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The Robots Are Leaving the Cage
Imagining the Future of Construction

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Abstract

Architecture today is challenged by technology advancements and the spread of new tools such as robots, which are mediators between digital and physical. This paper aims to outline future trends that will introduce substantial changes in the construction sector and architecture technology. In support of the topic, representative examples of ongoing experimentations are provided. They are relevant to understand the potentials of tools and foreseeable applications to update the building culture. The introduction of new instruments and procedures might affect building methodologies and the relationship between upstream and downstream design workflows. This relationship is an important aspect because upstream strategies inform downstream processes and vice versa. Also, advanced construction tools enrich the creative phase by providing an opportunity for innovative data integration. The use of computational design, digital fabrication, robotics, and cobotics allows for innovating the building sector by promoting a method based on the customization of forms to be operated on-site. In this scenario, robots play the role of compressing the distance between design and production. Current trends open hypothetical potential for the future of construction: there is a chance for the perfect storm to overwhelm the industry shortly, in compliance with The Fourth Industrial Revolution and the Digital Transformation. Digital Transformation will result in the automation of every task that can be automated, accepting that robots want to "leave the cage," to be embedded in material workflows within hybrid human-machine workspaces. It is expected that architecture, which usually absorbs innovation from other sectors through technological transfer, will become an early adopter of new systems and technologies, always focusing on the design quality at all scales.

Keywords
Digital Transformation, Fourth Industrial Revolution, Construction Robotics, Cobotics, Design Workflows

Cultural background: Digital Transformation and new challenges

In contemporary practice, architectural projects must confront digital infrastructure at different scales of application. The impact of the digital environment on design and construction is led by the Digital Transformation or D(x). It is a technological shift that is changing social balances, work structures, and traditional decision- making phases in favor of iterative data-informed and data-driven approaches. According to the definition adopted by *Educause*,[1] the term Digital Transformation summarizes technical-scientific advancements that result in a modification of the work culture in multiple sectors. These advancements are made possible by the current development of Artificial Intelligence, cloud, computing, big data, social networks, and data storage capabilities. D(x) is a driver of change that profoundly affects the manufacturing industry - and as a consequence building construction - by taking advantage of technology and data to respond efficiently to market demand. D(x) brings together the innovations dictated by the Fourth Industrial Revolution, Industry 4.0, and Industrial Renaissance, a set of technological paradigms that come from the field of economics and have slightly different meanings.

The concept of the Industrial Renaissance recently spread through academic research. The concept refers to the production sector and is based on the economic theory formulated in 1983 by William Abernathy, professor at the Harvard Business School. Abernathy advocated for the American industry's modernization through the competitive advantage gained from the integration of - at the time, emerging computer-aided design (CAD) and computer-aided manufacturing (CAM) systems (Abernathy, 1983, 12-13). The integration consists of the possibility of bringing design and production closer together in a single digital workflow based on the data transfer to inform upstream decisions iteratively.

Similarly, the term Industry 4.0 refers to industrial production and describes the current state of manufacturing. In addition to Abernathy's vision, it focuses on evolving assets such as smart manufacturing, smart factories, and advanced logistics. It relies on interconnected tools driven by the industrial Internet of Things[2]. Industry 4.0 can be considered a subset of the Fourth Industrial Revolution (Schwab, 2017), which encompasses areas that are not necessarily related to production. It is currently building on the Third Industrial Revolution, and "it is characterized by a fusion of technologies that is blurring the lines between the physical, digital, and biological spheres"[3]. The term was coined by Klaus Schwab, founder of the World Economic Forum. It indicates a palimpsest of underway transformations including IoT, AI, automation, and robotics - that are taking place faster than any other revolution of the past. Among the innovations led by this complex ecosystem, robots are increasingly getting the attention of a wide audience, mostly due to their growing economic accessibility and therefore wide commercialization. The manufacturing sector is tied to the production of architecture, which can benefit from the use of innovative resources and equipment to update design processes and overcome standardized architectural prefabrication. In this instance, robots in architecture have the potential of breaking the limits imposed by traditional production methods toward mass customization (Davis, 1987, 168-173), a notion outlined for the first time by Stanley Davis in 1987.

The digital culture entered architecture in the early 1990's with the Digital Revolution that marked the transition from mechanical to digital technologies. This cultural shift in design is known as Digital Turn (Carpo, 2013). This new paradigm happened when architecture criticism was still busy formalizing deconstructionism, in the works of Zaha Hadid, Frank Gehry, and Peter Eisenman. At the time, the architectural design sector started to absorb digital workflows from the naval and aeronautic industries. Indeed, the production of ships has always been to the architects' attention: naval architecture is one of the oldest in construction. This relationship depends on the fact that both ships and buildings are complex systems: "interconnected spaces inhabited by people" (Kolarevic, 2004, 12) with the difference that, in addition to gravity, ships must withstand hydrostatic pressure. The Encyclopédie Méthodique Marine of 1783[4], as an example, reports a definition of naval architecture as "the art of building" or "the basis of the building science" that requires rigorous skills of drawing "vertical, horizontal, and oblique planes of smooth surfaces" (Blondeau, E. N., & Du Clairbois, 1793, 10). Today, as with aerospace engineers, shipbuilders no longer use drawings for the construction of high-tech products with the utmost precision, but perform design processes with a "comprehensive three-dimensional digital model from design to production" (Kolarevic, 2004, 14). In the shipbuilding sector, professionals use digitally-driven technolo-

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[1] *According to the definition adopted by the journal Educause, Digital transformation (Dx) "describes a cultural, workforce, and technological shift, enabled by advances in technology that include analytics, artificial intelligence, cloud, mobile, social networks, and storage capabilities". D(x) calls for a rethinking of higher education (higher ed), to prepare future professionals to face the global changes dictated by the ongoing digital transformations. For further details, see: https://library.educause.edu/topics/information-technology-management-and-leadership/digital-transformation-dx (online: March 1st 2020).*

[2] *The Gartner Glossary describes the Industrial IoT as a set of integrated software capabilities. These capabilities "span efforts to improve asset management decision making, as well as operational visibility and control for plants, depots, infrastructure and equipment within asset-intensive industries". Moreover, the industrial IoT "is engineered to support the requirements of safety, security and mission criticality associated with industrial assets and their operating environments". For further information, see: https://www.gartner.com/en/information- technology/glossary/industrial-iot-platforms (online: May 18th 2020).*

[3] *"The Fourth Industrial Revolution: What it Means, How to Respond", in World Economic Forum. Available at: https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/ (online: May 20th, 2020).*

[4] *The Encyclopédie collects the knowledge of the time on shipbuilding. Along with the definitions of wood types and naval technical terms, it contains a set of detailed drawing boards. They illustrate how to exploit the natural shape of trees to make timber element for the construction of ships, boats, and vessels.*

gies to generate the drawings needed to automate the manufacture of the components adopting a file-to-factory strategy, which is synonymous with process modernization.

In architecture, the Digital Turn introduced a new design culture contributing to the spread of computational thinking and digital tectonics. It enabled architects to interface with a common language, reduce uncertainties, and ensure greater awareness in decision-making phases. Moreover, the Digital Turn allowed for the integration in the discipline of computational workflows that “has emerged in an attempt to leverage the potential of digital tools to link existing sectors of the industry and bring in new sectors in response to the growing demand for intelligent processes and intelligent buildings" (Marble, 2012, 150). The spread of digitization favored the creation of new formal languages: “the new digital style of smoothy and curvy, spliny lines and surfaces [..] now called parametricism” (Carpo, 2017, 131). However, the Digital Revolution had a major limitation; it gave way to the production of digital drawings and two-dimensional simulations that resulted in a secondary role for material culture in architectural production (Picon, 2014). The rise of digital fabrication helped filling this gap. Therefore, the decade that followed 2010 witnessed a push toward a renewed design complexity, characterized by experimenting with robotics and reprogrammable tools to materialize the digital space with great flexibility. This approach expresses the opportunity of “turning data into things” (Gershenfeld, 2012, 44) to find new digital-material possibilities. The convergence of the digital environment with the material world allowed for a subsequent academic theorizing: the Second Digital Turn (Carpo, 2017).

The Second Digital Turn describes an ongoing cultural breakthrough – within the current framework of the Fourth Industrial Revolution - that aims at making the digital space tangible and perceivable (Gramazio and Kohler 2008). It refers to the diffusion, in design, of programmable tools, such as robotic arms, 3D printers, smart-assembly or combined tools, which are the mediators between design and production. These tools make it possible to compress the distance between digital and physical, in a hybrid cyber-physical workspace that expands the design options and elevates the impact of material culture. Therefore, design is not separated from construction and the translation between one and the other becomes nearly instantaneous.

The resulting “digital continuum” (Kolarevic, 2004, 91) can lead to pioneering conceptual results and renewed aesthetic paradigms pointing towards the possibility of transforming roles and disciplines of professionals working together within the digital environment. Given the trajectory of Digital. Transformation as an evolving ecosystem (Figure 1), a new conception of the master-builder – a professional figure that comes from the Middle Age - might represent a balanced point between the advancing technological level in building construction methods and the artisanal approach that characterizes the making of architecture (Figure 2). The new master-builder could constitute a group of figures between the various actors operating in the complex building process and the expression of digital complexity and dexterity. The present-day master-builder could also be the promoter of a renewed project culture and the supervisor of all the design - construction - management activities that take place in the design process. Consequently, design output links between the conceptual phase and the built result, as in the past with craft traditions. Digital manufacturing technologies occupy a fundamental role in this scenario. They are the foundations for mass-customization and performative architecture.

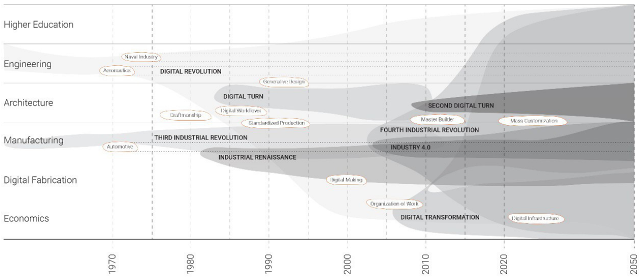

Figure 1. Graphic representation of the development of the digital infrastructure that connects intertwined sectors such as Architecture,

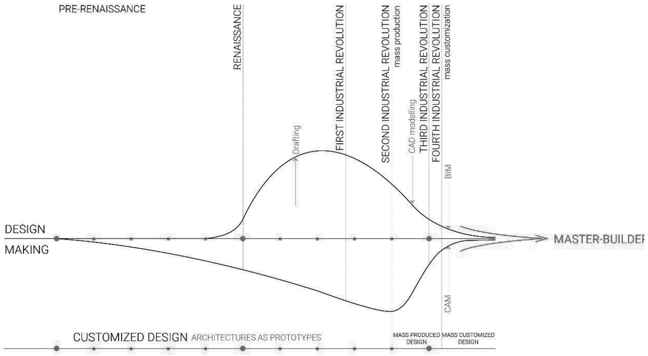

Figure 2. Contraction and deviation of design and making in architecture through industrial revolutions. The current convergence is synthesized by the figure of the master-builder. (Diagram by the author).

Addressing robotics in architecture: approach and methodology

This paper aims to outline future trends that will introduce substantial changes in the construction sector and architecture technology. These changes affect not only the building methodologies but also the relationship between upstream and downstream design workflows. The latter is an important aspect because upstream strategies inform downstream processes and vice versa. The upstream process is the early-stage phase, where the morphological decisions are made, and the design language is defined. On the other hand, the downstream design process concerns production. Advanced construction tools enrich the creative stage by providing an opportunity for innovative data integration. By speculating on the future of construction, the international scientific community shares the idea that the next decades will be characterized by research focused on the development of:

- Cobotics, or human-machine collaboration in a shared physical workspace;

- On-site robotics, which means the use of automation for the customized production on-site of construction components;
- Automated monitoring of building processes for the real-time validation of BIM-based projects.

In the paper "Cobots: Robots for Collaboration with Human Operators", published in 1996, the Northwestern University professors Edward Colgate and Michael Peshkin described for the first time their prototype of cobot. They defined it as "a robotic device that manipulates objects in collaboration with a human operator" (Colgate et al., 1996). Cobots, or collaborative robots, are machines designed to communicate with people and share a physical workspace[5]. To enable safe collaboration, they operate at low speeds and are equipped with sensors that allow them to detect and avoid obstacles. Cobots were developed to overcome the idea of a robot that, according to Isaac Asimov's[6] vision, operates as a mere "autonomous, automatic, and reprogrammable on three or more axes for use in industrial automation applications"[7]. These applications are possible through the installation of a fixed or mobile multipurpose actuator. Cobots, instead, are interactive and responsive devices that can be coordinated with human operations. The integration of AI in the operating systems could open possibilities for enhanced flexibility and problem-solving tasks. As brought up by Paul Daugherty and James Wilson in the publication Human + Machine: Reimagining Work in the Age of AI, unlike robots, cobots are designed "to work closely with people" literally "expanding worker's physical capabilities" (Daugherty and Wilson, 2018, 140, 148). Cobots are useful in a scenario in which "manufacturers are able to reimagine previously static processes" and "workers take on new roles when they collaborate with these smart machines". As a consequence, "business can make more various, adaptable choices about the kinds of products they offer their customers" (Daugherty and Wilson, 2018, 140). This approach is aligned with the Digital Transformation logics. Moreover, it represents an operable methodology to address the progressive loss of labor and skills that is occurring in the construction sector, resulting from the financial crisis that damaged global markets in 2007[8].

In addition to advanced tools, the development of on-site robotics for building site automation is a key factor in academic and industrial research. The traditional building process consists of a sequence of complex operations performed to transform a system and to obtain a superior unity for each phase of transformation. In other words, a sequence of discrete steps, where every operation happens after the previous one is completed, with a clear threshold marking the termination of each stage and the commencement of the next (Zaffagnini, 1981, 9-11). These operations are structured to organize and bring together "a set of inputs into a specified building output or product, in a given period of time, on a specified site" (Groak, 2002, 121). The decision-making phases have a relevant impact on the organization of work, as well as "you cannot have 40 people showing up on-site and figure out the materials to be used by the end of the day. We need processes, logistics. We need to know which progress is supposed to be made after a certain amount of time"[9]. As Pierluigi Spadolini states in the book Designing in the Building Process, building production sequences come from artisan production, where "the designer's knowledge was related to that of the highly specialized manufacturer with direct control of resources and technologies to provision" (Spadolini, 1981, 15). The technological influence in production processes varies in historical periods according to the tools used. The connection between design and construction has weakened with the beginning of industrialization, which has delocalized production and deskilled the technological elements for their repetitive production. Industrialization "has determined a flattening of the artisan interpretation" and has brought constraints to the design determined by the downstream production technologies (Spadolini, 1981, 16-17). This has inevitably led to restrictions in the work of the architect forced to limit formal and constructive choices based on industrial production. The 1980's, at the threshold of the Digital Turn, allowed designers to visualize a socio-cultural transition between hand, mechanical, and digital making. The theme of digital making has opened to philosophy, with the Theory of Objectile by Bernard Cache (Cache, 1998) and the theme of multiple variations (Deleuze, 1993) introduced by Deleuze. As a consequence, digital making is seen as a possibility to generate calculus-based forms, creating variations that can be produced using digital manufacturing technologies through the language of the algorithm (Carpo, 2011).

The use of computational design, digital fabrication, robotics and cobotics is an opportunity to innovate the construction sector and architecture by promoting a method based on the

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[5] *"You've Heard of Robots; What are Cobots", in Forbes. Available at: https://www.forbes.com/sites/co gnitiveworld/2019/12/15/youve-heard-of-robots-what-are-cobots/ (online: May 20th, 2020).*

[6] *Isaac Asimov is the author of the sci-fi short story "Runaround", published in 1942 in the Astounding Science- Fiction magazine. By describing positronic robots, the author expresses the Three Laws of Robotics. In 1985, with the novel Robots and Empire, Asimov introduces a fourth law, called the Zeroth Law, according to which "a robot may not harm humanity, or, by inaction, allow humanity to come to harm". From this axiom derives the reformulation of the cited Three Laws. First Law: a robot may not injure a human being or, through inaction, allow a human being to come to harm by inaction, as long as such orders do not conflict with the Zeroth Law. Second Law: a robot must obey the orders given it by human beings except where such orders would conflict with the Zeroth and the First Law. Third Law: a robot must protect its own existence as long as such protection does not conflict with the Zeroth, First, or Second Laws.*

[7] *Definition provided by the IFR, International Federation of Robotics, which adopts the guidelines provided by the International Organization for Standardization. The ISO 8373:2012 - "Robots and Robotic Devices" states that "an industrial robot is an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications". Available at: https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-2:v1:en:term:3.11 (online: May 20th, 2020).*

[8] *Faced with the lack of response to concrete needs in the construction sector, the Robotic Industries Association estimates that by 2022 the construction robot market will reach a value of 321 million dollars. It could grow at a constant annual rate of 8,7%. For further information, see: https://www.robotics.org/service-robots/construction- robots (online: May 20th, 2020).*

[9] *From a lecture given by Karl Daubmann for the kick off of the course Critical Practice – Fall 2019 at Lawrence Technological University – College of Architecture and Design – MI, USA.*

customization of forms to be ideally operated on-site. Indeed, we still construct in the same way that Gothic cathedrals were erected

- with the only difference that the tools are more sophisti cated
- with the same philosophy: "manual control, human opera torvisual feedback, and big positioning error" (Balaguer, 2000).

As mentioned, current trends lead to the conclusion that in the near future there is a chance for the "perfect storm" to overwhelm the construction sector, in compliance with The Fourth Industrial Revolution and the Digital Transformation. In architecture, some of these trends - which will be described in detail in the following paragraphs - include: the spread of CAD/CAM tools and skills globally; the increasing investments in digitization in multiple sectors; the democratization of automation and the decreasing cost of robots; the enhancement of digital interfaces for algorithmic design and robo-scripting; and the definition of new high-engineered materials compatible with 3D printing and robotic production. Today there are numerous limitations which make it difficult to scale-up the digital manufacturing approach from the Fab Lab to the construction site. However, there are some aspects to be considered in the advancement of First World economies. On the one hand, construction jobs are perceived as "Four Ds" working environments, which means dull, dumb, dirty, and dangerous. Even on the verge of a forthcoming global economic meltdown that could be worse than the collapse of 2007, building site labor is rarely the first choice for the unemployed. On the other hand, the upheaval of post-pandemic working conditions may hasten the research to find solutions and economic advantage from the use of machines within a cutting-edge digital infrastructure.

Cobots and on-site robotics: a brief overview of case studies

In this section, representative examples of cobotics and on-site robotics are provided. They are relevant to introduce the tools and foreseeable applications in the building sector. These technologies have been used mostly in industries that revolve around architecture. For instance, as it happens for robotics, the manufacturing industry is a testing ground for cobotics. In parallel, construction robots, including monitoring devices and autonomous vehicles, are experimented mainly in the research sector, to push the Technology Readiness Level[10]. The analysis of case studies provides an opportunity to clarify limitations and potentials of existing best practices, in the formulation of future scenarios.

In 2012, the start-up company Rethink Robotics[11] created Baxter, a collaborative robot intended to perform repetitive tasks alongside humans. Baxter is provided with multiple sensors that allow it to detect the presence of static or dynamic objects nearby, and circumvent them at a low speed to avoid causing harm to anyone. User-friendly cobot programming is easily done by unskilled workers, reducing overspending in coding. Based on variable inputs, Baxter is able to adapt accordingly. Its geometry includes two arms, defined by three nodes each (shoulder, elbow, and wrist), ending with the actuators, or hands. The hands could be customized, and often they were grippers equipped with extra sensors for picking and placing objects. The most innovative feature is the flat screen on its face. It displays various expressions that helps collaborators to understand its current status. By moving the eyes, Baxter foretells its next positioning in the working area. Compared to the technology available today, the project pioneered early-stage research on intelligent robots. An approach for a collaborative machine in construction is the Mule (Material Unit Lift Enhancer) project[12]. It is a programmable device that handles building materials to human workers, who are relieved of arduous and exhausting tasks.

Nowadays, examples of collaborative automation tools can be found in manufacturing plants. At BMW's factory, to name one, cobots "rub elbows" with humans[13]. They are installed by the company Universal Robots[14] that produces lightweight and low operating-speed robots to be adopted safely in shared workspaces. BMW business model is currently under study by researchers at MIT in response observations that maximized automation does not imply higher efficiency. According to their analysis, the human-robot collaboration in the car facility reduced by 85% the workers' idle time.[15] Moreover, the collaboration turns the assembly line into a flexible system that makes manufacturing labor less manual and more supervisory. This aspect is beneficial to workers, who become more appealing on the job market because of their renewed skills and greater awareness of production processes. Mercedes-Benz plant invested in cobots too, due to the increasing demand of customizable cars. As a consequence, "with so much variation in car manufacturing, the only way to assemble cars fast enough is to bring people back", instead of "dividing manufacturing plants into a heavy lifting robot section, usually fended off from people for safety reasons and another area for to perform more delicate tasks" (Daugherty and Wilson, 2018, 148). Customization is tied to architecture too, which could rely on hybrid human- machine completion of laborious tasks by keeping the craftspeople consciousness involved in making. This balance might be crucial to prevent construction sites from becoming standardized manufacturing sites, often theorized and never realized.

In the construction industry, the Hadrian X Robot[16], by Fastbrick Robotics (Perth, Australia), pioneered on-site automation. In 1994, the mechanical engineer Mark Pivac conceptualized a robotic arm for lifting, positioning, and installing building materials. Between 2005 and 2008, Pivac filed a patent for an "automatic bricklaying system" called Hadrian. It was used to successfully demonstrate the construction of a wall made of bricks and mortar. After this experiment, the Hadrian project was put on hold due to the financial crisis and rebooted in 2014 in combination with a global renewed interest in robotic construction. In 2016, the Hadrian Robot built, as a proof of concept, an architectural unit from a digital CAD model with no human intervention. The architects Gramazio and Kohler contributed to making the concept of automated bricklaying popular with the parametric facade of the Winery Ganterbein project of 2006.

In the European framework, the project Hephaestus addresses autonomous systems like cable-robots with modular end-effectors to install curtain walls in new buildings. In particular, as specified by the researchers, the project “focuses on high-risk and critical construction tasks such as prefab wall installation”18 with the aim of innovating the building sector, where the presence of robots and automation is minor. A further example is the P2-Endure project. Instead of working on new constructions, it promotes "evidence-based innovative solutions for deep renovation based on prefabricated Plug-and-Play systems in combination with on-site robotic 3D-printing and Building Information Modeling"[19], opening new scenarios in the field of redevelopment and retrofitting. P2- Endure is based on an interpretation of European data assets. 70% of the residential real estate stock is composed of buildings originating prior to 1970 and needs to be adjusted to new levels of energy efficiency, seismic safety, inclusivity, and living comfort. On a larger scale, about 35% of the EU's buildings are over 50 years old[20]. 90% of the existing building stock in Europe was built before 1990[21]. In both projects there is a commitment to accelerate the access to advanced technology in architecture, from new construction to deep renovation.

By considering the possibility of opening the robotics market to restoration and deep renovation, Skanska is taking pioneering steps in robotics. The company is leading a research consortium to study robotic applications for mechanical, electrical, hydraulic, and carpentry tasks to produce or fix building components. A relevant outcome of this research is the creation of a prototype, called Camera, designed to contribute to the overall productivity of building construction cost-effectively. It is a semi-autonomous lightweight mobile platform capable of moving around the construction site assisted by visual sensing. Skanska's approach considers the lack of flexibility and reconfigurability of existing automation systems. These systems are still committed to intensive prefabrication. The Camera platform, instead, operates with small units that may require high-precision non-invasive repair or assessment.

A final example worth mentioning is the DFab house[22], the first full-scale architectural system built entirely with digital fabrication, additive manufacturing, and on-site robotics. The project was developed in 2018 at ETH Zurich. For the completion of the work, the robots were programmed to perform multiple tasks and collect data in real-time on the construction advancements. The DFab house included the construction of a double-curved reinforced concrete wall. The reinforcement grid was built by a six-axis robot that operated on a mobile platform to assemble and weld the technological components. Before erecting the structure, the wall footprint was determined on the floor by markers that served as reference points. A camera positioned on the robot’s head measured the tags and geo-referenced it in space via a calculation system with no need to use external measuring devices. Two additional cameras monitored the accurate construction of the steel mesh. The surface of the wall was finished by spraying concrete. Computer vision and advanced feedback loop systems allowed for the realization of a complex output guided by a technological-driven and digital-informed design workflow. Overall, the use of robotic sensing has triggered experimentation and encouraged the diffusion of digital services[23] that supported the adoption of automation fueled by algorithms and AI. This technological combination allows for the robotic applications in site monitoring and evaluation of constructions as-built, displaying the potentials of the Fourth Industrial Revolution.

Trends in the construction industry and critical analysis of relevant data

Since the global economic crisis of 2007, the construction industry was forced to reduce most of the workforce. The dynamics of the market have prevented these workers from returning to the building sector. In the Italian framework, the European Construction Sector Observatory in 2018 reported that the number of workers in construction decreased by 26.5% between 2010 and 2016. As a consequence, this pattern led to the current inability to meet the demand for the labor force in building construction, particularly in the first world economies.

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[10] *The Technology Readiness Level is a scale to evaluate applied research. It was elaborated by Nasa in the 1990’s. Later, the classification was adopted by the Europan Commission within the Horizon2020 framework program for research and innovation. For further information, see: https://ec.europa. eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf (online: May 20th, 2020).*

[11] *Rethink Robotics: https://www.rethinkrobotics.com/ (online: May 20th, 2020).*

[12] *Mule project: https://www.construction-robotics.com/mule/ (online: May 20th, 2020).*

[13] *A Universal Robot at the BMW assembly line: https://vimeo.com/78283765 (online: May 20th, 2020).*

[14] *Universal Robots – Collaborative Robotic Automation: https://www.universal-robots.com/ (online: May 20th, 2020). The company provides also open source courses for the dissemination of the robotic culture in manufacturing.*

[15] *How Human-Robot Teamwork Will Upend Manufacturing in MIT Technology Review. Available at: https://www.technologyreview.com/2014/09/16/171369/how-human-robot-teamwork-will-upend-manufacturing/ (online: May 20th, 2020).*

[16] *Hadrian X Robot by Fastbrick Robotics: https://www.fbr.com.au/view/hadrian-x (online: May 20th, 2020).*

[17] *Winery Ganterbain project with the non-standardized brick wall by Gramazio and Kohler Research at ETH - Zurich: https://gramaziokohler.arch.ethz.ch/web/e/projekte/52.html (online: May 20th, 2020).*

[18] *The European project Hephaestus, developed with Horizon2020. For further information, see: https://cordis.europa.eu/project/rcn/206251/factsheet/en (online: May 20th, 2020).*

[19] *P2Endure project. For further information, see: https://www.p2endure-project.eu/en (online: May 20th, 2020).*

[20] *For further information, see: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analy sis_in_support_en_0.pdf (online: May 20th, 2020).*

[21] *A European long-term strategic vision for a prosperous, modern, competitive, and climate neutral economy, study for the ITRE Committee: http://www.europarl.europa.eu/RegData/etudes/STUD/2016/587326/IPOL_STU (2016)587326_EN.pdf (online: May 20th, 2020).*

[22] *DFab house at ETH Zurich: https://dfabhouse.ch/ (online: May 20th, 2020).*

[23] *Today, there is an increase in consultant companies that combine AI, computer vision systems, and hardware for the construction industry. Among them: Voxel, https://www.doxel.ai/, and Scale Robotics, https://www.scaledrobotics.com/ (online: May 20th, 2020).*

The value of skilled workers in the job market is continuously increasing, in parallel with the growing cost of construction materials. In parallel, the cost of robots is gradually decreasing, facilitating investments in automation. As confirmed in the article "The Construction Labor Shortage: Will Developers Deploy Robotics?" published in Forbes, "when the recession hit, 600,000 workers left construction jobs never to return. Today workers avoid construction jobs, perceiving them as dangerous, difficult, and dirty"[24].

Taking the Unites States context as a reference where – pre Covid19 pandemic, the new paradigm shifter – the construction crisis seemed to be over, in 2019 the US Bureau of Labor Statistics in 2019 reported 434,000 jobs offers[25] in the AEC sector: Architecture, Engineering, and Construction. The disparity between supply and demand is due by the lack of skilled workers[26], which means those able to manage firsthand complexity and building site unpredictability. The skilled workers are the professionals to rely on within the intricate relationship between owners, designers, contractors, and users for each project.

In 2013, Emilio Pizzi presented a comprehensive analysis on a foreseeable new scenario in the future of construction, with the publication "Toward the simplification of the design process chain aimed at optimizing the productive processes to improve innovation and competitiveness". In the text, he talks about new design tools and the progressive diffusion of BIM technologies that, together with the interconnection with robotic production techniques, "may lead to new premises for a new control over the project, over the different components, their assembly, life cycles and recycling after their [disassembly]". This statement is supported by the idea that "The construction industry will be enhanced by introducing robotic equipment - within the manufacturing plants - and adopting on-site automated construction systems" (Pizzi, 2013).

Construction companies that are investing in automation are convinced by the possibility of: reducing production and labor cost, responding to labor shortages, reorganizing work and redundant sequences, increasing productivity, improving quality, reinforcing safety by reducing tasks that are too dangerous for employees, and enabling higher flexibility in production[27]. Moreover, robots have expanded physical capabilities. They manage tolerances to a hundredth of a millimeter, and can take long, uninterrupted shifts without drawing a difference between day and night. The co-existence human-robots has the requisites to be the best choice. The tasks can be divided in order to optimize the result. By comparing the cost and time required by a human and a robot to complete a chore, as complexity increases, automation pays off. As mentioned before, all these instances are taking place at a time in which the economic accessibility of robots is challenging the increasing value of the workforce[28] (Figure 3). In Italy, data updated to 2016 show that to 10,000 workers in the manufacturing sector correspond 185 robots; 25 more than in 2015 and above the world average, which is 74. The pole position is occupied by South Korea (631), Singapore (488), and Germany (309). They are followed by Japan (303), Denmark (211), and United States (189)[29]. In parallel, the advancement of research in AI/ML, allows for programming devices to facilitate a safe collaboration between human and machines in a physical work- cell validated through digital simulations and predictivity of working conditions.

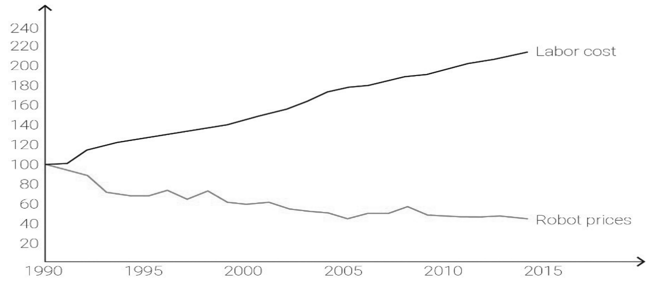

Figure 3. Cost of automation. Index of average robot prices and labor compensation in manufacturing in United States, 1990 = 100%. Source: graphic elaboration by the author, based on the analysis carried out by Economist Intelligence Unit, IMB, Institut fur Arbeitsmarkt und Berufsforschung, IRF, US Social Security data, and McKinsey&Company.

The translation of robotics from manufacturing to construction is not a disruptive new concept. The race for automation on the construction site happened between the 1960's and the 1980's in countries that invested the most in technological advancement. In the 1970s's there were opposing trends in the economies of Japan and the United States that are worthy of mention. In 1973, the oil embargo in the USA triggered recession. The awareness of limits on economic growth arose. Therefore, attempts to fully industrialize the building process declined or were abandoned in both Europe and the US. Simultaneously, in Japan the growing population led to an incremental demand of social housing. The lack of skilled labor in the building industry was a driving factor to lead the promotion of automation in prefabrication and construction. It was an alternative to traditional construction practices. As Thomas Bock and Thomas Linner explain in the publication Changing Building Sites: Industrialization and Automation of the Building Process, in the Japanese context a massive research was directed toward automated housing prefabrication, on-site single task construction robots, and integrated automated construction sites. The integrated automated construction sites were organized "as partly automated, vertically moving on-site factories providing a shelter for on-site assembly, which was controlled, structured and systemized, and unaffected by the weather, as well as for a disassembly process of prefabricated, modular low, medium and high-level detailed building components" (Bock and Linner, 2014). In the 1960's, Japan shifted from the building site to a structured and automated factory-based work environment. Where 85% of the work was executed off-site for the most part by human labor. The processes still relied on the assembly line, rather than real automation. In contrast with European approaches, where prefabrication was primarily optimized to achieve fast and cheap production of large numbers of identical elements, Japanese prefabrication was more oriented to customization and personalization. The assembly-line work, combined with the advantages of human labor in a factory, "allowed for the individual adaptation of single parts meeting customer demand without disturbing the production chain. They could be taken out of the assembly line and replaced manually, to be reworked or finished, before being introduced back into the next stage of the production process, causing minimal disruption to the overall productivity" (Bock and Linner, 2014). This approach can be considered a precursor of today's promotion of robotics in architecture. The enhancing of research in this field during the following decade was based on the "robot boom" in the manufacturing industry. As a consequence, the adoption of robots was a logical approach for Japanese construction firms. Single task construction robots were subsequently developed. They could execute a single, specific task repetitively. They could be used on construction sites for demolition, surveying, excavation, paving, tunneling, concrete transportation and distribution, concrete slab casting and finishing, welding and positioning of structural steel members, fire-resistance and paint spraying, inspection, and maintenance. Sites would be structured and designed like factories. The final objective was the implementation of automated manufacturing and construction technologies, which is not a Fourth Industrial Revolution approach. That said, why aren't construction sites populated by robots? What's the missing link in the innovation chain? As per tradition, every building is a prototype and every architectural realization is the result of a "temporary coalition of people and organizations" (Groak, 1994, 128), probably working together for the first time. For this reason, despite a long history of collective building tradition, individual professionals have little opportunity for learning between one project and another. Technology has evolved substantially since the 1970's-1980's. The design industry has not. Some of the world's largest firms still do everything on paper from managing blueprints to keeping track of employee hours and pay. The past efforts of automating construction failed for several factors. For instance, robotic applications required high initial installation costs. For this reasons, the integrated automated building sites were used when contingent conditions required them, such as high labor cost, traffic, noise, and waste restrictions. Moreover, these efforts failed because computing power was still weak[30] (Figure 4). Finally, there was a lack of regulations (building codes specify "what", not "how"). The historical precursors show that the implementation of robotics in architecture at a large scale requires a substantial change in the early design stages as well as in the construction process that goes far beyond imitating existing building technologies. Instead of trying to copy and perform factory automation methods, new robotic tools require: appropriate conditions, design strategies, kinematics, programming, and control. Every innovation in construction technology needs at least one generation to establish itself. Advances in automated construction continue to be developed today. The use of flexible industrial robots in the prefabrication of building elements, as well as in architectural research institutions, is becoming widespread. Now the technological and economic accessibility foundations are being laid.

Consequences in the culture of making and conclusions

Robotic spread scares workers. However, the emergence of the economy of scale is a precedent that shows the tendency of the market to restore a balance, after a stressful transition. Yuval Noah Harari expresses this concept is the book 21 Lessons for the 21st Century in a chapter called sarcastically "When You Grow Up, You Might Not Have a Job". He states: "fears that automation will create massive unemployment go back to the nineteenth century, and so far, they have never materialized. Since the beginning of the Industrial Revolution, for every job lost to a machine at least one job was created, and the average standard of living has increased dramatically" (Harari, 2018, 19). Data collected from the US Bureau of Statistics show that in 165 years technology has created large sector shifts but also new jobs[31]. For instance, "agriculture's share of US employment was close to 60% in 1850, but today it represents just 3%

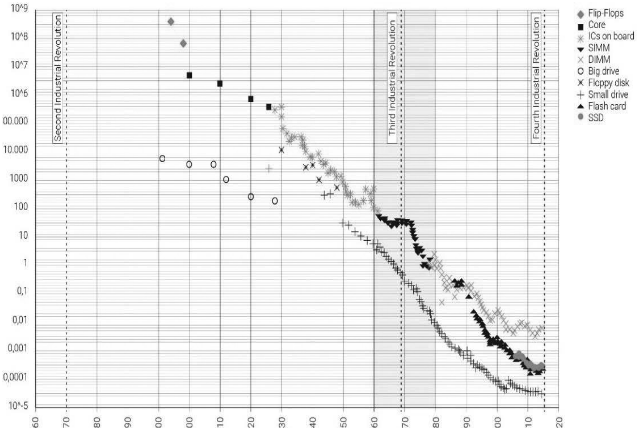

Figure 4. Historical cost of computer memory and storage. Between the 1960's and the 1980's, 1 MB used to cost around 50 dollars. A gigabyte was worth 50,000 dollars. Source: graphic elaboration by the author, based on Hblok data.

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[24] *"The Construction Labor Shortage: Will Developers Deploy Robotics?" in Forbes. Available at: https://www.forbes.com/sites/columbiabusinessschool/2019/07/31/the-construction-labor-shortage-will-developers-deploy-robotics/ (online: May 20th, 2020).*

[25] *US Bureau of Labor Statistics available at: https://www.bls.gov/news.release/jolts.t01.htm (online: May 20th, 2020).*

[26] *"The Construction Industry Needs a Robot Revolution" in Wired. Available at: https://www.wired. com/ story/the-construction-industry-needs-a-robot-revolution/ (online: May 20th, 2020).*

[27] *The main drivers triggering investments in automation have been studied by McKinsey&Company. The report "Industrial Robotics. Insights into the sector's future growth dynamics" is available at: https://www.mckinsey.com/~/media/McKinsey/Industries/Advanced%20Electronics/Our%20Insights/Growth%20 dynamics%20in%20industrial%20robotics/Industrial-robotics-Insights-into-the-sectors-future-growth- dynamics.ashx (online: May 20th, 2020).*

[28] *"Automation, Robotics, and the Factory of the Future" in McKinsey&Company. Available at: https://www.mckinsey.com/business-functions/ operations/our-insights/automation-robotics-and-the-factory-of-the-future (online: May 20th, 2020).*

[29] *Source IFR - International Federation of Robotics. For further information on the diffusion of robotics in the market, see: https://www.therobotreport.com/10-automated-countries-in-the-world/ (online: May 20th, 2020).*

[30] *Historical Cost of Computers Memory and Storage, available at: https://hblok.net/blog/posts/2017/12/17/historical-cost-of-computer-memory-and-storage-4/ (online: May 20th, 2020).*

of jobs”[32]. In parallel, new sectors emerged in entertainment, trade, professional services, and education. To mention a European example: in Italy, between 1910 and today, people employed in agriculture fell from 60% of the working population to 3,8%[33].

Agriculture has some similarities with the construction sector. In both working contexts, the “Four Ds” are applicable. With the advancement of technology, wherever labor conditions are repetitive, humble, or exhausting, there is a tendency for automation. The 2016 publication Farm Workers Futurism – Speculative Technologies of Resistance by Curtis Marez shows several examples of mechanized production systems for harvesting that were developed experimentally between the 1930’s and 1960’s. Among them, an experimental cotton picker (1942)[34], an automatic pump to milk cows (1933)[35], and a prototype of humanoid robot that could be controlled remotely (1938)[36]. The reason for these efforts to automate agriculture lay in the urgency of improving efficiency by taking the best advantage from machines[37] (Marez, 2016, 20). Anyway, the technological advancement of agriculture has reduced job opportunities that no one wants to take anymore.

In the future of construction, innovation is encouraged by market demand and work perspective. In the US, from 2007 to 2010, the building industry saw a massive decline due to the recession. In the decade 2010-2020, it rebounded with an expectation of a positive employment trend projected to 2026 (Figure 5). The study highlights that in July 2018 there were 7.2 million construction jobs, the "highest employment level for the construction industry in a decade. Leading into and through the Great Recession, the industry experienced declines in employment. In recent years, however, employment has trended upward” [38]. The previous paragraph shows trends that would have continued had it not been for the Covid19 global pandemic. As soon as the lockdown imposed in various countries of the world is over, the global community will confront an unknown and unexpected market reaction to Covid19 containment measures. The post-pandemic scenario is unknown: it does not follow a normal pattern. As Joshua Gans would argue, “this time is different” and soon we might face a “dark recession”[39]. Given the current building culture, construction workers can’t do smart working because their activity takes place outdoor with the support of specialized machinery. However, the pandemic, the new normativity of social distancing, and the need to ensure safe work spaces could encourage Research & Development sectors to “rallying innovation” taking into account that “the innovation challenge is so potentially large that it is very important that we pursue as many different paths as possible”[40]. In this scenario, there is an opportunity for first world countries to undergo a transition to a knowledge economy, where the figure of the master-builder becomes the professional who has intellectual control of processes by instructing construction tools on how to operate. To add a note of disbelief in this discussion, the pandemic has highlighted that, in architecture, the flexibility afforded by knowledge work does precede the actual active construction. All stages prior to construction are manageable remotely and digitally, such as: design, estimates, and logistics. Conversely, the building phase still relies on the physical strength of workers moving things around the construction site, where knowledge and creativity are not deployed. As a result, the transition to a knowledge economy approach in construction is not likely to happen quickly. The current trends in construction are operationalizing robots as a real option to innovate the obsolete organizational structures that connect human labor, architectural production, and advanced making (Figure 6). There real-time interactions could take place in a digital continuum that ties closer together the decision- making phases and the management of human and economic resources for the translation from digital to material data. Technological development will allow for the use of integrated and interconnected tools directly on site, shortening the supply chain of building materials and improving the sustainability of construction processes. It is expected that architecture, which usually absorbs innovation from other sectors through technological transfer, will become early adopter of new systems and technologies. Digital Transformation will result in the automation of every task that can be automated, accepting that robots want to “leave the cage”, to be embedded in material workflows within hybrid human-machine workspaces. As summarized in the 2017 document Re-Imagining Work 4.0 issued by the German Federal Ministry of Labor and Social Affairs, “a new generation of robots is emerging with progressive advances in AI. While in recent decades robots were primarily used to automate simple production steps, the latest industrial robots are now also capable, thanks to AI-based high-performance sensors, of taking on fine-motor tasks and interacting directly with their human

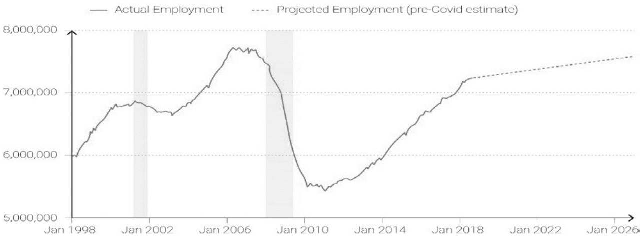

Figure 5. Construction industry employment, January 1988 – July 2018 and projection to 2026. Source: graphic elaboration by the author, based on US Bureau of Labor Statistics data.

Figure 6. Citizen Robotics, the nonprofit FabLab in Detroit that provides access to robots and training to upskill the construction workforce of the future for the built environment. Source: citizenrobotics.org.

co-workers. […] The previous spatial separation of people and robots is becoming irrelevant; the machines are leaving the “cage”4 and they are adventuring in our world. In addition, the integration of AI and machine learning might question the role of human experience, making traditional work obsolete and redundant. The technological advancement of physical-systems determined the First and Second Industrial Revolution. After that, the Third Industrial Revolution developed cyber-systems. Finally, the Fourth Industrial Revolution integrated the virtual and material worlds by introducing the cyber-physical- systems. In this circumstance, it is essential to understand and manage an increasing amount of data in multiple information spaces (Floridi, 2014). In the near future, professionals in the architecture production chain will operate in a cyber-physical infrastructure defined by AI, machine learning, and robotic automation. These professionals, referred to as master-builders, are teams of data-informed architects that will be able to manage the impact of technology within upstream design phases and the languages that rule them.

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[33] *For further information, see: https://www.istat.it/it/agricoltura (online: May 20th, 2020).*

[34] *Mechanical cotton picker, available at: https://www.wisconsinhistory.org/Records/Image/IM23599 (online: May 20th, 2020).*

[35] *Vacuum Pump and Milker on Display at "A Century of Progress", available at: https://www.wisconsinhistory.org/Records/Image/IM49700 (online: May 20th, 2020).*

[36] *“Harvey the Harvester”, available at: https://www.wisconsinhistory.org/Records/Article/CS3488 (online: May 20th, 2020).*

[37] *In the cited paragraph of the book Farm Workers Futurism – Speculative Technologies of Resistance, the author refers to a 1951 Harvester World article called “Way Out West in the Land of Cotton” that talks about the development of mechanical cotton pickers in the industry.*

[38] *“Careers in Construction: Building Opportunity” in US Bureau of Statistics. Available at: https://www.bls.gov/careeroutlook/2018/article/careers-in-construction.htm (online: May 20th, 2020).*

[39] *Economic in the Age of Covid19 by Joshua Gans, chapter 4. The open source text is available at: https://economics-in-the-age-of-covid-19.pubpub.org/pub/mh2yb73z/release/1 (online: May 20th, 2020).*

[40] *Economic in the Age of Covid19 by Joshua Gans, chapter 7. Available at: https://economics-in-the-age-of- covid-19.pubpub.org/pub/pyu3z6d4/release/1 (online: May 20th, 2020).*

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