From Technology to Strategy: Robotic Fabrication and Human Robot Collaboration for Increasing AEC Capacities

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Abstract This position paper unpacks the relationship between intangible pre- and post-production and tangible production processes under an Industry 4.0 framework for architecture and design to mitigate the Architecture Engineering Construction (AEC) sectors' contribution to climate change and investigate potentials for SDG 9 (industry, innovation and infrastructure). As Industry 4.0 is describing a business model or strategy foremost that utilises and incorporates technology via a cyber-physical system, we investigate how robotic technologies and human robot collaboration can enable methods, frameworks, and systems for the AEC sector; and what opportunities and challenges outside the tangible production floor can be considered to tie in architecture and construction. By reviewing state-of-the-art tangible production processes, robotic fabrication, and robotic interfaces, we aim to outline potential research domains in intangible pre-and post-production towards Next Gen Architectural Manufacturing. We conclude with objectives for reducing architecture's resources appetite using computation and modern manufacturing strategies and a strategic framework to enable this in the AEC sector. This investigation, its proposed hypothesis, methodology, implications, significance, and evaluation are presented in this chapter.

Keywords Cyberphysical systems · Robotic fabrication · Human robot collaboration · Data-driven design strategies

United Nations' Sustainable Development Goals 9. Build resilient infrastructure · promote sustainable industrialization and foster innovation

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1 Introduction

The building sector contributes significantly to the current climate crisis on a global scale by using the largest amount of natural resources (~60%), producing excessive emissions (~50%) and waste production (~50%)—all of which are related and interlinked [63]. A discussion of Industry 4.0 in a context of the Architecture Engineering Construction AEC industries must thus have at its centre a reduction of use of resources, a reduction of emission, and a reduction of waste. Consequently, in this position paper, we discuss and outline a strategic approach for Industry 4.0 geared towards enhancing collaboration amongst various departments to increase efficiency and productivity [4] and so assist in improving the AEC industries carbon footprint. We align with two critical comments. As Adams notes, 'the technology of Industry 4.0, while important, is less important than the business model that utilises and incorporates' [3]. Moreover, as MIT economists argue, 'digital is not about technology but strategy' [69]. Section 2 opens the discussion with an overview of second machine age general purpose technologies and cyberphysical systems and continues towards reconsidering production values via intangible pre- and post-production processes. Here we see an important role and contribution of the architectural business sector. Section 3 reviews a case for current AEC with research and knowledge in robotic fabrication as tangible production floor. Section 4 overlays the AEC sectors version of intangible pre- and post-production processes; *synthesis* (creative process), *management* (business process), and *analytics* (data process) and outlines pathways for an integrated, cross-disciplinary framework as strategy to address the building sector's climate problem. Section 5 concludes with overarching objectives for an industry 4.0 framework in AEC sector and potential SDG9 contribution.

2 Smile Curve for AEC Industries, a Development Space

Referred to as a descriptor for developments and advancement of information technology in the German economy in 2011, the term 'Industry 4.0' was rapidly adopted by the Architecture Engineering and Construction industry (AEC). The continued high interest in this concept—of industry, research and academia—is evidenced by recent web discussions, with a keywords search ('Architecture' AND 'Industry 4.0') yielding in Scopus 25,903 document results: and with an exponential rise in the years 2014–2020 (access data 5. July 2022). While this provides by no means a qualitative insight, it clearly presents the growing interest that exists in architecture and construction for the concepts, methods, tools and adoption for an Industry 4.0 framework.

2.1 Industry 4.0 and General Purpose Technologies

The interrelation of technologies that facilitate the emergence of the 'Smart Factory' is a base concept that is highly valuable for architecture design practice and adoption into the construction industries. Design principles that can inform the design to construction workflow and thus enable implementation to Industry 4.0 scenarios include *interoperability* (ability of systems connection); *virtualization* (data-based models, digital twin); *decentralisation* (ability for local decision making); *real-time capability* (data collection, analysis and evaluation); and *modularity* (flexible adaptation through modules) [35].

The fact that new approaches in architecture have become available results from new general-purpose technologies such as digitised and social data analytics, sensors, machine learning, or robotics which allow the automation of cognitive tasks and offer human and software-driven machine substitutes [12]. Similar to electricity or the combustion engine that rendered labour and machines complementary in the First Machine Age, these general purpose technologies are identifiable as single generic system or equipment; recognizable over a lifetime; have scope for improvement, and will be used and enable uses with spill over effects [45]. Significantly, IT driven changes in manufacturing systems are expected to affect product- to service-orientation even in traditional industries (Lasi 2021).

Key advanced technologies associated with Industry 4.0 are manifold, ranging from the Internet of Things (IoT)/Internet of Services (IoS), Cloud Computing, Big Data, Smart Factory, 3D-Printing, Mobile Computing and Radio-Frequency Identification (RFID), the Cyber-Physical Systems (CPS) or Embedded systems, Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR) and the Human–Computer-Interaction (HCI) [43]. Their adoption brings benefits for design-to-make production processes alongside digital technologies within industrialised construction, which are much needed for certainty of cost, schedule, and scope in the AEC industries [51].

As Fig. 1 shows, methods that become thus available include processes and strategies that enable digitisation and integration of work and construction processes at different stages, where this work alongside Building Information Modelling (BIM) and manufacturing concepts such as Product Lifecycle-Management (PLM) and Modularisation. Out of the range of these general-purpose technologies, as this chapter argues, robotics holds a particular significance, as this enables computational data to being seamlessly integrated with work processes and thus bridging between digital/virtual realms and the physical/real. At the core, robotics opens different strategies in terms of how to approach data and labour. Beyond management (data capture, simulation analysis), robotic applications as part of Industry 4.0 enable connectivity and interoperability between human workforces, data, material and machines, in the domains of robotic fabrication and human–robot interaction (HRI) or collaboration (HRC), as will be further discussed in Sect. 3.

Ross et al. [69] propose in 'Designed for Digital—How to architect your business for sustained success' that the true impact of the digital stems not primarily

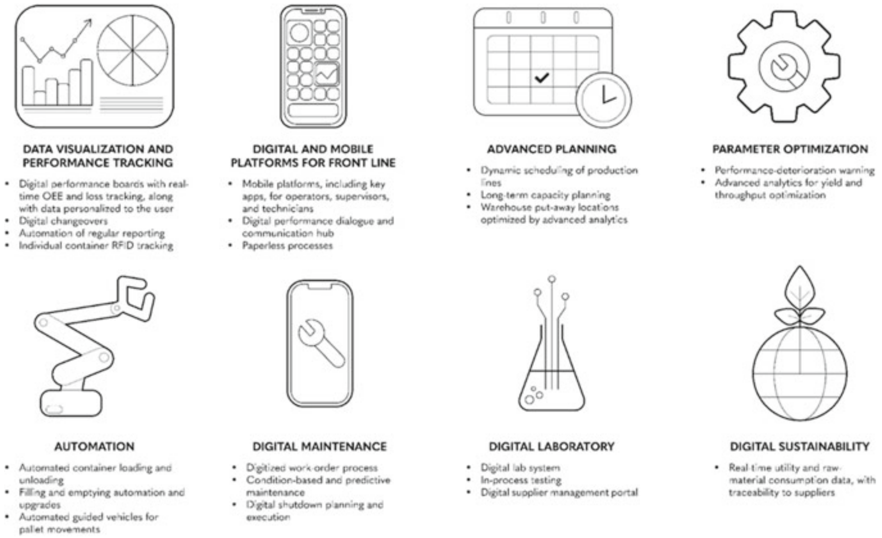

Fig. 1 Available technologies and methods for a context of architecture and construction (after McKinsey report) [53]

from application as a technology but considering these as a strategy. This is important when reviewing existing challenges in the AEC industry [15], which include field-level barriers for strategic innovation; fragmentation as a barrier for collective action; limited understanding for business models and use of digital transformation; investments not driven by strategies; lack of orchestrated or common approaches; and lack of knowledge and skills for digital transformations. Consequently, we need to move towards better discernibility for all phases of plan to production to support companies' productivity increase and add value for design, production and services.

2.2 Increased Productivity Through Cyber-Physical Systems

Internationally, the AEC industry is one of the least digitised and least efficient industries [18, 54, 55]. A growing list of performance and productivity problems are directly linked to the sector's failure to embrace advanced technology [26, 52, 72]. The current divide between advanced manufacturing's move towards Industry 4.0 and architecture's stagnation on a status quo suppresses opportunities to improve cost competitiveness and value differentiation.

In this context, cyber-physical systems (systems linked to computation) present an alternative pathway for architecture and construction; by providing an increased potential for data capture and integration [54]. Cyber-physical systems can further adopt a concept of *digital twin* (a highly complex virtual model that is the exact counterpart of a physical condition, object or entity, process or service). Benefits arise from data being continually updated and mapped against it, which can then be simulated, analysed and evaluated to trial different scenarios and enable decision-making. Such accessibility of future scenarios allows investigating systems performance—and consequently being able to operate, maintain and repair systems with no physical proximity and affordance. Importantly, by bridging mechanisms for communication, control and sensing via sensors, cyber physical systems further enable collaboration between design and manufacture, and interoperability through open-source libraries and hardware. The integration of cyber-physical systems into construction workflows via data processing techniques and inter-device communication allows fabricators, manufacturers and constructors to overcome process fragmentation and directly link physical production processes to computational processes [76]. Cyber-physical systems for coordination play an increasing role in construction and are adopted for surveys, task planning and networking control systems. The introduction of sensors informs on required ad-hoc changes, and enables direct, responsive, intelligent and interconnected workflows through continuous online monitoring on the basis of data acquisition. In opening for diagnostic protocols and adjustments, this allows for overcoming stereotypical, standardised or modularised building methods and construction processes. Yet despite the adoption of Industry 4.0 technologies and ongoing research and development, there remains a considerable gap between research, industry and practice collaborating for manufacturing and construction [17]. There is a strong focus on production activities, yet there is limited exploration on how Industry 4.0 principles could be applied across different phases. Hence, we ask: In which way can opportunities and challenges outside the tangible production floor and beyond CAD/CAM and robotics digital manufacturing technologies enable an Industry 4.0 framework for the AEC sector?

2.3 Smile! Lifting the Pre and Postproduction process for AEC

Implementation of Industry 4.0 solutions empowers manufacturing companies by enhancing collaboration: effectively providing relevant information for people on a real-time basis [4]. We argue that a close look into the distinct and successive phases in manufacturing holds the key to opportunities in the AEC industry in a context of Industry 4.0. Linking three core phases is essential, the pre-production phase with R&D, design and logistics; the production activities with the 'actual' production; and the post-production phase with distribution, sales and service. Since failing in one would sabotage and hinder success in the overall production process, all must be considered for Industry 4.0 as changes affect the entire supply chain, not only the tangible production activities. However, improvements in productivity become more accessible by coupling tangible production activities to include in-tangible pre- and post-production phases. As the so-called 'smile curve' in Fig. 2 illustrates, value can

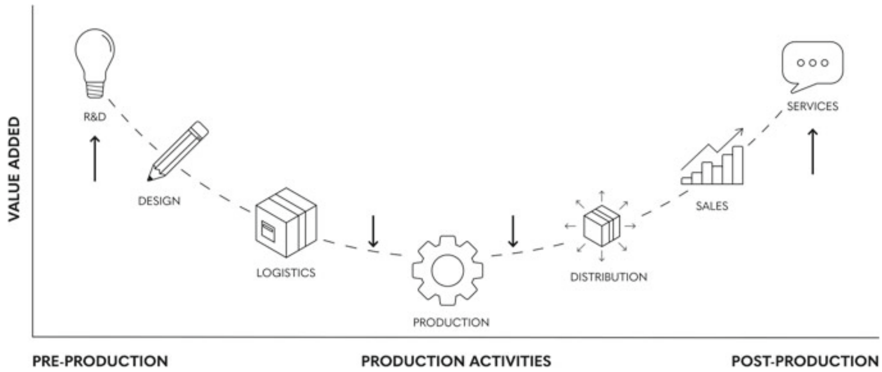

Fig. 2 Value added in a 'smile curve' for manufacturing context, embedding phases of pre-production (R&D, design), production (logistics, production and distribution) and post-production (sales and services)

be added across the different stages of bringing a product on to the market in an IT-related manufacturing industry (Industry Insights).

Daniel Chuter, CEO of the Innovative Manufacturing Cooperative Research Centre (IMCRC), refers to value increase as 'moving up the smile curve' [46], where production (including logistics and distribution) can be largely enhanced by introducing focus (resources, investments, knowledge) to pre-production (R&D, design) and post-production (sales and services). In a context of AEC industries, ignoring phases outside of core production creates a bottleneck for manufacturing industries; and a similar bottleneck exists in the form of architecture and building practices that model and manage design and construction data, used to establish, and later maintain building stock, infrastructures and services. For example, architects provide phase-based information for builder/manufacturer through design and documentation. They are thus external and as a result usually unavailable for partnering in pre- and post-production with advanced architectural manufacturing and construction. Architecture's digital practices, systems and platforms can significantly support the AEC industries (with advanced architectural practices on the basis of advanced computational modelling and scripting and fabrication knowledge, development of Artificial Intelligence, Machine Learning, and Big Data approaches to digital twins) as core technologically intersecting domains and phases via methods and processes, and so connecting parts and sectors of the building industry which are central to improving efficiency and competitiveness and increasing innovation and ensuring direct links to manufacturing [6, 53, 52]. A collaborative workflow through taking cyber-physical systems in full advantage, and early integration of R&D with a focus on modelling within the machining/manufacturing framework can raise the value of architecture and construction equally—a Next Gen architecture manufacturing approach.

Figure 3 illustrates a framework for three systemic lenses: *synthesis, management* and *analysis*, interrelated through new cybersystem technologies, digital twin and digital business models that allow for interoperability. Each of these lenses holds specific potential to align capacities and knowledge in architecture with manufacturing processes. *Synthesis (creative process)* accommodates pre-production (R&D/Design) through advanced computational scripting, parametric modelling (PM) and machine learning (ML) enhances understanding, optimisation and automation of complex, repetitive tasks and 'workflows' in practice. As a result, the creation of more efficient, reliable and machine-readable manufacturing instructions would enable manufacturers to complete new product designs and achieve operational productivity gains for small scale production [13, 60, 18, 33]. Furthermore, this phase is core for integration of industry competencies with architectural design and planning. *Management (business process)* addresses post-production (sale) and targets commercial advantages and risks of 'business as usual' models in architectural business. Changes in a combination of consumer spending patterns, economical, ecological, and external political pressures can support the AB sector to reconsider business models towards new digital 'XaaS' (Anything as a Service) models, thus redirecting towards design (synthesis) and innovative manufacturing [15, 18, 27, 70] Colins et al. (2016).

Analytics (data process) incorporates post-production (services) for simulation, analysis and evaluation of existing and new data (from CAD to BIM to PM) across the architectural service industry [43]. AI, Machine Learning, Parametric Modelling and Big Data can be adopted to establish digital twins of buildings as extracts from architectural data to use for services. Equally used for describe-for-production, these digital twins can be employed to maintain and repair their physical counterparts and increase operational efficiency [7].

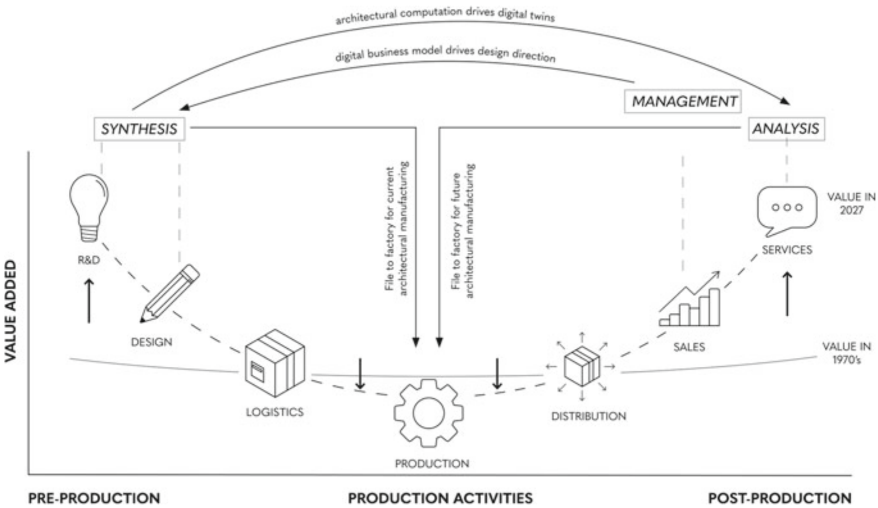

Fig. 3 Co-opting the Australian Government's Modern Manufacturing Strategy's (AGMMS) 'smile curve' [30]

Importantly, knowledge for processes and agency through technology can be increased between research, architectural practice, and industry, by closely reviewing potential intersections for architecture along the manufacturing curve. These systemic lenses inform the ‘smile curve’ and add greater value from architectural services both in pre-and post-production including ongoing maintenance, specifically for architecture to construction. Consequently, we argue for two ways to increase the potential for architecture and construction to work better together within the technologies of Industry 4.0. Firstly, by enhancing and enabling the core phase of production (ie human labour, machines, data workflow, for example robotics and AR as is discussed in Sect. 3). Secondly, by delivering a targeted approach to intangible and tangible production activities such as robotic fabrication, collaborative robotics and interfaces for architecture.

3 Industrial Robotic Fabrication and Human Robot Collaboration

The AEC industries continue to be slow in integration of six axis industrial robotic arms and defining robotic tasks due to perceived barriers including safety, costs and skill applications [62]. Yet six axis industrial robotic arms, robotic fabrication technologies, sensor systems and haptic interfaces can change the way in which architectural design practice, manufacturing and construction are conducted, through robotic fabrication methods and technology; mobile and onsite robotics; and human–robot collaboration, as is discussed in the following.

3.1 Robotic Fabrication for Architecture Development of Material Applications and Construction Methods

Digital fabrication tools (CAD, CAM) have continuously risen in popularity for manufacturing and fabrication, with articulated arm robots that are reliable and flexible; can effortlessly execute an unlimited variety of non-repetitive tasks, and which have become increasingly affordable, accessible, and usable. Initially adopted for high precision, autonomous workflows and independent locomotion in the automotive industry, robotic applications are now considered a catalyst technology that leverages mass customisation to a more elaborate and even architectural scale. Current robotic system providers include ABB, UR, KUKA, Boston Dynamics, Fanuc, with a large range of differentiated robot specifications and types. These industrial robots provide the ideal combination of human and machine labour, connect to a wide bandwidth of general-purpose technologies of Industry 4.0 (AI, ML, Data, AR/VR) and consequently can support the AEC with a potential for further developing/customising a wide variety of existing building and construction materials. It can

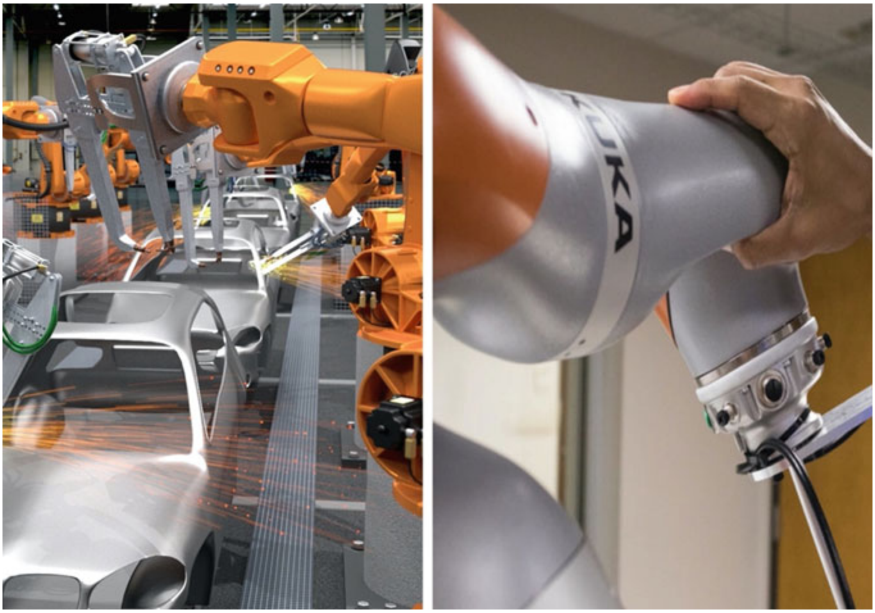

Fig. 4 Development of robots from automotive to architecture: task and workspace restrictions (left) towards intuitive haptic interfaces (right)

already be observed that construction automation technology, STCR approaches, service robot systems, and other microsystems technology are merging with the built environment, becoming inherent elements of buildings, or building components [8] (Fig. 4).

Global research into robotic applications has been developed between multiple partnerships (variably with industry, research, academia, software and robot developers, or architectural practices). Designing for robot production (architecture) and operating robot setups (fabrication) has become accessible through multiple programming languages such as C/C++, Python, Java, C#/.NET, or directly intersect with architectural modelling and scripting data (on the basis of McNeel Rhinoceros and GH plugin), Robot Operating System (ROS); robot programming coupled with motion simulation such as KUKA|prc; or KUKA|crc: Cloud Remote Control.

In the last decades, research on robotic fabrication with six-axis industrial robotic arms has been thoroughly investigated with new potentials for processes, systems, materials, construction methods [31, 16, 74, 78]. This laid the foundations for an enormous spectrum of potential applications for bespoke and customizable fabrication processes and robotic control protocols and has been widely disseminated through bi-annual proceedings [10, 52, 1] and across journals (Springer Construction Robotics; Automation in Construction; Robots in Construction). A non-exhaustive overview for research robotic applications between 2012 and 2018 shows:

- Robotic brick laying [31, 78, 21]

- Robotic modular timber assembly [31];
- Robotic wood processing [64]
- Robotic assembly (Gandia et al., 2018; Snooks Jahn, 2016)
- Robotic subtractive cutting/milling (Clifford McGee, 2011; Clifford et al., 2014; Feringa McGee, 2014)
- Incremental sheet forming (Kalo Newsum, 2014; Nicholas et al. 2016; Ficca 2017);
- Robotic bending (Culver et al., 2016; Tamre et al. 2013);
- Robotic 3D printing (Johns et al. 2012; Oxman et al. 2017; Hyperbody/Bier/Mostafavi, 2015; Dubor 2016; Branch technology, 2015; Feringa, 2017; Huang et al., 2018; Alothman et al. 2018; Battaglia et al., 2018; Gaudilliere et al., 2018)
- Robotic (carbon fibre) weaving (Yablonina, 2016; Doerstelmann et al. 2016; Witt, 2016; Reinhardt et al., 2018).

As a consequence, research on robotic fabrication protocols, systematic applications of a variety of end-effectors that can inform standard construction processes (assembly, positioning, punching, drilling, cutting, sawing, fixing, plastering) and non-standard productions (3D printing, wire cutting, weaving/threading) together with an understanding for workspace scenarios, workflows and operative has been widely disseminated. However, several challenges remain, including (a) knowledge and skill transfer from research to industry applications for methods and techniques of robotic protocols; (b) upscale to industrial building processes and building site; and (c) increased human–machine or human–robot interactions with intuitive feedback and interfaces.

3.2 Onsite Robotics-Large Scale Construction

While the construction industry has not kept up with manufacturing in adopting robotics despite the promise of improvements in quality and enterprise performance and a shortened time-to-market for products [11, 58] this is partially due to underlying conditions that differ strongly in the two sectors: manufacturing uses closed work settings, construction is produced in multi variant, unstable and uncertain environments. Standard construction sites pose challenges for operating industrial robots due to complexity as a consequence of unstructured environments, and thus limiting transfer and direct adaptations to this sector. Other typical characteristics of construction industries impede the adoption of robotics such as a high volume of manual operations, inconsistent deviations and variability of the construction site over long periods, large and heavy building structures, and in general limitations resulting from outdoor operations [50]. Other barriers exist due to scalability—robotic arms and thus workspace and range are restricted to the systems in which they are mounted, for example on a crane, track rail or gantry system, and so robotic reach and work scale is determined by the platform. However, significant achievements to date include gantry based modular components (Sequential Roof, Gramazio Kohler), integrated robotized construction site [28], or mobile robotic construction units [21].

An exert overview of industrial robotic applications with large-scale construction and buildings includes: HadrianX's FastBrick (2018, Australia) demonstrated in a commercial application for a mobile robotic system for construction of block structures from a 3D CAD model in unstructured environments with construction of a residential unit in three days. Odico Construction Robotics (2021, Denmark) developed Factory-on-the-Fly as a platform technology for mobile on-site robotic construction, driven by Sculptor® operating system for constructing with a robotic cell through intuitive interface programming (iPad). DFAB House by NCCR/ETH researchers (since 2016-, Switzerland); a 1:1 demonstrator for implementation of novel robot driven construction methodologies, including In Situ Fabricator (an autonomous on-site construction robot), Mesh Mould (a formwork-free, robotic process for steel-reinforced concrete structures), Smart Slab (integrated ceiling slabs fabricated with 3D-printed formwork); and Spatial Timber Assemblies (robotically fabricated timber structure). SQ4D Inc. Autonomous Robotic Construction System (ARCS) (USA); Robotic 3D printed residential house with use of sustainable materials (mold and fire resistant) and assumed 70% reduction of cost and labour. MX3D/Laarman MetalXL (Netherlands [18] combines a standard industrial robot and power source for 3D metal printing, showcased with a 3D printed steel bridge.

On a smaller scale, robotic technologies that aim to assimilate conventional construction approaches for building construction represent a larger percentage of the developments. These often focus on singular construction activities, tasks or components, such as protocols developed for a single, formatted and modularised material (bricks and blocks), for fluid-controlled material deposition (concrete and clay printing), or for customised protocols (steel-welding), preparation for masonry walls (marking, fixing), plaster deposition or tile laying. Principle knowledge exists in research for robotic fabrication, yet this does not extend to actual knowledge for AEC industries, nor does it connect to performance criteria or values (use, location, cost, durability, performance, materials, construction method), or to business models (integration, service, maintenance). Only recently research has moved from closed robotic protocols to knowledge-based systems [23], which originate with workers' embodied expertise. More research is needed to streamline construction workflows, such as innovative use for robotically processed construction materials, adopt improved robotics interfaces and hardware, to achieve sufficiently versatile, on-site, and human-interactive robotic systems.

3.3 Cyber-Physical Pathway for Robotic Fabrication

Commercial building processes are commonly conducted by multidisciplinary teams (architects, engineers, consultants, and on-site/off-site contractors) and consequently the way in which construction information can be successfully communicated to builders or contractors is highly relevant. Data feedback on issues of material affordances, labour and production protocols, or unpredictability and uncertainty across construction sites through cyber-physical systems thus represents a huge potential for connecting human workers, robots, machines, materials and control devices (tablets, computers) for collaborative workflows [75]. Importantly, while this can enable architects to create, test and build in a virtual environment and so support evidence-based collaboration and inclusive decision-making, this also enables architects to connect to data controlling design to fabrication processes inclusive of resource data; enhancing existing building information models with operating data; and overview of lifecycle demands comparative analysis.

Whereas the full control of the computational or building information model, fabrication method, and assembly can be affordable, a highly specialized workflow and customised robot setups in industrial or commercial projects can present challenges related to economics and time. In this context, the adoption of robotic fabrication, and recent developments for human–robot collaboration hold significant potential to change in construction industries. In the last five years, increased efforts have been made to connect robots to the bandwidth of cyberphysical systems with the aim to move beyond static systems, closed operations and linear protocols (Fig. 5).

Coupling digital monitoring, sensor feedback and haptic interfaces with physical robotic manufacturing methods enables robots to sense, analyse and respond to changes in movement, tasks, material resources and thus gives access to new possibilities for production. This includes the potential for startups and entrepreneurship, whereby industrial robotics allows new manufacturing technologies to gradually evolve from initial tests and pilot studies to industrial processes—a new generation of construction [22]. Here, the raw production capacity of industrial robotics brings 'design and build' approaches to construction into view. Robotic startups revisit the

Fig. 5 Cooperation to Collaboration: human support of robotic fabrication process for robotic carbon fibre winding (Reinhardt et al, 2017, left), versus data capture for fabrication techniques and knowledge of motion, force and material resistance (Reinhardt et al, 2016, right).

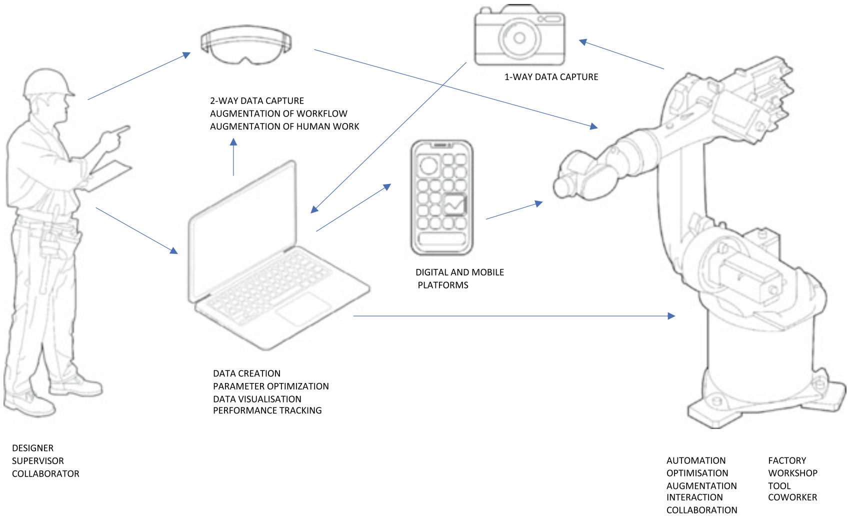

Fig. 6 Network for Human–Robot Cooperation across cyberphysical systems, digital twinning and intuitive interfaces in onsite conditions

idea of an architect-builder through computational design knowledge coupled with the means of production thus opening new career paths and in fact new professions for the AEC industries (Fig. 6).

3.4 Human–Robot Collaborations

The fourth industrial revolution changes the role of humans in operations systems, and so integrating human work contributes towards a successful digital transformation [58]. Whereas industrial robotic robotic arms were previously confined to factory settings with strict safety controls [25] and regulated in standard manufacturing environments by the ISO 15066 safety standard [66] with explicit limitations to robotic work environments to prevent accidents and injuries to human operators, this has opened with the concept of Human–Robot Collaboration (HRC), introduced by Colgate and Peshkin [14]. Collaborative relationships allow human(s) and robot(s) as one of the most important modes, where humans and robots have intersections in space and time domains through the shared work/tasks. This translates to shared working environments and shared working time for human–robot collaborations, with shared non-fenced zones and direct physical interaction. Approaches of human-centred and creative methods, user interfaces and machine learning have started to be developed in recent years, so that more direct access and control over processing of data to machinery—and with that, more direct interaction between human–robot processes—become available [29], with systems and methods for better understanding the human as active agent in the workflow with robotics.

Instead of fully autonomous or automated robot setups, collaborative robots (CoBots) in partnership with humans are the future of construction work: robots can perform tasks that are repetitive, dangerous, harmful, monotonous, or even physically impossible for a human worker while the operator would manage the more skilled work that required more finesse and experience. Instead of using industrial robots as 'human' substitutes, robots can be used intuitively and actively in an immediate interaction between design and motion. The current (r)evolution in human–robot interaction shifts the procedural/prescriptive programming of robots (typically via 'recipes' written in industrial robot languages) towards declarative/if–then scenarios and criteria based robotic protocols.

3.5 Lifting the AEC Smile Curve Through Robotic Interfaces

Human Robot Collaboration (HRC) recenters building and manufacturing processes from the product towards a human or user-centric process. Emergent interactive strategies explore sharing of tasks and actions where humans and robots have intersections in space and time and here, the concept of coexistence manifests as a shared working environment and shared working time. Importantly, this means that the smile curve can be significantly lifted through direct integration of production knowledge at the early stages R&D and Design, as a direct and iterative loop for logistics and production. To achieve this, the integration of data, but more importantly interactions or collaborations between human and machine, digital twinning in the form of data visualization of workflows, positions, and reconsiderations of robot workspace and movement protocols in relation to human co-workers is crucial. This means that robot-specific software that couples particular robot programming with robot products, such as aforementioned RobotStudio, ABB robots or KUKA|prc software needs to be expanded to directly and intuitively interact with the user—and thus bringing trained/skilled/embodied knowledge systems from the factory floor/construction site to the architect's office. While these distinct robot languages commonly require a specialist to operate the software and create robot instructions, this is about to change. Recent research explores Java programming via KUKA LBR-iiwa, using seven axes with integrated force-torque sensors to safely safe interact and further enabling entirely new applications that use hand-guiding and utilize the force-sensors to compensate for high tolerances on building sites, like manual assembly tasks [9]. Other alternative methods of interacting with robots that reach beyond previously required complex bus systems or industrial data interfaces include vision-based safety systems for human–robot collaboration [34]; haptic programming approaches where a collaborative robot physically manipulated/taught a movement based on feedback loops between the robot controller and its associated force sensors [19], vision systems [49], application of alternative robot programming through tablet [60] and augmenting robot processes through AR via Microsoft Hololens [42], fologram; [37]. The collaboration for the same goal [5] and research into classification of collaboration levels [40] changes the directive of human–robot collaboration from subservient strategies or a confined placement. Distinguishing between the different levels is important because of the requisite safety issues and for the purpose of designing and evaluating the worker aspects of human–robot interaction (e.g., acceptance and workflow), but moreover, for facilitating best practices to implement future human–robot collaboration on the factory floor [2]. The organisation of industrial robots in a human–robot team approach [78] frees interaction space considerably, where human and robot have agency, task sets and are single, team or multiple constellations (for example a singular robot, a robot-human team, or a multiple robot-multi operator setup). This includes turn-taking, handover, or multi-party and situated interaction [73]. Current developments for defined relationship frameworks include reference models for human–robot interaction [20, 18], and systematically define interactive intention between human and robot [75],with models of 'leader–follower' (human to robot), or status descriptions for both agents including 'active' (leader status), 'inactive' (rest), 'supportive' (following prompts/external control) or 'adaptive' (changing roles). Moreover, this requires a different form of robotic interaction and entails a move from robot to control a process segment, towards development of a communication language with task content, specified interactive nodes, and task process transition between agents (and here is where haptic interfaces are extremely useful in instructing the robot through discrete visual systems adaptation with special symbols and prompts).

4 Discussion

In the following, we discuss the potential of robotic fabrication and human–robot collaboration for new strategic prompts in Industry 4.0, core objectives for the AEC sector, and the Big Picture Thinking for better integration for SDG 9 (industry, innovation and infrastructure) and Climate Change.

4.1 Moving Robotic Technologies Forward

Robotic fabrication, as has been discussed, has solvers for applications in advancements in the construction industries. The increasing need for agile production equipment can be addressed by collaborative robots in dynamic environments, working alongside human workers, and while this require reconfiguration and agile control methods, plug and produce frameworks are currently developed with exchange of hardware modules coupled with agent-based system extending the robot operating system [69]. Consequently, multiple pathways for production chains could be orchestrated, and applications that are highly customised to serve the special user needs, solve specific issues and tasks can be optimised through multi-agent reinforcement learning [24]. What is required are frameworks for integration, collaboration between construction trade and architecture practices to enhance synthesis (creative process) and production processes. A focus on the construction of hardware (sensing technology, end-effector design, etc.) and software (programming AI algorithm) needs to implement tasks and balance exploration and innovation for human–robot collaborations, and methodology and system configuration, to achieve a coordinated development of AEC.

4.2 Developing Core Objectives for Industry 4.0 Frameworks

In addition, core objectives can be outlined for the AEC sector, given the technological advancements available through robotic technologies, cyberphysical systems and digital twinning for tangible production. Firstly, training, upskilling and transfer of process knowledge between architects and manufacturers needs to be increased, to make them fit to deliver complex, high value-add architectural manufacturing. The integration of both business operations between intangible and tangible production will be extremely valuable and further fuelled by population growth and increased demands on the industry. Secondly, contributing to digitalise architecture and engineering firms can increase productivity and potential speed of project delivery, by creating manufacturing-specific design tools and frameworks. The World Economic Forum estimates that full-scale digitalisation has the potential to generate 12–20% in annual cost savings in the construction industry. Thirdly, establishing the methodological foundations for a profound rethinking of the design process in the AEC sector. This chapter has presented a new paradigm, adopting an integrative and cross-sectoral approach encompassing digital business models, computer science, architecture, and engineering for architectural manufacturing. It consequently works toward a future industry where organisations, products, and services are arranged around specific projects or problems rather than distinct disciplines. Fourth, research is required into how to remove the bottleneck between design as an intangible pre-production process with tangible production activities, where cross-lateral training between architects and manufacturers will make construction and production cost effective, feasible and innovative. Lastly, we aim to contribute to accelerate digital transformation in AEC businesses by developing industry and organisational interventions. The digital transformation investigation will include business models (e.g. platform models), future scenarios, ecosystem collaboration (e.g. open innovation) and processes that will enhance organisational efficiency, agility, growth, and profitability.

4.3 Investing in SDG 9 to Counteract Climate Change

Industry 4.0 and circular economy knowledge can radically transform waste management [51], reduce resource consumption in a manufacturing context [45], or contribute towards achieving the Sustainable Development Goals. Understanding opportunities in the tangible and intangible pre- and postproduction in the architecture business sector and enhancing collaboration between different stakeholders is an immediate and important means of systematically connecting technologies available through Industry 4.0–with the larger scope of moving construction towards better resource management, circular economies, and increased building performance. Computational architecture practice coupled with advanced manufacturing and robotic fabrication strategies can unlock opportunities for AEC, when instrumentalised not merely as a technological pathway, but as strategies that can inform and change the way in which we operate. If the AEC sector plans to unpack via computational methods, strategies, and tools, quantity and type of resources in buildings and by applying modern manufacturing strategies—to build less, with less and with new materials and material systems—to mitigate resource demands of the building sector—then we need to develop a strategic framework first for upskilling all parties involved. To this extent the development of integrated, cross-disciplinary, innovative training frameworks from technology to strategy will address the building sector's request for advancement and at the same time provide pathways for answering the current climate problem.

5 Conclusion

This position paper has explored the utilisation of technologies for Industry 4.0 towards advancement of AEC industries, with a focus of applications of cyber-physical systems, digital twins and architecture robotics. We have discussed state-of-the-art tangible production processes in the domains of robotic fabrication and manufacturing, and ways in which these systems impact on challenges and opportunities outside the tangible production floor, with contributions in the form of a framework that integrates pre-and post-production phases and so uplift the manufacturing/construction smile curve, adding value for the AEC sector. We have outlined potentials for increased knowledge integration between architecture practice and the construction sector and defined objectives and potentials for the digital as major change agent in the AEC sector's role and impact in a climate change context.

Increasingly buildings will have a digital twin, a virtual model designed to accurately reflect a physical object. Building file to factory capabilities within architecture will help manufacturers to viably engage in design-led production via file to fabrication, so a pathway to develop sector-specific IP and training for AI-driven specialised architectural manufacturing out of digital twins will be an important aspect of architecture in a context of Industry 4.0. Data on building performance under changing environmental conditions will enable a deeper understanding for individual buildings but more importantly of larger building groups and their interferences, enabling better overview of complex data for building collectives and urban scapes that can respond for subtle and extreme changes, such as increased heat, floods and bushfires of the past years. In that scenario, digital twins could not only pass data back to manufacturing, but robot fabrication could be continued into robotic maintenance, human–robot collaboration embedded in buildings, and extend to different robotic ecologies—including industrial arms, drones, robot swarms and augmented support through interactive and haptic interfaces.

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