Leveraging advances in automation to benefit the construction industry in the structural steel sector

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Abstract. The global structural steel market was reported to be valued at $96 Billion in 2018, and according to some projections, it will amount to about $140 Billion by 2025. This means that the structural steel industry is expected to have a Compound Annual Growth Rate (CAGR) of about 5.4% over this six-year period. Consequently, this sector is set to perform better than the construction industry as a whole, which is projected to have a CAGR of 4.2% over approximately the same period. This projection represents good news for the structural steel industry but it also magnifies some of the challenges that the industry has been facing or has faced in the past. For example, the US Bureau of Labor Statistics projects that overall employment of ironworkers will see an 11% growth from 2018 to 2028, which is much faster than the average growth for all occupations. On the other side of the equation, the industry is facing some challenges that may make it difficult for it to meet the projected demand. For example, there is a very well documented shortage in the construction labor force, and this shortage is already causing problems and driving construction costs upward. Moreover, there is an expectation of increased accountability towards the environment while dealing with generally larger and more complex projects. In this paper, the authors propose that increased automation may be the most effective way to solve the labor shortage problem in the steel construction sector. An overview of advancements in related automation technology is first presented, followed by an analysis of the areas of the industry that may benefit from an increased use or the introduction of automation. The authors conclude by presenting a set of recommendations for adding more automation in the production, servicing, fabrication, and erection of structural steel.

1. Introduction

Construction Automation (CA) has been defined and perceived in different ways, based on the context of use or interpretation [1]. Two main streams of thought exist – stemming from the divide between design and construction processes. Whilst automation may be viewed as automated design and planning processes, the context of construction leans more towards the use of robotic elements on site [2,3,4]. Still another context of automation proposed by Chen et al. [1], following a review of relevant literature and text-mining of the concept of construction automation; summarized the definition as the use of recent technologies to improve construction productivity. More recently, the concept of automation in construction has been expanded to integrate the concept of digitization. This stemmed from the Industry 4.0 concept developed by Oesterreich & Totenberg [5], where information modeling was linked with manufacturing concepts, and it is being applied in construction today. Terms such as “digital fabrication”, “digitization”, “3D printing”, “simulation”, “virtual/augmented reality” and “visualization” [1,6,7] are indicative of the fluid integration between computer based modeling and...
robotic technologies for construction manufacturing, fabrication, assembly and maintenance. Vaha et al. [7] take it further to introduce the concept of control systems and information technologies to apply industrial automation principles to construction.

Despite the potential of automation to improve construction industry site safety, productivity and production, Oesterreich & Totenberg [5] noted that the uptake of new technologies is still slow. Following a qualitative and quantitative content analysis of 268 articles from 10 countries on the subject, they identified a disconnect between research and practical implementation. Numerous technologies were identified, such as Building Information Modeling (BIM), Simulation and Modeling, The Internet of Things (IoT), Radio-Frequency Identification (RFID), Big Data, 3D-Printing/Additive Manufacturing, Smart Factory, Human-Computer-Interaction (HCI), Modularization, Cyber-Physical/Embedded Systems etc. A comparison of literature between conceptual scientific papers and case study applications showed a marked difference in volume, as only a small number of case studies were recorded. They identified the fact that the construction industry lags far behind other industries in digitization and automation.

However, following a renewed surge in digital and technological capabilities, numerous authors maintain optimism that the construction industry can still adopt and benefit greatly from automation. Castro-Lacouture’s [8] survey of respondents from 24 countries identified benefits such as safety, enhanced working conditions, increased productivity, quality and reliability, savings in labor and lifecycle costs and standardization of components from the responses given. Bock [3] argued that the increasing potential of robots to work in unstructured environments and increasingly diverse fields, bodes well for construction. His study also noted that microsystem technologies, Single Task Construction Robots (STCR), IoT and smart home technologies have already become a part of construction and building technologies. His paper highlighted the concept of “technology disruption” and the potential of robotics in the construction process and in buildings. Whilst noting that CA is “capital intensive and machine-centered”, the benefits appear to far outweigh its cost or initial limitations. Bock [3] analyzed the potentials and application of robotics in different contexts:

- Robot-Oriented Design (ROD) – design and management tools for the deployment of automation and robotics in construction
- Robotic Industrialization – automation and robotic technologies for customized prefabrication of “low-level” components such as steel, wood and concrete; differentiated from “high-level” building components such as larger modules e.g. prefabricated composite units.
- Construction robots – Single-Task Construction Robots (STCRs) and elementary technologies (simple systems that can perform single construction tasks in a repetitive manner).
- Site Automation – automated/robotic on-site factories (controlled, factory-like environments on the construction site).
- Ambient Robotics – technologies for maintenance, assistance and service such as merging robotic technologies with building components and furniture to produce “ambient intelligence” through the use of medical sensors for assisted living. Examples such as the Patient Transfer Assist and Care-O-Bot are in use.

A recent survey conducted by Cai et al. [9] analyzed the opinions of construction industry experts across numerous fields including academia, general contracting, earth and foundation works, steel structure works, mechanical, electrical, electronic, waterproof and thermal insulation, formwork and scaffold subcontracting etc. Their study combined the results of surveys with focus group sessions on two main themes comprising the developmental needs and influential factors of automation in high-rise construction. The top ten issues under each theme from the surveys were analyzed, with interesting results. The top ten developmental priorities resulted in higher proportions for the superstructure and safety issues, as opposed to other categories such as earthwork, finishes and material quality inspections. Their ranking of issues in order of priority are summarized in Table 1:
### Table 1. Ranking of issues in order of priority for the automation of high-rise construction.

| Rank | Developmental Priorities                                      |
|------|---------------------------------------------------------------|
| 1    | Steel welding                                                |
| 2    | Monitoring of the deformation and internal force of the steel structure |
| 3    | Steel coating                                                |
| 4    | Safety control of work performed at high elevations          |
| 5    | Vertical site logistics of materials and equipment            |
| 6    | Prefabricated component assembly                              |
| 7    | Construction quality inspection                               |
| 8    | Safety control of construction equipment                      |
| 9    | Steel assembly                                                |
| 10   | External wall painting                                        |

The results of the rankings on influencing factors are shown in Table 2, and these prioritized the level of technological development, uncertainty and support as the factors with the highest influence on deployment and success.

### Table 2. Ranking of influencing factors on automation of high-rise construction.

| Rank | Influencing Factors                                                                 |
|------|------------------------------------------------------------------------------------|
| 1    | Initial investment cost of automation and robotics technologies                     |
| 2    | Maturity and proven technology for robust performance and ease of use               |
| 3    | Application of other information technologies (e.g. BIM, IoT etc.)                  |
| 4    | Uncertainty of the economic benefits of automation and robotics                    |
| 5    | The ability of on-site management                                                  |
| 6    | Governmental support for application                                               |
| 7    | Governmental support for academic research                                         |
| 8    | Social attention to occupational health and safety                                  |
| 9    | Age structure and education of the workforce                                       |
| 10   | Labor cost of construction                                                         |

Results from the focus group sessions, which were attended by seven university professors, two senior engineers and two software company specialists from three countries echoed many of the prioritized areas from the survey. The top three influencing factors included the immaturity of technology, uncertainty of economic benefit and the incompatibility of existing construction patterns and robot applications. Thus, the highest development priorities were noted by this group to be prefabricated component assembly, safety control of work performed at high elevations of construction equipment, and steel works. In summary, steel works, vertical site logistics, and safety needs ranked highly amongst the development priorities of the study.

Though numerous authors have studied CA in the overall context of construction, there is a dearth of studies that focus on the potential of CA in the steel industry. This study aims to analyze developments and upcoming potential in the application of CA to steel production, fabrication, and assembly.

### 2. Automation in the steel production industry

The steel industry has come a long way in terms of automation since improved processes for mass producing steel were developed in the mid 1800’s. The steel making industry was very dynamic and saw significant improvements in processes and production over short periods of time towards the end of the 19th century and beginning of the 20th century with production capacity at least doubling every few years [10] with better product quality and lower prices. As an example, Spoerl [11] compared the production of steel between 1867 and 1884. He stated that in 1867, 460,000 tons of wrought iron rails...
were made and sold for $83 per ton, while 2,550 tons of Bessemer steel rails were made and sold for $170 per ton. By 1884, iron rails were basically no longer available and rail steel was being produced at an annual rate of 1.5 million tons and selling for $32 per ton. But however impressive the progress of that era was, it is dwarfed by today’s capabilities, which utilize fully automated computerized processes to produce more than 1.8 billion tons of steel (2018) [12] at a cost of about US$ 750 (4,830 CNY) per ton, or the equivalent of roughly $23.50 per ton in 1900 US dollars. Automation and other improvements in the making of structural steel did not only affect the rate and cost of production of the material, it also made it possible to produce many different grades of structural steel of a superior quality while improving the safety aspect of steel production and the effect on the environment.

3. Automation in the structural steel fabrication industry
The fabrication of structural steel components comprises a number of laborious tasks that include cutting, drilling, bending, coping, and welding of structural steel components to prepare them for erection. The success of the fabrication process is highly dependent on the detailing phase that precedes it. Steel detailers perform extensive geometric calculations and produce accurate drawings of steel components to allow fabricators to prepare these components for straightforward erection and assembly in the field. In the not so distant past, i.e. prior to the 1970’s, all the tasks associated with the fabrication of structural steel components, such as layout, cutting, bending, drilling, and hole punching were performed manually. In contrast, nearly every structural steel fabrication process can be automated today. Morrall [13] provides a good summary of the evolution of structural steel fabrication technology, starting with the introduction of beam punch lines in the 1970’s.

The 1980’s and 1990’s saw additional advancements in automation. First, there was automated drilling, coping, and weld preparation, and then it became possible to create details in 3D CAD systems and download the data directly into machines that were able to cut members to length and mark the locations of holes and attached parts. Before too long, automated systems, referred to as MSI for multisystem integration, were developed to handle and move steel pieces through different setups to perform numerous automated tasks including cutting to length, drilling holes, coping, and even welding connected parts, all with limited human intervention. Introducing automation to the fabrication of structural steel components benefited the industry on many fronts including workers safety, productivity, accuracy and quality of final products, economy, and effect on the environment. The structural steel fabrication shop of the future will see even more integration of emerging technology, such as AI, robotics, and additive manufacturing.

4. Automation in the erection of structural steel
On the construction site, steel erection is not only a big-ticket item in terms of price and logistics, it is also a heavy determinant of the schedule – stemming from its criticality to the superstructure. Liang and Kang [14] identified steel beam assembly as heavily reliant on manual labor, and a main part of the critical path. Steel beam erection has been especially identified as labor-intensive and challenging in terms of safety of workers [2, 14]. Several studies have been conducted with the aim of improving the automation levels of steel erection. Cai et al. [15] categorized superstructure erection systems into three groups: automated construction systems, automated lifting systems and robot-based steel assembly.

Automated Building Construction Systems (ABCS) generally stem from the concept of the Super Construction Factory (SCF), introduced by the Obayashi Corporation. This system comprises a steel structure with a roof and surrounding walls that is designed to simulate a factory on the construction site [16]. A climbing mechanism lifts the structure higher from floor to floor and can incorporate crane lifting mechanisms, automated welding and bolting etc. These reduce the dependence on human labor but require strict supervision. The Takenaka Corporation developed the Roof Push up Construction Method, where the top level of a structure is constructed on grade, and then gradually “pushed up” to accommodate each floor as these are assembled [17]. Other systems include the SMART system which is similar to the SCF and the Roof Push up method, as the automated system auto erects, assembles, lifts and joints structural components from floor to floor. Automated steel beam assembly was taken further
by Chu et al. [18] and Jung et al. [2, 19, 20]; a team of Korean researchers that proposed the Robotic Beam Assembly System (RBA system). The RBA attached a robotic bolting device to a control system and robotic transport mechanism. The latter version of this allowed for the operator to manipulate the system remotely from outside of the cabin, via joysticks, multiple screens and other control equipment. Their main aim was to increase safety on the site for workers.

A clear limitation of these systems is the limited versatility, weight and costs, in addition to the complexity of set-up and tear down of the systems themselves [15]. Liang & Kang [14] developed an autonomous joint system for steel hauling and automatic beam assembly, intended to reduce the weight and complexity of the SCF system. Their system attached an aligning mechanism to each beam-column joint prior to hauling the beam, and comprised a magnetic clip to help with alignment prior to bolting with a robotic arm. Kang et al. [21] attempted to decrease the impacts of weight and cost by developing the Robotic Crane-based Automatic Construction System (RCA), where the crane was placed at the core of the building, independent of the CF. Kim et al. [22] also developed a cost/benefit analysis process, in addition to several CF alternatives to evaluate the economic viability of automated systems.

5. Structural steel construction-BIM integration

Building Information Modeling (BIM) has been gaining widespread use in building engineering and construction. The advantages of using BIM technology are numerous and have been vastly studied by researchers in the field. However, investigations related to the use of BIM to enhance means and methods of the construction of steel structures is still in its early stages. For example, while a general search for articles dealing with the ‘use of BIM in structural steel’ on Google Scholar produced more than 21,000 articles in the first week of June 2021, a search at about the same time requiring the title to have the two words ‘BIM’ and ‘steel’ only produced 113 hits, and a search requiring the title to have the two words ‘BIM’ and ‘concrete’ produced 123 hits. In contrast, a search requiring the title of the article to contain the words ‘BIM’ and ‘design’ produced close to 2,000 hits, and a search requiring the title of the article to contain the words ‘BIM’ and ‘construction’ produced close to 3,000 hits. This informal search analysis, provides some insights on where the focus of the use of BIM has been over the last decade. Note that a general search looks for articles that have any of the search terms in them.

Some of the investigations related to the design and construction of steel structures include the use of BIM data to achieve a sustainable steel design by estimating labor cost [23] and the use of BIM-based data mining to estimate job man-hour requirements in structural steel fabrication [24]. However, most investigations dealt with design and sustainability related topics, such as the development of a BIM extension for the sustainability appraisal of conceptual steel design [25], using BIM technology for the design of steel bridges [26], [27], BIM based connection design in steel structures [28], the design of steel box girders [29], and others.

It is clear that there are still many opportunities available to study the use of BIM for structural steel fabrication and erection and other phases of a project. As the needs for automation rise due to the continuous shortage in skilled labor, an integrated framework will need to be established to facilitate the management of structural steel construction projects from conceptual design through construction. This will best be done by expanding BIM technology to include information that will go beyond modeling for design and constructability and allow for the automatic production of construction details, automate material procurement activities, automate the process of transferring data from a BIM model to automatic fabrication machines, automate the task of generating construction sequences, incorporate the ability to control cranes and robots to perform various construction tasks from within a BIM platform, and enhance the safety aspects of a structural steel construction project.

6. Conclusions

The production of structural steel and the fabrication and erection of structural steel components and systems traditionally involved labor-intensive processes with considerable concerns for workers safety and continued well-being. The processes are often carried out in harsh environments and may necessitate the handling of heavy pieces of metal at elevated heights. Furthermore, repetitive actions by
workers are often required for fabrication and erection of structural steel. This can lead to workers fatigue, which leads to elevated risks of injury and error and decreased quality and productivity. Automation has been playing an incrementally important role in the manufacturing sectors for centuries but the accomplishments of the last few decades were especially phenomenal. The outstanding advances in computer and other technologies, such as laser and GPS, allowed for the development of automated processes that produce impressive results in terms of safety, quality, and speed of completion of tasks. As it relates to the steel construction industry, automation has been greatly taken advantage of in the steel production sector and incrementally taken advantage of in the structural steel fabrication sector. However, there are many advantageous technologies that are available but the use of which still needs to be leveraged for enhancing the fabrication and erection of structural steel. The authors propose that future progress in structural steel construction will be heavily dependent on advancements in the collection, dissemination, and use of information related to each project. This will need to be done by advancing the use of Building Information Modeling (BIM) to include information that can be used through the various project phases from design to detailing, procurement, fabrication, and then erection.

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