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Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall

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ABSTRACT

Although automation has been actively and successfully used in different industries since the 1970s, its application to the construction industry is still rare or not fully exploited. In order to help provide the construction industry with an additional incentive to adopt more automation, an investigation was undertaken to assess the effects of digital fabrication (dfab) on productivity by analyzing the cost and time required for the construction of a robotically-fabricated complex concrete wall onsite. After defining the different tasks for the conventional and robotically fabricated concrete wall, data was collected from different sources and used in a simulation to describe the distribution of time and cost for the different construction scenarios. In the example, it was found that productivity is higher when the robotic construction method is used for complex walls, indicating that it is possible to obtain significant economic benefit from the use of additive dfab to construct complex structures. Further research is required to assess the social impacts of using dfab.

1. Introduction

1.1. Productivity problem in the construction sector

The built environment is a sector of high strategic importance for each economy. With annual revenues of nearly 10 trillion USD, or about 6% of global GDP, the engineering and construction industry is a cornerstone of the world's economy [1]. However, studies show that the construction sector's productivity has been stagnating in recent decades worldwide and that it has not been able to keep pace with the overall economic productivity [2]. The causes are numerous and include factors such as the resistance to introduce changes in a highly traditional sector, low industrialization of construction processes, poor collaboration and data interoperability, and high levels of turnover, which make difficult to implement new methods [3].

The construction industry is facing challenges to improve the current situation and increase the overall productivity. One way of doing this could be, as suggested by Barbosa et al. [4], to adopt elements of the technology industry, such as cross-functional teams, with an emphasis on learning and deploying the latest technologies. For example, researchers have found successful applications of scrum techniques from software project management to construction projects [5]. These management changes should be fully supported and integrated with new technological advancements. In that direction, Agarwal et al. [6] proposed a shift to a digital construction organization by exploiting and combining existing technologies such as rapid digital mapping, BIM, digital collaboration, internet of things, and future proof design and construction. Bock [2] shares this view and sees in the strategies coming from the general manufacturing industries under the notion of “industry 3.0” and “industry 4.0”, “*in which highly autonomous and networked automation and robot systems cooperate to produce complex products with consistently sustained productivity*” [2], the promise for the needed change in a construction industry that has been stagnating for decades. Bock summarizes this new set of technologies and processes under the term of “construction automation”. Another often heard term is digital fabrication (dfab), describing the link between digital technologies and the physical construction process [7], which will be used instead in this study.

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1.2. Digital fabrication processes and technologies for construction

The use of robots in construction has been investigated since the early 80s [8]. Warszawski [9] published one of the first critiques about the use of robots in the building sector and proposed different robot configurations to address different construction tasks. Skibniewski [10] presented an expert system for decision support in regard to implementing advanced robotic technology on the construction site; however the implementation of robots in construction sites is still limited. Nonetheless, their use will undoubtedly increase as more cost effective applications are found. The field of digital fabrication (dfab) is quite broad and has many applications. Dfab techniques are based on the combination of computational design methods and automated construction processes, which are typically categorized as subtractive, formative, or additive [11]. Subtractive fabrication involves the removal of material using electro-, chemically- or mechanically-reductive (multi-axis milling) processes. In formative fabrication mechanical forces, restricting forms, heat or steam are applied to reshape or deform a material. Finally, additive fabrication consists of incremental aggregation of material layer-by-layer through extrusion, assembly, binder jetting, etc. The use of subtractive and formative digital fabrication is becoming mainstream in the prefabrication (off-site) of building parts (e.g., by using laser cutting, CNC milling, etc.). Examples of these applications include the generation of a unique shape for each of the 10,000 gypsum fiber acoustic panels at the Hamburg Philharmonic by Herzog & de Meuron [12]. Other architects, such as Frank Gehry and Zaha Hadid have also employed similar digital fabrication processes in their projects [13]. In recent years, additive fabrication processes, especially 3D printing, have experienced a rapid development in many industries. As interest in additive fabrication grows, research into large-scale processes begins to reveal potential applications in construction [14]. Additive construction consists of material aggregation through diverse techniques such as assembly, lamination and extrusion. Existing additive dfab technologies can be classified in two big clusters: on-site and off-site construction technologies.

On the one hand, on-site digital fabrication aims to bring additive fabrication processes on construction sites. Sousa et al. [15] classified on-site technologies in three main categories: large-scale robotic structures, mobile robotic arms, and flying robotic vehicles. A well-known example from the first category is Contour Crafting, a robotic structure for 3D printing large-scale construction, developed at the University of Southern California [16]. An example of a mobile robot for on-site construction is the semi-automated mason (SAM) developed by construction Robotics [17], or the “In situ Fabricator” (IF), developed at ETH Zurich [18]. Finally, the use of flying robots in construction is a novel technique developed to avoid mobility constraints and the need for cranes on construction sites. Imperial College London developed an application of these technologies for polyurethane foam deposition [60]. On the other hand, off-site digital fabrication aims to custom-design and prefabricate large-scale complex architectural elements off-site. Among existing additive dfab technologies, the most common for prefabrication include gantry robots, fixed robotic arms, and 3D printers. For instance, the timber roof of the Arch_Tec_Lab at ETH Zurich was robotically fabricated and preassembled with a gantry robot at the ERNE Holzbau AG factory [19]. An example of additive prefabrication with a fixed robotic arm is the project DEMOCRITE from XtreeE and ENSA Paris-Malaquais. This project aims to construct complex concrete structural elements with increased performance and material optimization [20]. Finally, the use of 3D printers is currently investigated for prefabrication of architectural elements. The project D-Shape developed by Enrico Dini uses this technology for 3D printing sand structures through a binder-jetting process [21].

1.3. State of the art for additive digital fabrication

Digital fabrication techniques can increase productivity rates in the building industry not only because they lead to significant time saving for complex designs, but also because they exhibit the ability to transfer design data directly to 1:1 assembly operations and automated construction [22]. However, additive dfab applied to large-scale construction is still in their infancy and need to face challenges on changing conventional construction processes and roles of project participants.

Initial attempts have been made to apply additive dfab in real practice to evaluate its potential for the construction sector. For instance, Gramazio Kohler Research at ETH Zurich has accomplished different building demonstrators constructed with robotic technologies. The brick façade of the Gantenbein Vineyard showed the possibilities of computational design and robotic construction for the prefabrication of complex multi-functional brick structures. As the robot could be driven directly by the design data, without having to produce additional implementation drawings, the designers were able to work on the design of the façade until the moment of starting production [23]. A more recent project “The Sequential Roof” successfully verified the potential of additive dfab processes for the prefabrication of complex timber structures at full building scale. This robotically assembled 2300 square meter roof is formed by 120 timber trusses, each one produced in 12 h. The development of robust computational design and automated construction framework allowed a reduction in construction time by 10 times [19]. Contributions have also been made for developing concrete structures, especially for non-standard building elements. For instance, the Concrete Printing process developed at Loughborough University consisted of the additive fabrication of full-scale building elements such as panels and walls with the use of a gantry robot. According to Lim et al. [24] this process enables design freedom, precision of manufacture with functional integration, and elimination of labor-intensive molding. There have been successful full-scale applications [14], the most recent by Apis Cor [25]. They have used a similar process for the construction of a 3D printed house in 24 h. The project presents a potential cost reduction up to 40% compared with a conventional concrete house [25].

Nevertheless, fewer research efforts have been made to investigate quantitatively the benefits that additive digital fabrication can provide to the construction sector. The state of the art includes quantitative studies in the field of sustainability assessment of digital fabrication, highlighting benefits such as material optimization or functional integration. For example, Agustí-Juan and Habert [26] evaluated the environmental potential of additive digital fabrication by assessing three case studies and comparing them with conventional building elements with same functionality. This study also brought up the need for finding the differences between conventional construction processes and dfab processes, while rarely being researched. It is still not clear yet to what extent the implementation of additive dfab techniques will improve the construction performance in real projects. However, to facilitate large-scale industrial applications, there is the requirement to conduct quantitative assessments that consider the construction time, cost, and design complexity of new techniques.

1.4. Goal and scope of the study

Construction productivity has been defined as “how well, how quickly, and at what cost buildings and infrastructure can be constructed” [27]. Although productivity is a very important metric, there is not a standard or official productivity index in the construction industry, which leads to some confusion when trying to compare different values [28]. The general consensus is that productivity denotes the output achieved by a given amount of input (i.e., a measure of how efficiently a worker transforms inputs to outputs) [29,30]. Output can be tons of rebar installed or cubic meters of concrete placed while input is generally the number of hours worked. When considering cost, the input can be the total cost (i.e., labor, material, and equipment costs) related to a given installed quantity. In these cases, it is more intuitive to use the inverse of output/input, to determine how much cost a fixed