housing construction alone, which comes with less stringent building codes to begin with. It nonetheless sustains that "tracking of industry hours, injuries, deaths, and compliance with government safety regulations would be feasible if the modular home classification code was moved up one level in the SIC/NAICS, so modular installation is equal to residential construction, and not a subset" (1). Further, it advocates for design solutions that come from a greater understanding of on-site processes, and for formal OSHA guidelines and regulations that address the uniqueness of prefabricated construction activities, as opposed to treating them as an aggregate of independent jobs tasks (1).

2.5 Indicators of Value and Pointers

The existing literature emphasizes the need to cohesively define and distinguish between prefabricated typologies as a necessary condition for gathering interpretable data on workers' health and safety based on current practices. Lumping all off-site products under a single definition makes it impossible to extricate the safety issues among many possible confounders. Where wall panels introduce relevant ergonomic concerns, pre-assembled reinforcement systems tend to remove them. Therefore, an opinion on ergonomic exposure cannot be formulated under the —exceptionally— broad conceptualization that is 'prefabrication'. *Understanding the uniqueness of the prefabricated processes, is also necessary to be able to evaluate the health and* *safety trade-offs, as well as to develop a framework that evaluates all the applicable work environments, and provide a platform for strategic action (risk management tools, specialized training, activity-based regulation, process planning) for each.*

There are ample, yet conditional, safety opportunities in both product and process design (1) (2) (3) (5) (10). Process design needs to acknowledge the changes in the production work methods brought by each prefabricated technique. Lack of understanding of construction processes is a barrier for managers to plan for safety, and for designers to contribute to their ease of execution. Product design has the potential to improve on-site workers' conditions, without sacrificing productivity. However, the readiness to include safety considerations in the design equation needs to be matched by architects, engineers, and designers alike with an adequate knowledge of health and safety hazard as well as of the construction processes.

Researchers noted that "decisions to use offsite are based on anecdotal evidence as opposed to data analysis, as no appropriate measurement procedures are available" (4), recognizing the ongoing need to fill this gap. There is also a call for metrics based on factors other than "capital cost or intuition" (4) to compare prefabricated methods and guide their use as much as their design, specifically around their interaction with health and safety.

Chapter 3. METHODOLOGY

This study triangulates (i) observations from the existing body of literature, (ii) a public records search on the OSHA Fatality and Catastrophe Investigation Summaries database, and (ii) a differential and process-based hazard and risk analysis for common pre-cast structural and envelope components. The merged outcomes form a contextualized and integrated evaluation of the health and safety risks related to prefabrication.

The *literature review* consolidates the existing studies, qualitatively evaluating the contents, trends, and findings on health and safety in relation to prefabricated construction. The *data analysis* is modeled after the study by Fard et al. (2017), and informed by the pointers that result from the job hazard and risk analysis. The *differential job hazard and risk analysis* looks at all occupational settings involved in the production and installation of a given building system in a total of four prefabricated and non-prefabricated scenarios.

Because the topic is marginally explored territory in the scientific community, the approach is primarily founded on indirect content and data analysis, and aimed at laying the grounds for future empirical research, with the added value of an interdisciplinary perspective, as it accounts for different professional viewpoints.

Chapter 4. INDIRECT DATA ANALYSIS

4.1 Scope and Search Parameters

In the former chapter, we have used secondary data resources (reports and scientific literature) as a narrative to navigate the domain of off-site construction. The second methodological dimension of this study is data-driven: it uses descriptive statistics of evidence collected from the OSHA Fatality and Catastrophe Investigation Summaries (here on referred to as FCIS) to create a point of convergence for the themes so far explored.

This approach was developed along the lines of a recently published study (Fard, Terouhid et al. 2017) that was also included in the systematic literature review, which used this same source to uncover patterns in the root causes of accidents involving prefabricated construction. Fard, Terouhid et al. formulated their question prescriptively, and sought associations with worker trade, equipment, and/or building type. Here, we will isolate the accidents from their cause(s), focus on descriptive questions (the *what*), and defer solutions. The intent is to add a tile to the map drawn so far with factual information, by answering the following:

- What was the location of the accident?
- What was the outcome of the accident?
- What prefabricated typology/component/system was involved in the accident?
- What activity was being performed at the time of the accident?

The Fatality and Catastrophe Investigation Summaries is a digital archival system made available through a public online search engine, where OSHA staff enters the findings of any inspection in response to an accident. Figure 18 shows the interface of the search portal, and the filter options.

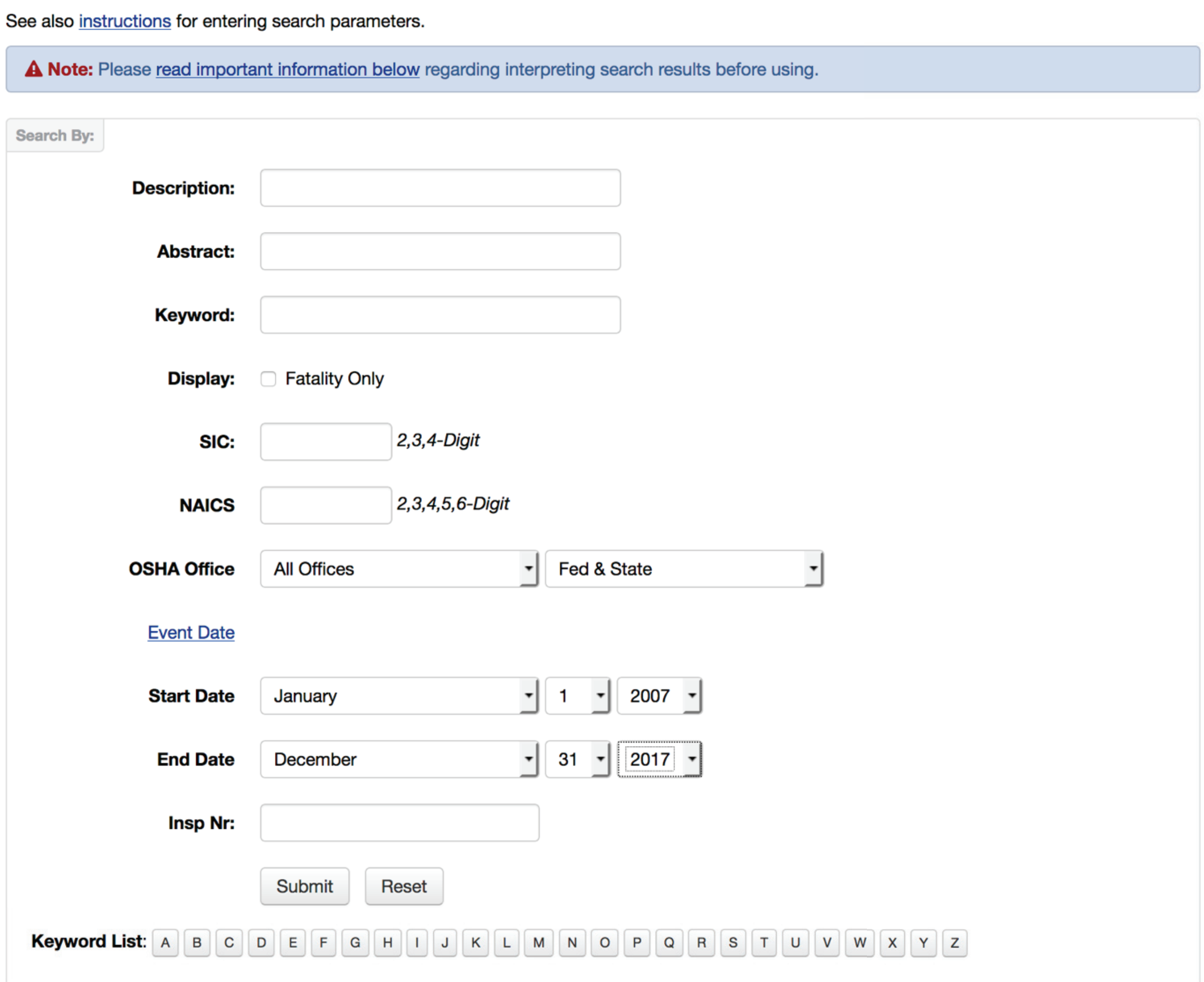


Figure 18. Screenshot of OSHA's Fatality and Catastrophe Investigation Summaries web-portal. Source: https://www.osha.gov/pls/imis/accidentsearch.html.

Because of the limitations of the system, which warrant a separate section (4.2), the search parameters were kept as undefined as possible to avoid triggering content tags that would hide pertinent records. Therefore, there was no narrowing by location, industry (Standard Industrial Classification (SIC)), or business type (North American Industry Classification System (NAICS)). The only fields used were the Description, the Abstract and the Keyword, and with a single word entry at the time, meaning that when a term was used in the Description field, the Abstract and Keyword fields would be empty. The period covered was the decade between January 1, 2007 and December 31, 2017, which is used as the window of time that frames the contemporary renaissance of prefabrication. Table 3 summarizes the formula for each search, and the screening and selection steps.

Table 3. Record search and selection report.

OFF-SITE CONSTRUCTION: ACCIDENTS & FATALITIES 2007-2017

Source: OSHA Fatality and Catastrophe Investigation Summaries
Timeframe: January 1, 2007- December 31, 2017
Exclusion criteria: 1) Component is employed in the construction industry
2) Component not considered a prefabricated tecnology under current definitions
3) Component not cause of the accident, or non-work related cause

	OSHA Search Fields					**Screening**			**Selection**		
	SIC	NAICS	Description *(title)*	Abstract	Keyword	Duplicates	**Records reviewed**	Exclusions	**Relevant Accidents**	Multiple victims	**TOTAL VICTIMS**
Word Search											
Precast	*blank*	*blank*	7	65	9	13	68	24	44	12	56
Prefab	*blank*	*blank*	0	0	0	0	0	0	0	n/a	0
Prefabricated	*blank*	*blank*	43	0	0	0	43	21	22	1	23
Prefabrication	*blank*	*blank*	0	0	0	0	0	0	0	n/a	0
Modular	*blank*	*blank*	2	32	0	2	32	17	15	n/a	15
Module	*blank*	*blank*	1	18	0	1	18	16	2	n/a	2
Offsite	*blank*	*blank*	0	12	0	0	12	12	0	n/a	0
Oversize	*blank*	*blank*	0	6	0	0	6	5	1	n/a	1
							179	95	**84**	13	**97**

After all word search iterations were completed, the system returned a total of 179 records, which were fed into a database, categorized by year, location of accident, outcome (injury/death), type of injury, type of prefabricated component, direct cause, indirect cause, activity at the time of accident. A nomenclature was developed to group items under categories in a consistent manner. Abstract excepts were also attached to each entry, to make retrieval and verification easier.

The collection and sorting process was tracked to allow to repeat the search, if needed. Three disqualifying criteria guided the shortlisting, and ensured that the records retained were relevant to the scope of the investigation:

1) The prefabricated method is not used in or for the construction industry.

2) The component is not considered 'prefabricated' under the common definition and understanding of the term, or under the interpretations provided in this study (e.g. "prefabricated cladding stones", "prefabricated granite countertop").

3) The prefabricated component—or its prefabricated nature—does not have a direct role in the accident.

After filtering the original bulk, the number of reports went down to 84. The event-to-victim ratio was not 1:1, as some accidents harmed or killed more than one person. This was factored in the number of victims, taking the total data points to 97.

4.2 Limitations of the Data Source

OSHA's Fatality and Catastrophe Investigation Summaries is described as a resource available to those "who wish to track OSHA interventions at particular work sites or to perform statistical analyses of OSHA enforcement activity" (OSHA). The makeup of the data, the way it is inputted, and the characteristics of the system that hosts it should guide users in the search as well as in handling the results.

As self-explanatory form the name, only accidents of certain magnitude are entered in this system. In fact, abstracts originate from OSHA-170 forms, which are used to "summarize the results of investigations of all events that involve fatalities, catastrophes, amputations, hospitalizations of two or more days, have generated significant publicity, and/or have resulted in significant property damage" (OSHA 2016). Any injury below this cutoff would not warrant a report in the database, thus excluding a wide array and amount of non-fatal injuries[12]. This also means that the analysis revolves around aspects of safety (or illnesses with acute immediate onset), as occupational diseases and illnesses are not captured under this definition.

Effective January 2015, OSHA's reporting rules for Fatalities and Severe Injuries changed to cover "all work-related fatalities, hospitalizations, amputations and losses of an eye to OSHA, even employers who are exempt from routinely keeping OSHA injury and illness records due to company size or industry" (OSHA). The lowering of the threshold may or may not show an uptick of yearly counts of accidents following 2015, given the specific triggers for Form 170, but

[12] The period of hospitalization is not a strict *sine qua non* condition, as some records did report non-hospitalized injuries.

certainly addresses the known problem of under-reporting, which accounts for an unknown—though likely high—hidden statistic.

Each report is structured around a brief description of the accident's dynamic, the outcome (fatal vs. injury), and the type of injury sustained by the victim. It also includes the name of the employer, demographic details of those involved in the accident (age, gender), and auxiliary details, such as use of the project, the type and cost of the project, and the number of stories of the building (when applicable). However, these line items are not always provided, or filled inconsistently, making them often insufficient or unreliable under narrow research boundaries. By OSHA's own admission, records are subject to inaccuracies, and continuously undergo updates and corrections until a case is closed. Because they are manually filed, misclassifications under NAICS and SIC codes are also possible, as already noted by Fard et al. (2017).

One of the system's greatest weaknesses lays in the way causal information is logged and coded for retrieval. As mentioned earlier, in keyword searches the engine pulls records from the Description, Abstract, or Keyword fields. The title typically describes the outcome, encapsulating direct causes, that is, the immediate event leading up to the accident[13]. Then, the body of the abstract adds detail to that, by describing the events leading up to the accident, but rarely provides clear pointers to indirect causes. Lastly, only additional establishment-related research (through a separate OSHA database) will disclose the root causes. As a result, a single keyword search might fail to retrieve a relevant document or capture the cause that led to the

[13] These are known as Level 1 causes. Level 2, or indirect causes, are the unsafe causes, actions, and conditions that contributed to the accident. Level 3, basic or root causes, are typically ascribable to management system, policies, or attitudes that failed to detect conditions leading to the damage.

outcome, thus hiding reports and/or information on risk factors that are more or less frequently associated with injury trends.

For example, title strings such as "Employee falls from ladder and is killed", or "Employee is killed when ejected from aerial platform" suggest fall from height and struck-by incidents being the primary cause of death. However, the information in the abstract reveals that the task that exposed the workers to the risk in the first place was working on a light bulb replacement. Slight changes to the keyword search entries may lead to exclude and therefore miss many accidents associated with light fixture repairs.

In searching by non-causal descriptors, the constraint comes from how the abstract itself is written. As we choose 'prefabrication' as our filter category, we are dealing with a two-fold problem: ambiguity of the definition (as amply discussed in earlier chapters), and its representative value in the context of safety, which makes the word and any of its synonymies a non-essential piece of information for reporting purposes. In other words, if an investigation involving a prefabricated wall or a modular mechanical racking system describes these components as "concrete wall" and "pipe rack", neither the search engine nor a reader would be able to detect a connection to prefabrication. Ultimate the accident dynamic, the specificity attached to the episode, and the style of the writer end up contributing to the record's visibility.

Lastly, because we are maintaining a job-based approach, we are including transportation in the analysis (hence the 'oversize load' key-term). This is a choice of consistency, though not expected to yield many or meaningful results, since OSHA's criteria for recording vehicle accidents are complex[14] and even less conducive to queries on vehicle load. OSHA is also not the first authority for road safety, and the data is managed by several organizations[15], depending on local and national jurisdiction.

4.3 Descriptive Analysis

Of the 97 reports, 43 (44%) resulted in fatality, 54 (56%) in injury. Most fatalities were a result of Crush-by, followed by Falls, while most injuries resulted by Falls, followed by Struck-by and Crushed-by (Table 4). There were occurrences across all years analyzed, with greater incidence in 2007 (20 cases), 2017 (14 cases), 2008 (13 cases), and 2012 (12 cases) (Table 5). The majority of reports were related to on-site accidents (73%), followed by manufacturing environments (21%), and transit (6%).

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[14] For a recent interpretation of the standard, see https://www.osha.gov/laws-regs/standardinterpretations/2012-06-06.

[15] Main sources include: The National Highway Traffic Safety Administration's (NHTSA's) Fatality Analysis Reporting System (FARS), a census of fatal crashes involving motor vehicles traveling on public trafficways. NHTSA's General Estimates System (GES), a probability-based sample of fatal, injury, and property-damage-only crashes. FMCSA's Motor Carrier Management Information System (MCMIS) Crash File. The Federal Highway Administration's (FHWA's) Highway Statistics.

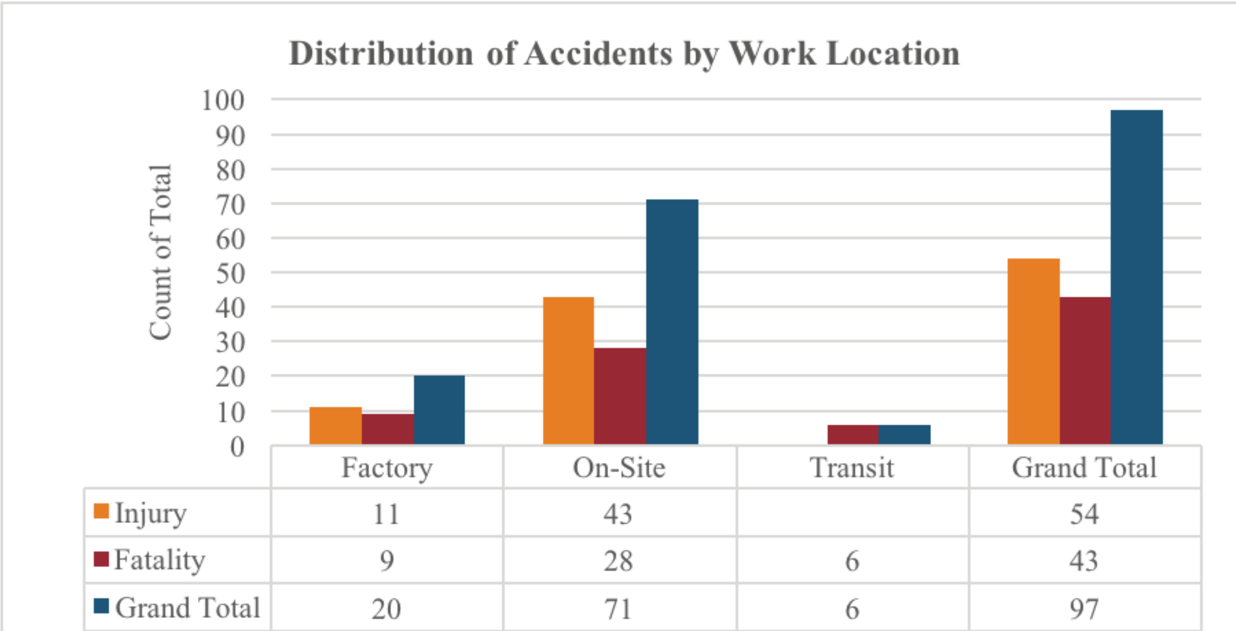

Figure 19. Distribution of accidents related across work locations.

Table 4. Distribution of cause by accident outcome (injury / death).

CAUSE OF ACCIDENT BY TYPE OF OUTCOME (INJURY / DEATH)	
Fatality	
Crushed-by	**23.7%**
Fall	**13.4%**
Struck-by	**4.1%**
Electrocution	3.1%
Injury	
Fall	**24.7%**
Struck-by	**15.5%**
Crushed-by	**13.4%**
Caught between	1.0%
Caught-in	1.0%
Grand Total	100.0%

Table 5. Yearly occurrence of accidents related to prefabrication by work location.

Yearly Distribution of Accidents By Location											
	2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**
Factory	3	5	1	1	1	3			1		5
On-Site	15	7	5	6	9	9	3	2	3	3	9
Transit	2	1	2								1
Grand Total	20	13	8	7	10	12	3	2	4	3	15

4.3.1 Direct & Indirect Cause

Regardless of location, the direct causes of accident were Fall (38.1%), Crushed-by (37.1%), ad Struck-by (19.6%) (Figure 20). In factories Crushed-by predominated, with 50%, followed by Struck-by (30%), and Falls (20%). On construction sites, the top three causes were the same with the first two in inverted order: Fall (46.5%), Crushed-by (31%), and Struck-by (18.5%) (Table 6). Transit fatalities were caused by Crushed-by (4 cases) and Electrocution (2 cases). These numbers confirm the presence of highly impactful hazards in all three work environments, as also shown in Chapter 5.

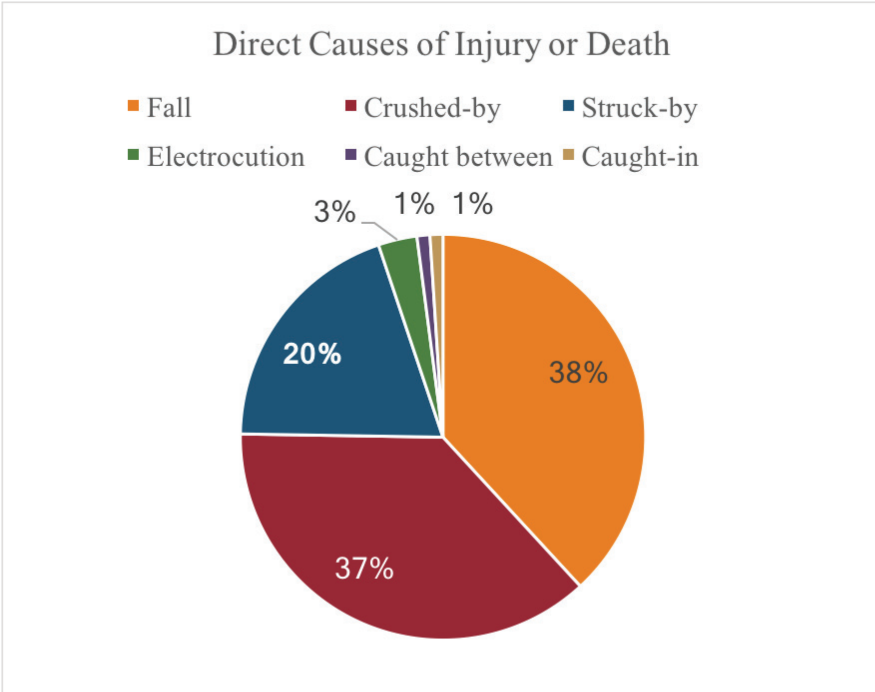

Figure 20. Direct causes of an event leading to injury or death.

Table 6. Cause of injury or death by work location.

Direct Cause of Injury or Death by Location		
Location	Direct cause	%
Factory	**Crushed-by**	50.0%
	Struck-by	30.0%
	Fall	20.0%
Factory Total		100.0%
On-Site	**Fall**	46.5%
	Crushed-by	31.0%
	Struck-by	18.3%
	Caught between	1.4%
	Caught-in	1.4%
	Electrocution	1.4%
On-Site Total		100.0%
Transit	**Crushed-by**	66.7%
	Electrocution	33.3%
Transit Total		100.0%

Table 7. Consequences associated to causes of accident.

Consequences by Cause of Accident	
Fall	38%
Fractures	21%
Death	12%
Bruise/Contus/Abras	4%
Amputation	1%
Crushed-by	37%
Death	24%
Fractures	8%
Bruise/Contus/Abras	3%
Dislocation	1%
Amputation	1%
Struck-by	20%
Fractures	9%
Death	4%
Strain/Sprain	2%
Amputation	2%
Bruise/Contus/Abras	1%
Cut/Laceration	1%
Electrocution	3%
Death	3%
Caught between	1%
Fractures	1%
Caught-in	1%
Amputation	1%
Grand Total	**100%**

Only half of the reports could identify an indirect cause, or rather a snowball effect trigger, showing that Crush-by accidents were mostly preceded by a Tip-over (20.4%) and Collapse (14.3%), and Falls resulted mostly from Collapses and Struck-by (both 12.2%), followed by Tip-over (8.2%). Tip-over also led the indirect cause of Struck-by (Table 8).

Table 8. Secondary causes of accident (49 of 97 data points available).

Secondary Cause of Accident		
	Count	%
Crushed-by	19	38.8%
Tip-over	**10**	**20.4%**
Collapse	**7**	**14.3%**
Unstable positioning	1	2.0%
Load drop	1	2.0%
Electrocution	2	4.1%
Caught-in	**2**	**4.1%**
Fall	23	46.9%
Struck-by	**6**	**12.2%**
Collapse	**6**	**12.2%**
Tip-over	4	8.2%
Trip	2	4.1%
Missing protection	2	4.1%
Slip	2	4.1%
Lost balance	1	2.0%
Struck-by	5	10.2%
Tip-over	**3**	**6.1%**
Trying to avoid struck-by	1	2.0%
Missing protection	1	2.0%
Grand Total	49	100.0%

4.3.2 Activity

Across all settings, connection work (27%), moving/lowering (19%), and placing (10%) of prefabricated components or modules were the most common task undertaken as the time of the accident (Figure 21). Sorting by 'Activity' (or task done at the time the accident occurred) shows that in factories most events happened while loading, followed by various hoisting operations. On construction sites, connection work was the activity predominantly associated with falls. It should be noted that activity is not presented as a secondary or root causal element, but only an association that could possibly have a role in predicting risk (Table 9).

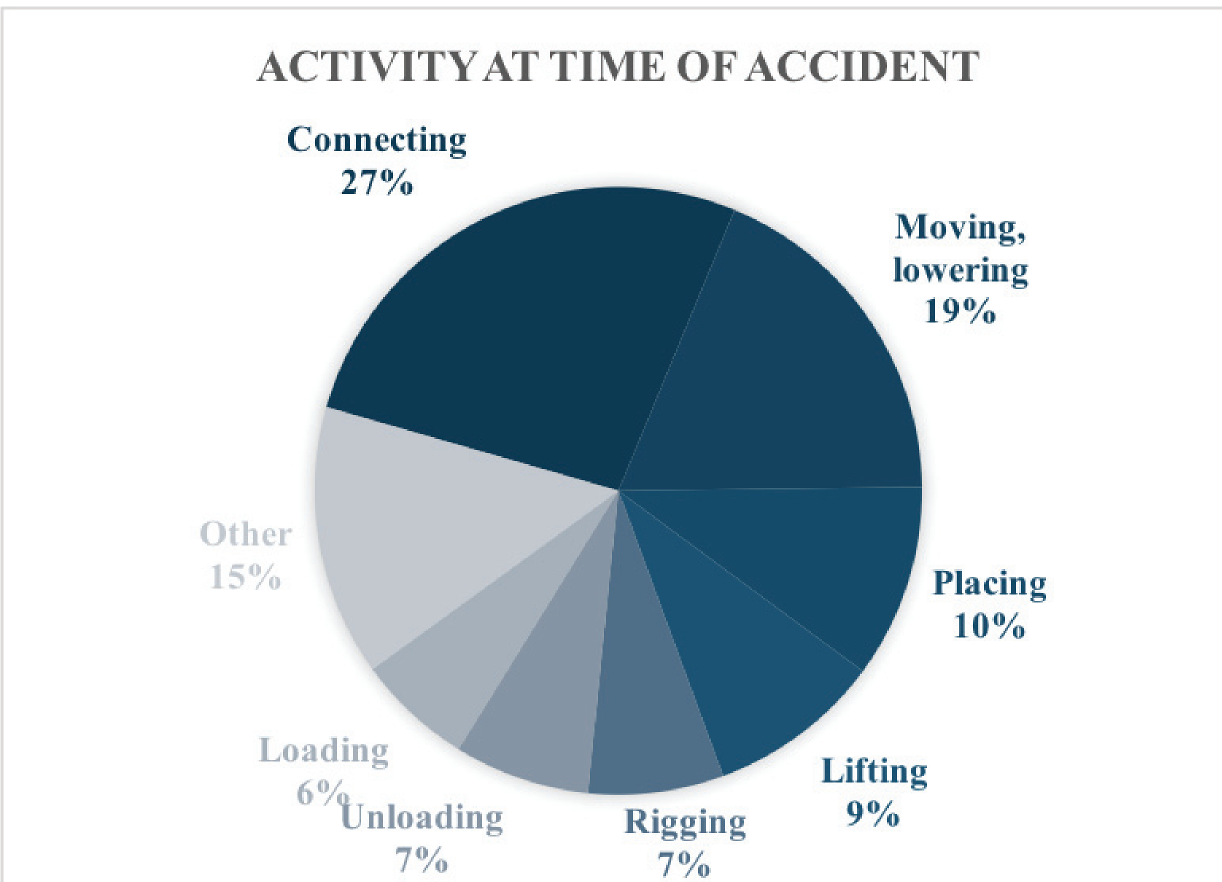

Figure 21. Activity undertaken by the victim at the time of the accident.

Table 9. Activity undertaken by the victim at the time of the accident, by location.

LOCATION	ACTIVITY	
Factory	**Loading**	**5.2%**
	Moving, lowering	**3.1%**
	Lifting	**3.1%**
	Connecting	3.1%
	Rigging	1.0%
	Transfer to storage	1.0%
	Screeding	1.0%
	Pre-assembly	1.0%
	Preparation	1.0%
	Placing	1.0%
Factory Total		**20.6%**
On-Site	**Connecting**	**23.7%**
	Moving, lowering	**14.4%**
	Placing	**10.3%**
	Rigging	6.2%
	Lifting	6.2%
	Unloading	5.2%
	Disconnecting	2.1%
	Preparation	2.1%
	Hoisting	1.0%
	Inclusion	1.0%
	Measuring	1.0%
On-Site Total		**73.2%**
Transit	**Unloading**	**2.1%**
	Transporting	**2.1%**
	Loading	1.0%
	Moving, lowering	1.0%
Transit Total		6.2%
Grand Total		100.0%

4.3.3 Typology

The typology most frequently involved in accidents is Precast Walls (22.7%) (Figure 22). Precast Walls (23.9%) are also most frequently associated to on-site accidents, followed by Structural Steel (19.7%), and Precast Structural (18.3%). All precast concrete components (structural, architectural, wall, utility) account for 52.1% of the on-site accidents. Precast Structural elements are associated with 25% of the factory accidents, followed by Modular Units, Precast Wall, and Structural Steel (all 20%). Modular units make for half of the statistics for transportation accidents, followed by Precast Structural (33%) and Precast Walls (17%) (Table 10).

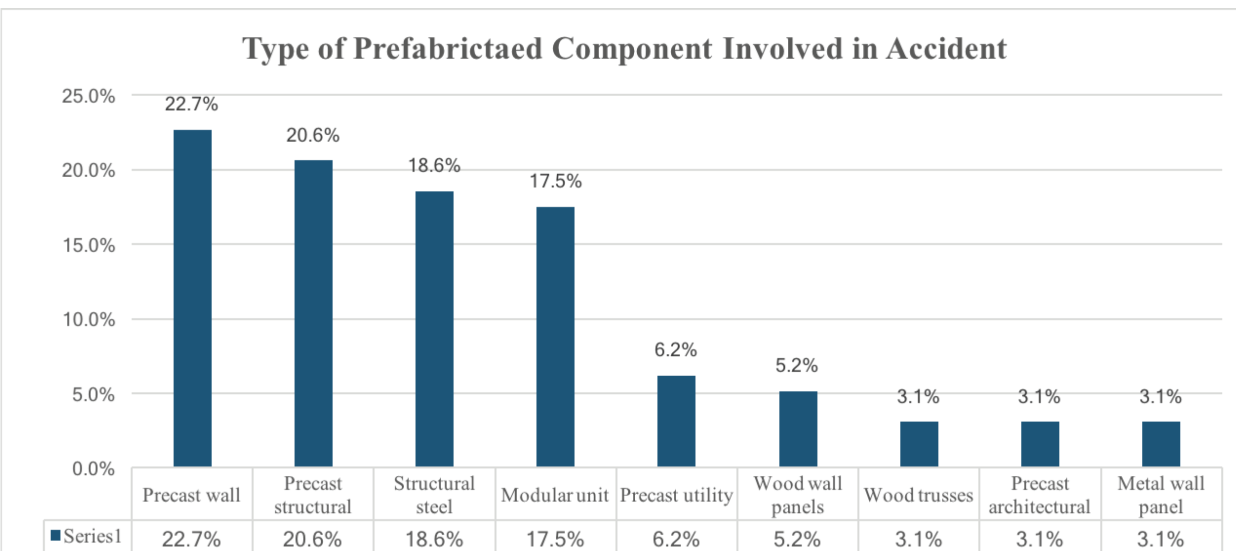

Figure 22. Prefabricated component involved in the accident.

Table 10. Prefabricated component involved in the accident, by location.

Location	Component	
Factory	**Precast structural**	**25.0%**
	Structural steel	**20.0%**
	Precast wall	**20.0%**
	Modular unit	20.0%
	Precast architectural	5.0%
	Precast utility	5.0%
	Metal wall panel	5.0%
Factory Total		100.0%
Transit	**Modular unit**	**50.0%**
	Precast structural	**33.3%**
	Precast wall	**16.7%**
Transit Total		100.0%
On-Site	**Precast wall**	**23.9%**
	Structural steel	**19.7%**
	Precast structural	**18.3%**
	Modular unit	14.1%
	Wood wall panels	7.0%
	Precast utility	7.0%
	Wood trusses	4.2%
	Precast architectural	2.8%
	Metal wall panel	2.8%
On-Site Total		100.0%

4.3.4 Observations

Depending on how these values are cross-examined and paired, they can tell different stories, often suggesting more questions than they are able to answer. However, the objective here is not to look for causes or solutions, but test the arguments that drive the hypothesis and the scope of this work, and this was achieved.

First of all, the information system's behavior confirmed the barrier that is semantics. This became evident during the initial screening and exclusion process, where in the reports the keyword of choice appeared associated with a range of definitions spanning across —and in some instances outside— all contemporary definitions of 'prefabrication'.

Secondly, the data suggested that prefabrication creates the conditions for types of hazards also common to traditional construction methods. What's more, it exposed risks that didn't emerge in the literature, but will be anticipated in the hazard and risk identification exercise (Chapter 5). An unexpected example of this, of no statistical significance, but notable for presence, is embedded in the transportation fatality causes. As we will see in Chapter 5, the hazards for that specific job phase draw from OSHA's reference knowledge on transporting equipment (applicable to heavy/oversized loads), which alerts to the dangers of striking overhead power lines. The data confirms the reality of this risk, showing as many as two cases of electrocution from being caught in a power line, but it is otherwise an unfamiliar worry to construction, or at least not the first, perhaps, to ever come up in a survey.

Chapter 5. JOB HAZARD & RISK ANALYSIS

5.1 A Process Based Approach

The problem of safety and health in the context of prefabrication has so far been presented in very broad, all-encompassing terms (market surveys researching prefabrication as a field), or in a very honed-in manner, by singling out one element/task/hazard (e.g. ergonomics in prefab wood panel installation). The analysis presented in this chapter positions itself in the middle ground between these two dimensions; it analyzes a prefabricated system, utilizes a more descriptive than comparative analysis, and looks at it as a new job process across multiple work stages and environments (Figure 23).

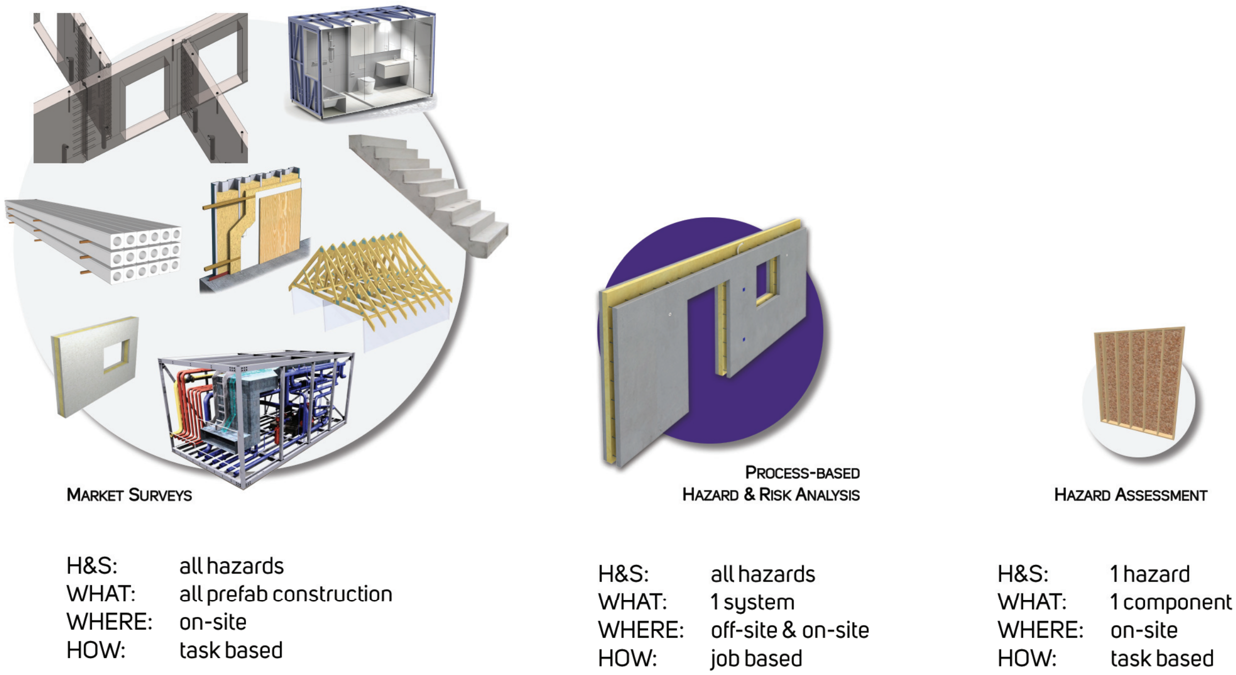

Figure 23. Positioning of the process-based Hazard & Risk Analysis respect to the mainstream (literature-based) approaches.

In acknowledging that an analysis based on comparative advantages may not be possible (Becker et al. 2003) it aims to be descriptive in nature, exposing differences by contrast, and providing a fresh reading of the phenomenon through one illustrative example. In other words, it will focus in on a prefabricated typology while applying a wide angled perspective to capture all stages and tasks, from production and transportation to installation, and what they entail from the occupational health and safety standpoint, per the following steps:

- Identify the corresponding most common 'traditional' method(s). For example, the alternative to a prefabricated wood wall, would be to frame the wall *in-situ* with dimension lumber.

- Compare tasks with a process-based approach that starts at manufacturing and ends with installation.

- Characterize the hazards.

- Evaluate the exposure potential.

- Estimate the risk components.

- Characterize the risk distribution between processes.

Concrete walls for commercial applications[16] were chosen as the object of scrutiny, because—as seen in the literature—they are one of the most popular prefabricated components, and because their general definition is easily understood consistently within the industry, while allowing for variety of size and features. Precast concrete walls also make for an interesting paradigm,

[16] Commercial may include multi-family residential, but not housing.

because they have two equally common alternatives: tilt-up panels cast *in-situ*, and concrete masonry unit (CMU) walls, also referred to as cinder blocks[17], which are very different in the way they are produced and assembled. Similarly, because it has proven to be relevant for understanding the off-site side of the process, the analysis will cover antithetical manufacturing scenarios: an almost fully automated and remotely controlled one, and one more similar to a sheltered version of a construction site. The four concrete-wall methods offer a good spectrum of real-world applications: two prefabricated, with different degrees of industrialization; two conventional, equally adopted but based on dissimilar components and sequences.

Time and resource constrains did not allow for direct observations, which are at the base of job task analyses. Many JHAs, though, do employ video recording to supplement and verify field notes, and there is a wealth of on-line videos produced by general contractors, as well as corporate clips, demos, and walk-throughs that show "how it's made", in factory settings as much as on construction sites. While many situational details cannot be verified from film footage[18], multiple examples for each type and job setting provided a rich collection of information[19]. A full list and description of the consulted videography is included in the Appendix.

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[17] Cinder blocks are CMU blocks that use fly ash or bottom ash as aggregate.

[18] Observation is one of the main identification methods recommended by OSHA, because it exercises all senses (hearing, touch, smell, and vision) as well as the knowledge and experience of the observer.

[19] Examples of the most advanced precast production systems were gathered from international manufacturers.

5.2 Elements of a Job Hazard and Risk Analysis

OSHA recommends using Job Hazard Analysis for various activities, including but not limited to "Jobs that are new to your operation or have undergone changes in processes and procedures" (2002). Further, "the JHA is used to assess the existing and potential hazards of a job, understand the consequences of risk, and act as an aid in helping identify, eliminate, or control hazards. The JHA is a tool that is used to focus on a specific job, define the steps required to do that job, and ultimately define each task required to perform each step." (Roughton and Crutchfield 2011).

OSHA defines hazard a "condition or set of circumstances that present a potential for harm" (2002), which could be physical or mental. In the occupational realm, hazards fall into two categories: acute damage to the body with an immediate effect (injury or death), and adverse health effects that take longer to manifest (illness or disease). Disease and illness are expressions of health hazards, while those that result in injury or death are safety hazards. Hazards and paths of exposures come in different forms: environmental (e.g. light, noise, rain, heat, cold, sun, imperviousness); chemical (e.g. fuels, dust, vapors); material (e.g. equipment, tools); electrical; dimensional (e.g. workspace layout and arrangement, components' height, mass, and size); organizational (e.g. procedures, policies, training, coordination, work patterns, requirements); behavioral (e.g. fatigue, incompetence, distraction, compliance).

Hazards inherent to prefabrication lack recognition from multiple directions. The construction industry at large seems dismissively optimistic; the Industrial Hygiene (IH) field may be more alerted to it, though recognition by those outside an industry would not generally prove recognition within the industry, unless regulated. The main expectation with hazards is that they be foreseen, not merely identified, and also mitigated, if not altogether prevented. However, the literature has shown how the variety of prefabricated products and methods makes it easy to imagine hazards in an intuitive rather than educated way, but difficult to isolate and foresee them in clear cut terms.

Awareness starts with identification, followed by risk assessment. When asking if off-site construction is safe(r), what we're really asking is "how risky do you think it is?", and the naturally following questions would be "for whom?", and "why?". What is being evaluated is the possibility (the odds) that a known hazard could strike, the likelihood of that happening, and the magnitude of the negative consequences for the workers and anyone else at harm's reach.

The IH tenets of prevention and control are modeled around an Anticipation-Recognition-Evaluation-Control cycle (Figure 24), with each element answering a specific question:

Anticipation → What hazards are likely to be present?
(trailing the more general: "what can go wrong?")

Recognition → What types of hazards are they?

Evaluation → What is the level of exposure to the hazards?

Control → How to remove/mitigate the hazards?

Figure 24. "The IH Decision-making Framework and Process." Adapted from: Systematic IH Decision-Making Framework and Process. Reprinted from "A Strategy for Assessing and Managing Occupational Exposures," 4th Ed., Edited by Steven Jahn, William Bullock, and Joselito Ignacio. [Copyright 2015 by the American Industrial Hygiene Association.] Source: Body of Knowledge, Occupational Exposure Risk Assessment/Management. AIHA.

IH organizes these same diagnostic actions under the domain of Risk Assessment, which precedes Risk Management (Figure 25), and is defined by American Industrial Hygiene Association (AIHA) as "the determination of quantitative or qualitative value of risk related to a concrete situation and a recognized threat (also called hazard)."

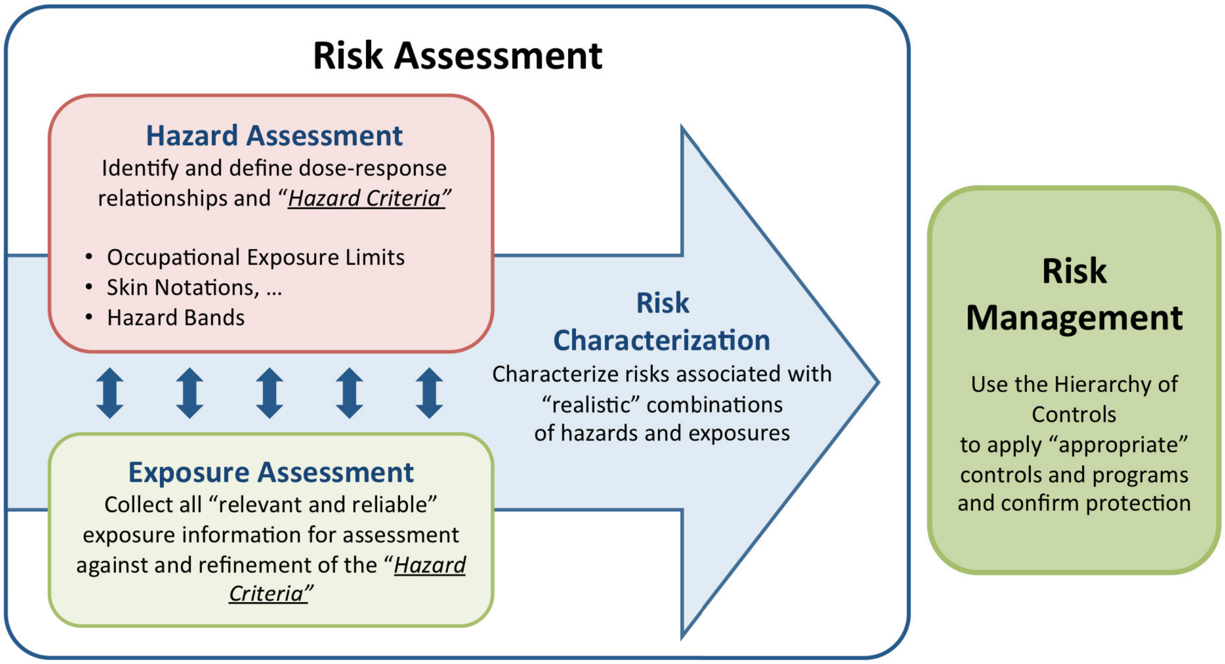

Figure 25. IH Risk Assessment Model. Adapted from: Systematic IH Decision-Making Framework and Process. Reprinted from "A Strategy for Assessing and Managing Occupational Exposures," 4th Ed., Edited by Steven Jahn, William Bullock, and Joselito Ignacio. [Copyright 2015 by the American Industrial Hygiene Association.] Source: Body of Knowledge, Occupational Exposure Risk Assessment/Management. AIHA.

Risk is commonly defined as a relationship between hazard and exposure: **RISK = HAZARD X EXPOSURE**, where exposure is the contact (and "dose", or the amount thereof) with harmful substances or circumstances that an employee might be subject to, as a result of performing their job duties. The concept of 'vulnerability' is commonly used in disaster preparedness to account for some intangible yet contributing aspects that increase the susceptibility to risk. In extreme events, vulnerability can determine the extent of destruction, economic and human loss (Figure 26). These elements are relatively harmless when taken separately, but can become dangerous when combined with certain others, or have a compound effect. In an occupational health environment, the concept translates into the set of individual—often intangible—factors, such as experience, age, gender, social status, etc., that alter the safety risk between two situations that present same hazard and exposure characteristics. Vulnerability thus enhances the risk equation as follows: **RISK = HAZARD X EXPOSURE X VULNERABILITY**.

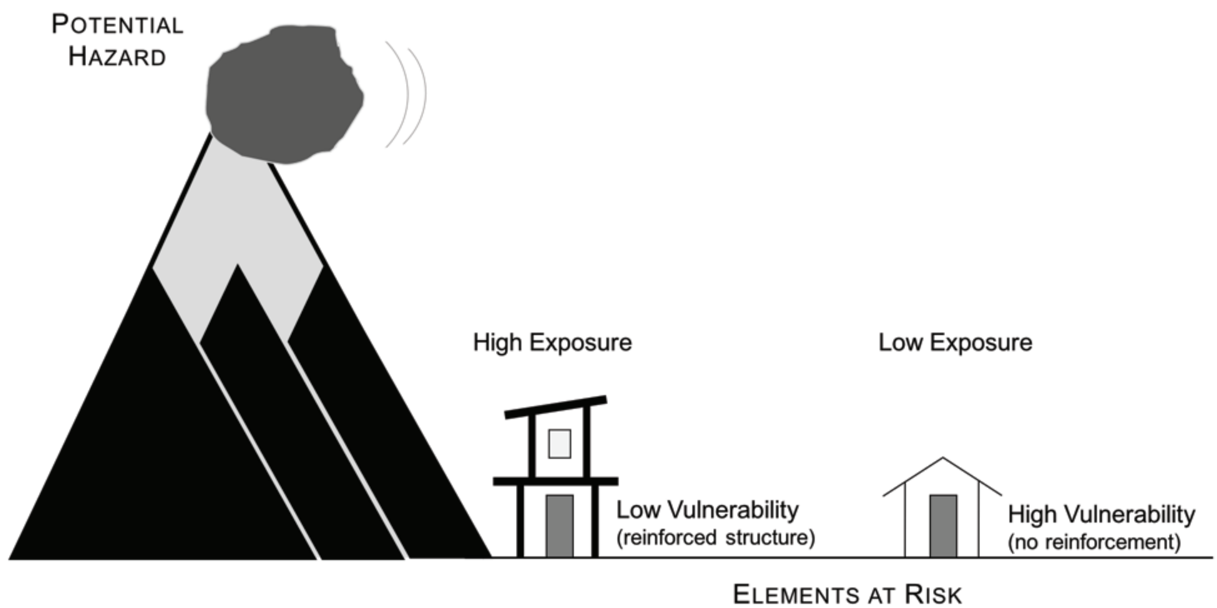

Figure 26. Defining Hazard, Vulnerability, and Risk. Adapted from Waidyanatha, 2015. Source: workshop presentation "Overview of Emergency Communication Practices, Methods and Expected Outcomes". Retrieved from: https://www.slideshare.net/waidyanatha/overview-em-commnuwandayone.

Because we will deal with four case scenarios, which have less definition and more uncertainty than a real-life case study, we will here use the concept of 'vulnerability' to assist in the characterization of risk. It will help us imagine those variables that can cause risk to increase or decrease significantly (in impact or likelihood) in a given situation, beyond the pre-established aspects of exposure. In this thought process, 'vulnerability' allows to account for an added layer of uncertainty (Figure 27).

The Job Hazard and Risk analysis will not make recommendations for safe job procedures, which is typically the follow-up step to hazard identification and assessment, and the third component of a JHA. Because the investigation is intended as groundwork for ad-hoc risk management strategies, a hazard control action plan would be beyond its scope. It will nevertheless borrow the JHA model to complete the first three stages: Anticipation, Recognition, and Evaluation, using the JHA outline provided by OSHA (2002) to guide the task description followed by hazard identification and description, (steps (1) and (2) in Table 11). Then, it will combine the IH concept of Risk Characterization with considerations on Vulnerability, and map out the outcomes (step (3) in Table 11).

Table 11. Job Hazard and Risk Analysis Process.

JOB HAZARD AND RISK ANALYSIS		Phase	Model
Hazard	Review, identify and describe the applicable hazard and its innate harmful effect.	Anticipation + Recognition	JHA
Exposure	Evaluate the patterns of human exposure to the hazard.	Evaluation	JHA
Risk	Vulnerability assessment.	Characterization	IH
	Estimate the incidence of adverse effects under various conditions of exposure. Map out risk distribution.		

Figure 27. The relationships between hazard, exposure, vulnerability and risk. Adapted from: Components of Health Risk. Source: BMP Public Health. Retrieved from: http://www.oilandgasbmps.org/resources/public_health.php.

5.3 Concrete Wall Panels: A Differential Analysis

The prefabricated typology of choice is an exterior concrete wall system, which will be handled as a job—that is, a process—divided in three location-specific stages: off-site production, transit, on-site assembly. Each of these segments entails a series of sequential activities, categorized as job tasks; some entail single repetitive actions (such as tying rebar), others a group of sub-tasks, for example, the making of a window or wood cutout form. For fabrication, the process begins with prepping the production area and ends with loading the wall system (or their components, for the traditional counterpart) for transport. The transportation phase has a single task entry, which corresponds to the movement of goods from the manufacturing site to the point of assembly, at the project site. Lastly, installation starts with unloading and ends with the elements that complete the erection or placement of the wall in its final configuration.

5.3.1 Job Task Analysis

The list of tasks was developed based on construction assembly information, in combination with professional anecdotal knowledge of practice, and after reviewing multiple videos of each phase of the concrete wall process and comparing a variety of real work conditions. The four process types were chosen and defined with the help of footage showing different factory interiors and production lines in action. It remains unknown how common each of the described settings is in the US, that is, how many highly automated precast wall manufacturing plants are operating, using tilting tables, and applying all lining, insulation, and even architectural finishes off-site (e.g. stone or brick cladding). Likewise, it's not known how many plants meet the description of the least automated production shops, and how many of these are indoor vs. outdoor plants. Lastly, this study was not able to make conjectures on the average production setup and quality standard for CMU blocks, or any raw materials to be used for casting on the construction site, even though they have been around a much longer time.

While abundant, the publicly available video documentation may not be the most representative sample of current practices, although it was partly corroborated by the literature and informal industry accounts. In this investigation, the aim is to identify and assemble realistic situations that capture an array of projects types, budgets, and industry practices, that is, subsets of case-scenarios within the broader spectrum of practices (Figure 28). For example, the highly-automated precast process does not describe a unique factory and project site, but a group of settings with some variance in equipment, workflow organization, and spatial configuration that can be classified as 'highly automated'. There is no need to establish exact boundaries for such set, because the closest alternative exemplifies a manufacturing plants that operate at the opposite end of the range.

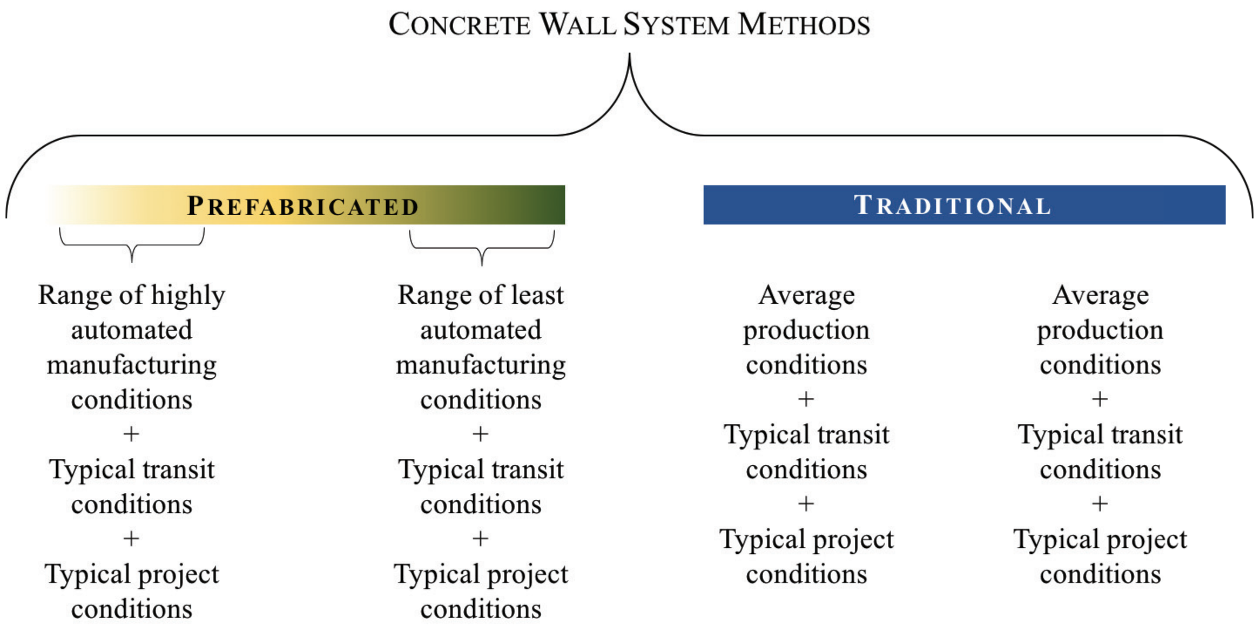

Figure 28. Ranges of practices captured under each job context.

Another point to note is that each process has varying capacity when it comes to the size of the elements (some methods may be utilizable only up to certain wall size), yield, turnaround time, but they will not be discussed in this context, as it would call for a digression on matters of productivity, efficiency, and categories of application. Therefore, it is assumed that the exterior wall in question is of similar nominal dimensions in each process example.

Table 12 summarizes and presents a side-by-side task description; this is not so much to suggest a one-on-one equivalence, but to juxtapose any disparities in a purely documentary way. To this end, similar tasks have been marked with orange font color, and even though the description is the same, they are nevertheless different by virtue the environment that hosts them, since the work setting is what determines the conditions of execution of a same task.

Table 12. Job task analysis of a concrete exterior wall system, by phase and process type.

EXTERIOR CONCRETE WALLS		CONSTRUCTION METHOD			
		PREFABRICATED		TRADITIONAL	
		Precast concrete wall		Cast on-site concrete walls	Concrete Masonry Units
	JOB TASKS	**Most automated** (indoor, tilting table)	**Least automated** (indoor or outdoor)	**Tilt-up cast on-site***	**CMU**
JOB PROCESS – OFF-SITE PRODUCTION	Preparation of working surface	manual spraying of release agent (w/ tilted table)	manually sprayed on horizontal ground-level surface	n/a	n/a
	Positioning of separators	manual rigging, elements lifted and moved with overhead factory cranes	manually lifted, moved, and placed	n/a	n/a
	Placement of conduit (if applicable)	application points mechanically plotted, manual placement at waist level	manual measuring and placement at floor level	n/a	n/a
	Preparation of reinforcements	mechanically laid out and assembled	laid out and tied by hand on ground	n/a	n/a
	Placement of reinforcement	mechanically hoisted, manual assistance to adjust positioning	manual lay-out of single rebar elements (floor level)	n/a	n/a
	Tying reinforcement bars, chair placement	automated tying, or manual, at waist level	manual, at floor level	n/a	n/a
	Verification/measuring/adjusting process	manual	manual	n/a	n/a
	Window/door cut-out form preparation	manual (miter saw, shot-gun), at waist level, in wood workshop	manual (miter saw, shot-gun), at floor level	n/a	n/a
	Placement of window/door cut-out forms	manually, stepping onto the pre-laid reinforcement; use of tools and/or fasteners might be needed	manually, stepping onto the pre-laid reinforcement; use of tools and/or fasteners might be needed	n/a	n/a
	Placement of pins for attaching	manual, at waist level	manual, at floor level	n/a	n/a
	Placing of insulation (if applicable)	manual placing of small elements of soft batting	placed (variable size), screwed (tools) and glued	n/a	n/a
	Concrete mixing	mechanical, remotely controlled loading and mixing	concrete manually loaded in mixer barrel	n/a	mechanical, remotely controlled loading and mixing
	Concrete pour	via overhead moving crane, mechanically operated	delivered on a concrete-mix truck, pumped from mixing barrel	n/a	mechanical, remotely controlled
	Spreading and compacting	table vibration, mechanical spreader	manual raking, manually applied vibration (hand-held hoses)	n/a	mechanical, remotely controlled
	Screeding / leveling	mechanical truss screed	manual	n/a	mechanical, remotely controlled
	Floating	remotely controlled power float	manually controlled power-float	n/a	n/a
	Inclusion of elements for assembly	manual, at waist level	manual, at floor level, or added after the concrete cures	n/a	n/a
	Covering/uncovering concrete for curing	tarp mechanically rolled over, insulation pads placed/removed by hand	tarp and pads placed over/removed manually	n/a	n/a
	Separators removal	manual release, mechanical hoisting	manual release, manual or mechanical removal	n/a	n/a
	Lifting from casting bed	automated tilting table, and mechanical hoisting; work on ladder (< 5ft)	mechanical hoisting	n/a	remotely operated forklift transfer
	Transfer to storage area	mechanical hoisting, supervised by employees	mechanical hoisting, supervised by employees	n/a	remotely operated mechanical lifting/stacking on ribbon
	Cleaning / housekeeping	manual	manual	n/a	manual
	Regular intensive equipment cleaning	hand-operated rotary cleaner, work at waist height.	n/a	n/a	n/a
	Mass production of single elements	n/a	n/a	automated	automated and remotely controlled
	Loading	manual rigging, bridge crane rolling over truck (manually assisted)	manual rigging, mechanical hoisting (manually assisted)	manual rigging, mechanical hoisting (manually assisted)	forklift or machine hoisting
		Precast concrete walls	**Precast concrete walls**	**Materials needed for concrete wall**	**CMU blocks**
TRANSIT	Ground transportation**	truck driving (variable distances): single oversized load	truck driving (variable distances): single oversized load	truck driving (variable distance): multiple regular loads	truck driving (variable distance): multiple regular loads
		Precast wall installation	**Precast wall installation**	**Wall assembly and and tilt-up**	**CMU wall assembly**
ON-SITE OPERATIONS	Preparation	delivery and setup of craning equipment	deliver and setup craning equipment	**all operations listed under the "least automated" off-site production process**	clear area for unloading; take in delivery of raw materials
	Unloading	Crane and manually assisted; traffic flagging required	Crane and manually assisted; traffic flagging required	Depending on size: crane, forklift, manual	forklift
	Lift	crane, manually assisted rigging	crane, manually assisted rigging	mechanical and manual wedging and jacking; crane lifted, manually rigged	n/a
	Moving, lowering	manual, assisted with pry bars (shims inserted by hand)	manual, assisted with pry bars (shims inserted by hand)	manual, assisted with pry bars (shims inserted by hand)	forklift for blocks, manual or crane for rebar
	Placement	manually assisted with pry bar and level	manually assisted with pry bar and level	manually assisted with pry bar and level	manual work at heights
	Bracing	retaining/push pull props manually secured to wall and ground	retaining/push pull props manually secured to wall and ground	retaining/push pull props manually secured to wall and ground	bracing elements manually secured to wall and ground
	Connections	manual, tool assisted	manual, tool assisted	manual, tool assisted	manual, tool assisted
	Chain releasing	manual work at heights	manual work at heights	manual work at heights	n/a
	Inclusion of additional components (rebar, concrete, insulation)	manual work at heights with tools	manual work at heights with tools	manual work at heights with tools	manual work at heights with tools

* Cast-in place not included, as mainly used in housing projects
**Air/rail/sea variants not investigated in this scenario
Orange text: indicates similarity of execution (referred to single task/row)

What emerges at a first glance is that factory conditions vary tremendously across methods, as suspected, with greater workflow control achievable through mechanized and remotely controlled operations. There is a progressive alignment as the process moves to the subsequent phase. All methods are rather dissimilar in the facility setting, but as we move to transportation, two (the prefabricated ones) become analogous. Finally, all but the cinder block wall set-up follow the same erection procedure past the preparatory phase, which for the tilt-up cast in place means moving all the production on the job site.

In looking at how industry practices converge around a specific technology, breaking down the processes of four different ways to build a concrete wall allows to unpack many aspects of generally assumed procedures that project stakeholders may not be aware of. For example, we have seen how designers have different levels of understanding of and involvement in construction operations (depending on their role and on the project delivery method), and generally not much of the supply chain and manufacturing of materials and elements.

GCs may, similarly, not be all too familiar with manufacturing settings, nor think it would be relevant for them to be. After researching a variety of businesses involved in prefabrication, their products, and service offerings, it’s been found that a number of smaller prefabricated manufacturers whose background is in construction (some provide transportation and installation services as well). This tends to heavily characterize their production setup, something that was already noted by McKay, Gibb et al. (2011). Those coming from a purely industrial background utilize sophisticated manufacturing systems, and plan for seamless workflow, though they may, in turn, be removed from the challenges of on-site assembly. Such nuances are difficult to carry over, and encapsulate concisely in the hazard recognition phase.

5.3.2 Job Hazard Analysis

To guide the identification and description of health and safety hazards two main methods were used: video observations, and OSHA reference materials (eTools, Worker Safety Series Publications) for concrete manufacturing, construction, and transportation. Table 13 shows the dangers associated with the concrete wall process, under the given conditions.

Table 13. Hazard analysis, by phase and process type of a concrete exterior wall system.

EXTERIOR CONCRETE WALLS		CONSTRUCTION METHOD											
		PREFABRICATED						TRADITIONAL					
		Precast concrete wall						Cast on-site concrete walls			Concrete Masonry Units		
JOB PROCESS	JOB TASKS	High automation	I	L	Low automation	I	L	Tilt-up cast on-site*	I	L	CMU	I	L
OFF-SITE PRODUCTION	Preparation of working surface	chemical; VOCs (Volatile Organic Compounds); flammability	2	2	chemical: VOCs (Volatile Organic Compounds); flammability; ergonomic (repeated bent posture)	4	3	n/a			n/a		
	Positioning of separators	struck by	4	2	trip; hit-by; WMSDs (Work-related Musculoskeletal Disorders)	4	4	n/a			n/a		
	Placement of conduit (if applicable)	WMSD (upper limbs)	1	2	WMSDs (whole body); chemical	2	3	n/a			n/a		
	Preparation of reinforcements	n/a	0	0	WMSDs (whole body); laceration; pinching	4	3	n/a			n/a		
	Placement of reinforcement	struck-by	3	2	struck-by; caught in; trips; slips; pinching	4	3	n/a			n/a		
	Tying reinforcement bars, chair placement	WMSDs (upper limbs); pinching	2	2	overexertion; WMSDs (whole body)	3	2	n/a			n/a		
	Verification/measuring/adjusting process	WMSDs (upper limbs)	1	3	awkward postures; trips; slips; pinching	2	3	n/a			n/a		
	Window/door cut-out form preparation	cuts; amputation; laceration; noise; eye and skin irritation	3	2	cuts; amputation; laceration; noise; eye and skin irritation	4	3	n/a			n/a		
	Placement of window/door cut-out forms	WMSDs; caught in; trips	3	2	WMSDs; caught in; trips	3	3	n/a			n/a		
	Placement of pins for attaching	pinching; WMSDs (upper limbs)	1	3	WMSDs (whole body); trips; pinching	2	4	n/a			n/a		
	Placing of insulation (if applicable)	WMSDs (upper limbs)	1	3	overexertion; WMSDs (whole body); trips	2	4	n/a			n/a		
	Concrete mixing	inhalation of respirable crystalline silica; noise	2	2	inhalation of respirable crystalline silica; overexertion; WMSDs (whole body); slips trips; chemical burns from wet concrete	5	4	n/a			inhalation of respirable crystalline silica; noise	2	1
	Concrete pour	inhalation of respirable crystalline silica; chemical burns from wet concrete; noise	2	3	overexertion; WMSDs (whole body); slips; trips; chemical burns from wet concrete	5	4	n/a			inhalation of respirable crystalline silica; chemical burns from wet concrete; noise	2	1
	Spreading and compacting	caught in; chemical burns from wet concrete	3	3	WMSDs (whole body); vibration; overexertion; slips; trips; chemical burns from wet concrete	5	4	n/a			n/a		
	Screeding / leveling	caught in; chemical burns from wet concrete	3	3	overexertion; WMSDs (whole body); slips; trips; chemical burns from wet concrete	5	4	n/a			n/a		
	Floating	n/a			ergonomic; whole body vibration; inadequate lockout/tagout systems on machinery; noise	5	4	n/a			n/a		
	Inclusion of elements for assembly	chemical burns from wet concrete; upper body ergonomics (upper extremities)	1	2	overexertion; WMSDs; slips trips; chemical burns from wet concrete	4	3	n/a			n/a		
	Covering/uncovering concrete for curing	WMSDs	1	3	WMSDs; slips; trips	4	4	n/a			n/a		
	Separators removal	WMSDs; struck by	3	3	WMSDs; overexertion; struck-by	4	3	n/a			n/a		
	Lifting	fall; pinching	2	1	struck-by; tip-over; crushed-by	4	3	n/a			noise; any accident caused by machinery malfunction	2	2
	Transfer to storage area	struck-by; crushed-by; caught in	5	3	struck-by; crushed-by; caught in	5	3	n/a			struck-by; crushed-by; caught in	3	2
	Cleaning / housekeeping	WMSDs; VOCs	2	1	WMSDs; VOCs; slips, trips	2	3	n/a			WMSDs; noise; VOCs	2	2
	Machinery maintenance	WMSDs; inadequate lockout/tagout systems; caught-in; crushed-by	3	3	n/a			n/a			WMSDs; inadequate lockout/tagout systems; caught-in; crushed-by	3	3
	Mass manufacturing of raw materials	n/a			n/a			variable: comparable to CMU production	v	v	noise		
	Loading and rigging	caught -in; struck-by; crushed-by; struck-by; pinching	5	2	caught -in; struck-by; crushed-by; struck-by; pinching	5	2	crushed against; crushed-by; struck-by; overexertion; WMSDs	3	3	crushed against; crushed-by; struck-by; overexertion; WMSDs	3	3
			2.5	2.5		3.7	3.4		2.2	1.8		2.2	1.6
		Precast concrete walls	I	L	Precast concrete walls	I	L	Materials needed for concrete wall	I	L	CMU blocks	I	L
TRANSIT	Ground transportation**	accidents resulting from wide and/or heavy loads being transported over narrow or uneven roadways and bridges; clearance; stopping distance; stability (rollover); flat tires; jackknife crashes; striking overhead power lines; unstable soil at destination	5	3	accidents resulting from wide and/or heavy loads being transported over narrow or uneven roadways and bridges; clearance; stopping distance; stability (rollover); flat tires; jackknife crashes; striking overhead power lines; unstable soil at destination	5	3	accidents caused by uneven load distribution; improper maintenance; unsecure load	4	2.5	accidents caused by uneven load distribution; improper maintenance; unsecure load	4	2.5
			5.0	3.0		5.0	3.0		4.0	2.5		4.0	2.5
		Ready-made wall installation	I	L	Ready-made wall installation	I	L	Wall assembly and tilt-up	I	L	CMU wall assembly	I	L
ON-SITE OPERATIONS	Preparation	tip over; struck-by; crushed against; an hazards from delivering and installing a crane	4	2	tip over; struck-by; crushed against; an hazards from delivering and installing a crane	4	2	all hazards listed under the "least automated" off-site production process + those added by difficult weather and site conditions **[score added separately to the average calc.]**	5	5	slip; trip; tip-over; struck-by	5	3
	Unloading	fall; tipping of equipment; struck-by; crushed by; injury to pedestrians in proximity	5	3	fall; tipping of equipment; struck-by; crushed by; injury to pedestrians in proximity	5	3	n/a			fall; tipping of equipment; struck-by; crushed by; injury to pedestrians in proximity	5	2
	Lift	any hazards from operating a crane or other heavy equipment; struck-by; tip-over; crushed against	5	4	any hazards from operating a crane or other heavy equipment; struck-by; tip-over; crushed against	5	4	any hazards from operating a crane or other heavy equipment; struck-by; tip-over; crushed against	5	4	n/a		
	Moving, lowering	any hazards from operating a crane or other heavy equipment; struck-by; tip-over; crushed against	5	4	any hazards from operating a crane or other heavy equipment; struck-by; tip-over; crushed against	5	4	any hazards from operating a crane or other heavy equipment; struck-by; tip-over; crushed against	5	4	equipment tip-over; overexertion; awkward postures; slip; trip	3	3
	Placement	caught-in; struck-by; crushed against	5	2	caught-in; struck-by; crushed against	5	2	caught-in; struck-by; crushed against	5	2	fall; repetitive movements; awkward postures; heat-related accident	5	5
	Retaining/push pull props	fall; caught-in; struck-by; crushed against; lacerations	5	2	fall; caught-in; struck-by; crushed against; lacerations	5	2	fall; caught-in; struck-by; crushed against; lacerations	5	2	fall; caught-in; struck-by; crushed against; lacerations	5	3
	Adjusting and locking	WMSDs; overexertion; noise; dust; struck-by; crushed against	5	2	WMSDs; overexertion; noise; dust; struck-by; crushed against	5	2	WMSDs; overexertion; noise; dust; struck-by; crushed against	5	2	WMSDs; overexertion; noise; dust; struck-by; crushed against	5	4
	Chain releasing	fall; pinching	4	2	fall; pinching	4	2	fall; pinching	4	2	n/a		
	Inclusion of additional components (rebar, concrete, insulation)	n/a			n/a			fall; inhalation of toxic dusts; WMSDs; any hazards coming from the use of power tools	4	3	fall; inhalation of toxic dusts; WMSDs; any hazards coming from the use of power tools	5	4
			4.8	2.6		4.8	2.6		4.9	3.9		4.7	3.4

I: impact of hazard
L: likelihood = exposure x vulnerability
Orange text: indicates same hazard type (referred to single task/row), does *not* imply same level of exposure

In looking at the breakdown of the hazards by stage, it can be noticed that:

1) Production: hazard and exposure levels change in relation to level of 'industrialization' of the plant. This holds true across all four jobs, and is particularly evident between the two under the traditional method. The same can be assumed between the CMU plant conditions and structural steel and concrete-mix goods, though demonstrating this would require an additional layer of alternatives, depending on the project's procurement approach of raw materials for cast-in place walls. The CMU wall process is also limited to the main concrete component, and does not look at the manufacturing process of structural steel, or mixed concrete, though the latter have been in use long enough to assume an alignment of standards. Besides, the production of elements such as rebar is a prerequisite common to all four processes.

Figure 29. Left: Automated CMU production line. Source: Pyatos. Retrieved from: https://www.poyatos.com/?attachment_id=3715.

Right: Non-automated precast concrete manufacturing. Source: Precast Concrete Manufacturing. Retrieved from: http://precastconcretemanufacturing.blogspot.com/2013/06/precast-concrete-manufacturing-process.html.

Figure 30. Highly controlled fabrication of precast wall panels. Source: Tekla. Retrieved from: https://www.tekla.com/solutions/precast-fabricators/fabrication.

2) Transit: transportation of oversized loads is expected to present a number of hazards in addition to the ones that come with regular truck deliveries. Classes of incidents include collisions, overturning, and jackknifing, but ‘location’ and ‘duration’ are unpredictable and more variable on the road than on construction sites. There is currently no uniformity in the approaches to quantify transportation risk, as there is an elevated number of uncontrollable environmental factors. It is nonetheless known that “workers in the trucking industry experienced the most fatalities of all occupations, accounting for 12 percent of all worker deaths”[20] (OSHA), and that trucks hauling oversize loads have a higher likelihood of being in a crash than regular trucks. Distance is also a factor that cannot be assessed here, but obviously weighs tremendously in the risk equation. Transportation is a topic worth expanding to include other means, since many pre-manufactured products are being imported or moved over long distances, which also raises the question on life-cycle sustainability.

[20] Retrieved from: https://www.osha.gov/SLTC/trucking_industry/hazards.html.

Figure 31. Top: A precast exterior wall system being loaded on the flatbed platform of a semi-tractor trailer truck. Source: PCI Northeast. Retrieved from: http://www.pcine.org/images/imageGallery/255/image23_c_550_385_95.jpg.

Bottom: CMU blocks loaded on an open-back truck. Source: W&J Chambers Concrete Products. Retrieved from: http://www.wjchambers.com/images/sce/concrete-blocks-top.jpg.

3) Assembly: While precast walls are said to save time (though not sufficiently proven, or quantified), their assembly include, in many tasks, the Fatal Four. What is not factorable in the simple side-by-side description is the number of workers exposed or involved in the operations, which may influence vulnerability. These aspects play a role when thinking in terms of risk.

Figure 32. Precast wall panel being hoisted in place. Source: National Precast Concrete Association (NPCA). Retrieved from: http://precast.org/wp-content/uploads/2014/08/Precast-Concrete-Wall-Panel-Install.jpg.

5.3.3 Risk Characterization

Quantitative risk assessment requires the calculation of two components of risk: impact, or magnitude of the potential loss (I), and the likelihood (L), or probability that the loss will occur, which considers 'exposure' and 'vulnerability' in each job context. While expressed quantitatively, the estimation of risk undergoes subjective variation, which can be in part knowledge/experience based, and perception based. As an example, the transit stage is a single activity, and the score for precast walls reflects the idea that transporting oversized loads increases the chances of road crashes by a significant factor respect to regular loads. Additionally—and with the exception of the preparatory phase of tilt-up walls[21]—it depends on the number of tasks that compose them, as they are unweighted.

Because the score depends on variables that are very situational, and the processes described are representative of a range, there is an additional degree of uncertainty on the evaluation. For example, within highly automated processes there is still a variety of configurations that can change the way employees complete a task; the same can be said of construction sites, as each is unique for location and organization. *For this reason, the proposed risk evaluation should be read as an exercise to characterize the distribution of risk across job phases for each method, rather than a tool for risk management, as it cannot address the organization-specific aspects of each process and phase.*

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[21] For tilt-up panels, the single "Preparation" line item condenses all the tasks listed under the production phase, which are similar to the least automated of the prefabricated production, but conducted on-site. The "preparation" score was thus averaged with the average resulting from the installation phase.

Table 14 synthesizes the outcomes from Table 13, and shows how patterns of risk are phase-related. It is important to approach this diagram not as a summary of outcomes, but as a conceptual visualization that invites us to reflect in terms of trade-offs, and understand it in progression and as the third of a sequence of interdependent analytical steps. The idea that prefabrication shifts hazards elsewhere is true in principle, but re-location doesn't mean even re-allocation: 'new' (though well-known) hazards replace 'old' ones, and the overall steps to produce the final component don't necessarily decrease, even after said redistribution.

Table 14. Comparative risk assessment chart.

Comparative Risk Assessment Chart

METHOD	EXTERIOR WALL TYPE	IMPACT	LIKELIHOOD	IMPACT	LIKELIHOOD	IMPACT	LIKELIHOOD
		Variability susceptible to manufacturer's safety maturity		Variability dependent on distance, experience, road & traffic conditions		Variability susceptible to safety practices, project complexity and uncertainty	
PREFABRICATED	+ automated precast wall	low to medium	low to medium	high	medium	high	low to medium
		≠		=		=	
	− automated precast wall	medium to high	medium	high	medium	high	low to medium
		≠		≠		≠	
TRADITIONAL	tilt-up cast on-site wall	low to medium	low	medium to high	low to medium	high	medium to high
		=		=		≠	
	concrete masonry unit (cmu) wall	low to medium	low	medium to high	low to medium	medium to high	medium to high

LEGEND

- ≤ 2
- 2.1 - 2.7
- 2.8 - 3.4
- 3.5 - 4.1
- ≥ 4.2

There is a pattern of similarities and differences running diagonally cross the matrix. Being able to examine Impact/Likelihood (I/L) as separate components of risk in a side-by-side analysis allows a better reading of the types of hazard that prevail in each method and phase, before risk attributes get blended in the matrix (Table 15).

Manufacturing environments offer opportunities for safety relative to the safety maturity of the establishment, as the benefits of indoor work (sheltered and static conditions, in contrast with on-site variability and exposure to the elements) are not, on their own, enough to make prefabricated processes a risk-conscious choice, particularly when evaluating the risk borne by each phase of the job. This is clear in the comparison of risk factors between most and least automated prefabrication scenarios.

In factories, risk can be controlled and mitigated if robust prevention programs and a good safety culture are in place. It is generally easier to establish effective safety protocols if the production of wall components, or their assembly, is streamlined, mechanized (less manual work), and remotely operated (puts more distance between the operator and the source of hazard). For this reason, it is not surprising that the prefabricated off-site phase that works under quasi construction-site conditions is subject to high likelihood of hazard occurrence.

The characterization of transit comes from a single, 'blanket' I/L entry, mainly based on the knowledge that transportation remains the sector with the highest fatality rate. Likelihood is considered in absolute terms, and likewise assumed from historical data, because assumptions on frequency with respect to the type and size of shipped goods are not possible. Broader speculations can be made, since construction remains the second sector, after trucking services, with the highest number of work-related deaths from motor vehicles (NIOSH 1998)[22]. However, if we consider the number and dimensions of precast components vs. the volume of raw materials (bricks, concrete bags), can we really say that prefabrication requires less shipments than the conventional method? Even so, it would not be possible to claim that the risk posed by one oversize load balances that of an—unspecified—number of regular of small(er) loads.

Vulnerability plays an important role in modeling the risk intensity and distribution. The jobs describe ranges, meaning that the I/L scores attach a value to a 'typical' setting, or 'industry-average' conditions, which were inferred from sector-specific safety materials and data, and observation of available examples (videos). It is thus a combination of circumstances that is being rated. If this same evaluation procedure was to be repeated using a case study for each of the four jobs, it would not necessarily add much, because findings wouldn't be generalizable. To understand meaningful factors that change the downstream (on-site) and upstream (off-site) safety dynamics of a project, we would need to test the variance by running simulations that reproduce many possible versions of each process. This would allow us to see what and how the pattern of I/L similarities and differences fluctuates or shifts between them, and across phases. Ultimately, workplace conditions and practices determine the safety risk level of a set of tasks, as much as their collocation.

It is relevant to notice that the on-site hazard impact is consistently high for all methods, in apparent contradiction with the general assumption that prefabrication moves some of that risk to the production environment.

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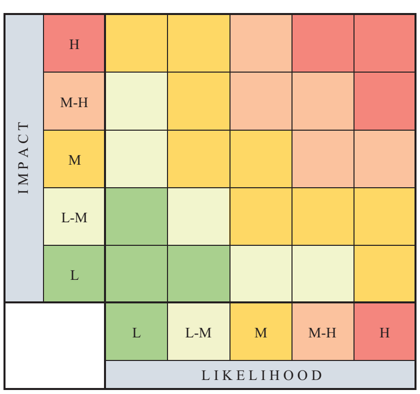
[22] This is a reminder that in the occupational statistics, transportation as a sector absorbs a lot of fatalities indirectly generated by construction activities.

Table 15 merges the I/L attributes. The resulting picture is flattened by the combination, and if we were to conduct a third level of iteration and combine the off-site/transit/on-site values of each method, any differences across wall type processes would be hardly appreciable.

Table 15. Comparative risk chart with combined I/L values.

METHOD	EXTERIOR WALL TYPE	**OFF-SITE** Variability susceptible to manufacturer's safety maturity	**TRANSIT** Variability dependent on distance, experience, road & traffic conditions	**ON-SITE** Variability susceptible to safety practices, project complexity and uncertainty
PREFABRICATED	+ **automated precast wall**	low to medium	medium to high	medium to high
		≠	=	=
	– **automated precast wall**	medium to high	medium to high	medium to high
		≠	≠	=
TRADITIONAL	**tilt-up cast on-site wall**	low	medium	high
		=	=	≠
	concrete masonry unit (CMU) wall	low	medium	medium to high

NOTE: Compares risk magnitude, not risk type



low	≤ 2
low to medium	2.1 - 2.7
medium	2.8 - 3.4
medium to high	3.5 - 4.1
high	≥ 4.2

Chapter 6. CONCLUSIONS

6.1 Summary and Contributions

This study has created a richer context for off-site construction methods, by providing an occupational health and safety framework through a systematic compendium of diverse knowledge on the topic. It contributes to the body of scholarship and posits a comprehensive approach for how we should think and talk about prefabrication, moving forward.

The first contribution stemmed from understanding how definitions and categorization can limit or skew the handling of safety and health concerns around prefabrication. It has further examined how prefabrication is discussed in the industry, in education, and in the scientific community. It sought to show how and when health and safety are brought into the mainstream narrative, as well as answer what is the role of health and safety in current R&D debates.

The synthesis of the professional and scientific literature validated the semantic underpinnings, introduced the main questions on health and safety, and reviewed possible actionable items: process and product design, JHA, risk assessment tools, regulations and guidelines. At the same time, it emphasized the need for more evidence-based data to continue the discourse, as the interest in prefabrication is fueled by market demands. Another outcome of the literature review was the identification of a pattern of concentration at the opposite ends of a topic (whether micro or macro, in scope) in current research. This leaves the middle dimension of the subject yet unexplored.

The gap identified from the literature was then examined and experimented through a hazard and risk analysis applied to a prefabricated system. The exercise reviewed the contribution, hypotheses, and potential fallacies of the relationship of health and safety to prefabrication. It proposed a descriptive, 'life-cycle' (i.e. production to erection) hazard analysis, and a side-by-side characterization of risk. In this exercise, we have looked deeper into exposures and vulnerability factors, shown the benefits of handling prefabrication as a set of processes/typologies, and zoomed in closely enough to scrutinize single job-tasks without losing connection with either the general dimension of the problem or a neutral perspective that respects trade-offs between safety and competing drivers.

We have learned that a single-task approach is limiting: prevention in the context of prefabrication is a complex formula that cannot be derived from a mathematical addition of hazards. Additionally, an overly microscopic perspective blurs out important processes and elements, such as logistics and sequencing, which are an essential part of the equation.

6.2 Limitations

The analyses rely on indirect evidence. The literature (by nature), the work environment observations, and the accident reports are indirect sources of quantitative and qualitative data, which carry influences that cannot be controlled for. At the same time, they limit the opportunities for original discovery that arise from conducting field research.

Each category of source has, in turn, its own limitations, which have been addressed separately in the relevant chapters.

6.3 Next Steps

The goal of this study was not to fruitlessly argue in favor or against prefabrication, but rather to provide a more comprehensive picture of the landscape to build on moving forward. Once there is awareness coupled with a solid basis of knowledge, the next step is to further the research effort and develop best practices to plan for and mitigate hazards. This multi-pronged approach should reach out to various areas of stake-holding and involve different professions and competencies.

There are many opportunities to advance the knowledge in health and safety topics around off-site construction. The list below presents some actionable items that can guide future efforts.

- Collect new data on the state of the art of off-site and on-site work environments that use prefabrication.
- Collect new, targeted, industry data on the effects of prefabrication on on-site health and safety.
- Conduct field research to gain insight on domestic manufacturing standards in the production of prefabricated components.
- International benchmarking: analyze highly efficient models of production and building protocols.
- Design risk assessment and management strategies.
- Explore the combination effects of prefabrication and collaborative processes and tools (BIM and/or Lean).

- Investigate the 'actionability' of product design improvements in relation with process design development.

- Map out professional actors and networks in the prefabrication process, and look for paths for knowledge exposure/exchange across disciplines.

While not within the scope of this study, prompts to develop appropriate tools have emerged recurrently at various points of the analyses.

- Standardized classification and definition: the built environments would benefit from a common vocabulary and a set of sub-categories (classes of systems) under which to identify sets of prefabricated systems to empower the terminology in use.

- Venues for integration with institutionalized knowledge and professional development. While awareness is the first needed step, the effective path to higher collaboration and initiative is through education.

- Libraries of process-based JHAs.

- Training resources specific to the prefabricated processes.

- Formalized guidelines, regulatory standards[23].

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[23] OSHA is traditionally hazard driven; its regulatory efforts are organized by single sources: fall, asbestos, crane etc., more rarely by operations (e.g. excavation or blasting). Prefabrication would instead benefit from activity driven guidelines, specific enough to recognize typology and sector of application; for example, modular units for housing.

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APPENDIX

VIDEOGRAPHY

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