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TRR 277: Additive manufacturing in construction

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Abstract

The building industry is one of the least digitalized sectors of the global economy to date. Unlike other industrial sectors, the manufacturing of buildings is characterized by traditional handicraft techniques and individualized construction processes. Digital production technologies from other industrial sectors have not become established in the construction industry because they do not allow the necessary individualization or are uneconomical to transfer to construction. The advantages of additive manufacturing (AM) technologies are that automation and individualization are not contradictory. Furthermore, a new design strategy is embedded in 3D printing, namely to build up material only where it is structurally or functionally needed. AM is, therefore, both economical and resource-efficient. The DFG Collaborative Research Centre/Transregio TRR 277 Additive Manufacturing in Construction (AMC) of the two universities TU Braunschweig and TU Munich wants to research the technology of AM fundamentally and also contributes to the digitization of the construction industry. This article gives an overview of the goals, work programme, and methods of the TRR 277, as well as its three focus areas and 18 scientific research projects.

KEYWORDS

3D concrete printing, additive manufacturing in construction, computational modeling, process control, robotics, digital design, and construction, particle bed–based 3D printing processes, depositing processes, TRR 277

1 | INTRODUCTION

The protection of our climate through the significant reduction of CO_2 emissions, the efficient use of our resources, and, in this context, the transformation of our linear material flowing into circular economies are the most important global challenges of our time. The construction industry has a particular role to fulfill here. According to the International Energy Agency, the building and construction sector is responsible for almost 40% of energy and process-related CO_2 emissions, 38% of global greenhouse gas emissions, 12% of global drinking water consumption, and 40% of waste generation in industrialized countries.[1–5] As the demand for new buildings and infrastructure structures will continue to increase in the coming decades due to the growing world population, there is a strong need for innovative construction techniques that minimize the use of resources as well as for low-waste and low-emission manufacturing processes.

The traditionally handicraft construction techniques are not able to meet these challenges economically. And economical technologies from

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industrial series production are not suitable for the building industry, as they either do not enable the necessary individualization of buildings or can only be implemented uneconomically, such as the CNC-supported production of free-form formwork made of polystyrene.[6,7] The technology of additive manufacturing (AM, 3D printing) is fundamentally different because the construction of a component takes place purely through the digitally controlled layer-by-layer application of material, without prior mold construction or subsequent forming processes. This new technology represents a paradigm shift from traditional construction processes, which are characterized by predominantly manual construction techniques with system formwork in concrete construction and standardized, industrially manufactured semi-finished products in steel, timber, and masonry construction. The great advantage of AM processes is that automation and individualization do not contradict each other, and AMC is, therefore, ideally suited for the high degree of individualization in the construction industry. While, for example, in traditional concreting, the space between the formwork elements is completely filled with material, in 3D concrete printing, the material is only built up where material is structurally or functionally required. This can significantly reduce the concrete masses in 3D-printed components up to 60%.[8] In this respect, the technology of AM is ecological and economical and has the potential to fundamentally change the way we build in the future. In order to fundamentally research AMC as a novel, digital manufacturing technology for the construction industry on the necessary large scale, the German Research Foundation (DFG) has established the Collaborative Research Centre/Transregio TRR 277 Additive Manufacturing in Construction (AMC) of the two universities TU Braunschweig and TU Munich as of January 1, 2020. Collaborative Research Centres (CRCs), as well as the special Transregional Collaborative Research Centre (TRR) established here, are long-term research initiatives of universities, designed to last up to 12 years, in which scientists and scholars work together within the framework of an interdisciplinary research programme. They are intended to enable the processing of innovative, demanding, and forward-looking projects through interdisciplinary collaborative research.

2 | SCIENTIFIC OBJECTIVES OF THE TRR 277

The introduction of AM in the construction industry does not only require technological developments. It also implies the search for new design strategies and forms of 3D-printed components and buildings. We are at the beginning of a new technological development era, and the first 3D-printed buildings, such as the apartment building in Wallenhausen, projected by the company PERI/COBOD, are still strongly characterized by the familiar shapes of our houses produced with traditional construction techniques. In this respect, the architectural forms of 3D-printed houses will evolve rapidly in the coming years. The scientific goal of the TRR 277 is to explore novel design strategies for AM technologies and to research end-to-end digital processes from design to production. In particular, the merging of AM technologies with parametric design and BIM planning methods makes it possible to align the complexity of components no longer according to the traditional handicraft manufacturing techniques but according to design-driven digital fabrication of novel lightweight and resource-efficient structures (Figure 1). The integration of further functions, especially from building physics and building technology, into the structural design is also a part of the scientific objective of the TRR 277.

Compared to existing AM manufacturing processes in other industries, there are still fundamental challenges to be solved for construction.

Firstly, the transfer of AM technologies to the large scale of the construction industry (the Challenge of Large Scale); *secondly*, the necessary diversity of materials, which is determined by the complete functional requirements of a building; and *thirdly*, the necessary high degree of individualization and flexibility in the construction industry. Against the background of these challenges, the established TRR 277 is pursuing two fundamentally new approaches, which are addressed in its three focus areas A, *"Materials and Processes,"* B, *"Modeling and Control,"* and C, *"Design and Construction"* (Figure 2).

1. Material and process combinations: The central topic of the research programme is the development of materials and

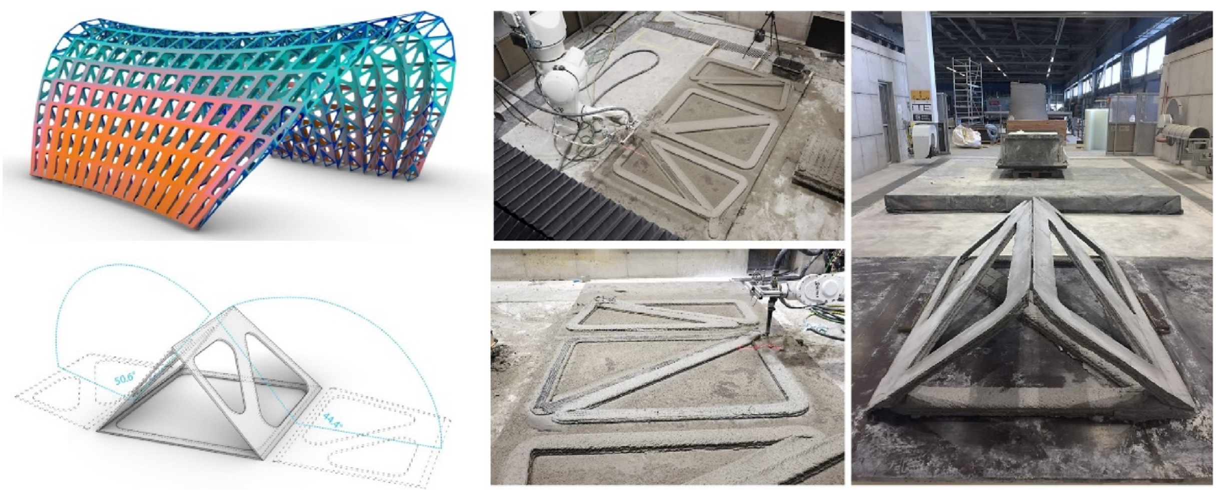

FIGURE 1 Design of a light triangulated concrete structure, consisting of flat-printed and folded carbon reinforced concrete elements, manufactured at the DBFL of the TU Braunschweig (photo: N. Hack)

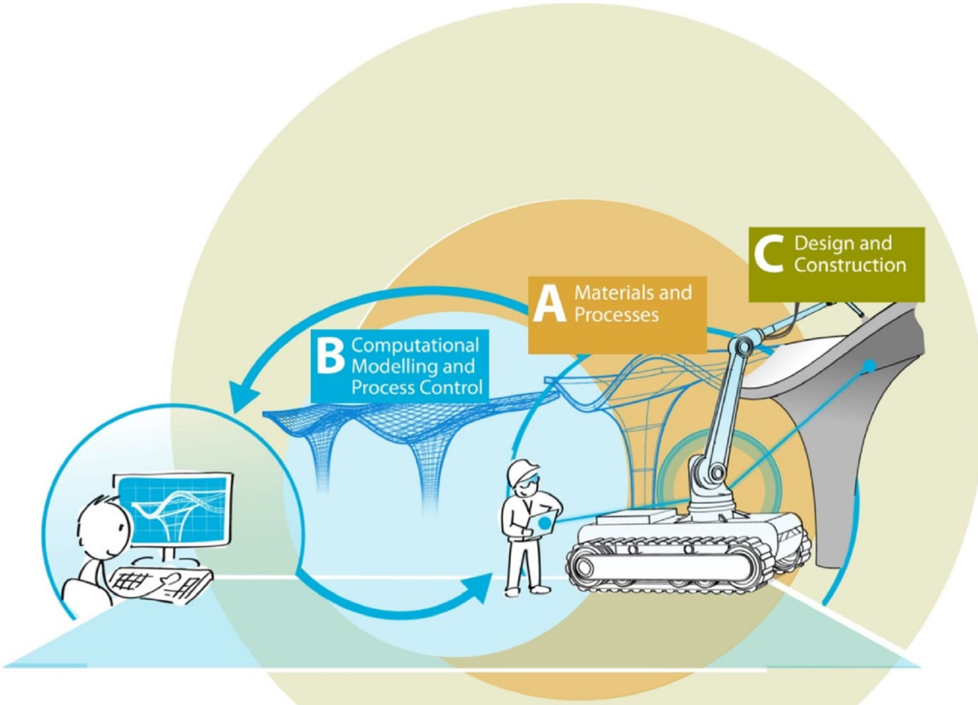

FIGURE 2 Interlocking of the TRR 277 focus areas: A, "*Materials and Processes*," B, "*Modelling and Control*," and C, "*Design and Construction*" (pic: TRR 277)

manufacturing processes as inseparable entities. In the central focus area: A, "*Materials and Processes*," various material-process combinations are therefore being investigated. Focus area B, "*Modeling and Control*" is intended to ensure the robustness of AM processes through associated modeling and simulation projects, as well as adaptive manufacturing strategies by means of online process control.

2. End-to-end digitalization in the construction industry: Continuous digitalization is of decisive importance for the successful introduction of AM in the construction industry. Focus area C, "*Design and Construction*," therefore, studies about the digital interfaces to the upstream planning processes and the downstream processes of the construction sites from the very beginning. The interaction between physical objects and digital models on different scales forms the methodological link of the TRR 277 and provides the networking across the focus areas A, B, and C. Large-format additively manufactured demonstrators and their digital twins repetitively bring together the research findings of the three focus areas.

3 | STRUCTURE AND METHODOLOGY OF THE TRR 277

In order to pursue the above-mentioned scientific goals and to be able to answer the questions posed, a coordinated network of scientists is required who, with their respective expertise and research methods, jointly work on the highly complex interrelationships in interdisciplinary teams. To this end, around 30 researchers from the fields of civil engineering, architecture, and mechanical engineering from the two universities TU Braunschweig and TU Munich have joined forces in the TRR 277 in a total of 18 individual research projects. Both locations are equipped with complementary large-scale research facilities. At the core of the research is the scientific examination of the AM of large-scale components, initially with the construction materials most commonly used in the building industry: reinforced concrete, steel, and wood. Within the framework of the research, materials are to be characterized and adapted to the respective printing technologies. This includes, among other things, the systematic material analysis of the raw materials utilized. In addition, it should be possible to describe the material behavior before, during, and after printing using modeling techniques. Research into material and process combinations includes important material-to-material interactions, especially when different materials are manufactured together at the same time or subsequently under production processes that, in some cases, interfere with each other. Ultimately, the 3D-printed components must be able to fulfill their intended function. In order to be used in practice, the intended performance of the components must also be verifiable. In other words, it must be possible to approve compliance with the requirements of the building authorities. Here, too, basic research is necessary in order to develop new design models and to integrate additively manufactured components into our regulations and standards (Figure 3).

The structure of the TRR 277 focus areas is described in detail below.

4 | PRESENTATION OF THE FOCUS AREAS OF THE TRR 277 (FOCUS AREAS A, B, AND C)

4.1 | Focus area A materials and processes

Focus area A "*Materials and Processes*" focuses on fundamental research on different material-process-combinations in AM in

FIGURE 3 Approval tests for material certifications (ZiE) for 3D-printed concrete components, carried out at the TU Munich (pics: D. Weger)

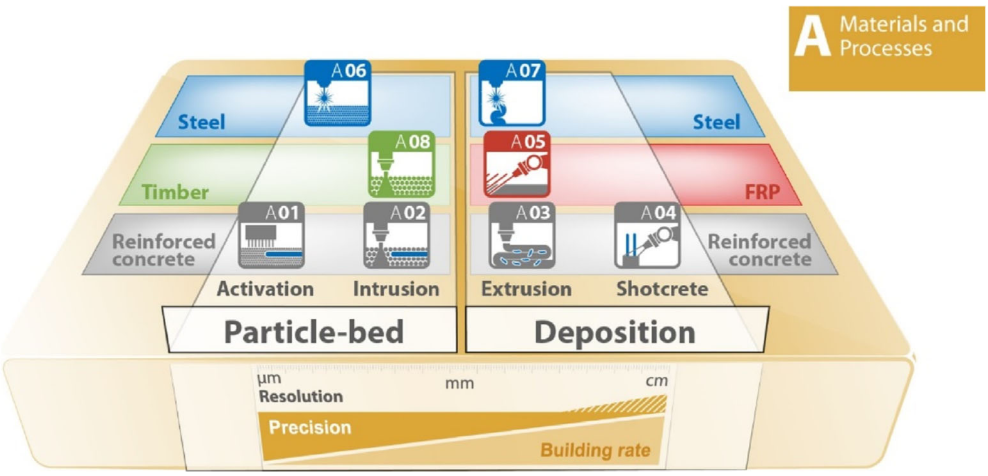

FIGURE 4 Structure of the TRR 277 focus area A: Basic classification of the A projects with regard to material, printing process, and resolution/building rate (pic: TRR 277)

construction. The basic research philosophy here is to no longer examine material and process separately, but to view them as inseparable parts. In the opinion of the researchers involved, this is mandatory in order to harness the great innovative potential of AM in construction. Accordingly, focus area A in particular is characterized by highly interdisciplinary research teams.

Another premise in focus area A is to investigate into a wide range of material and process combinations from the very beginning and not to limit the research to single materials and/or processes. Therefore, in the first funding period, a great range of materials traditionally used in construction, from concrete to steel to wood, will be considered (Figure 4).

Based on the state of research and the results of preliminary research projects carried out by the scientists involved, two groups of AM technologies were identified as suitable for an implementation in construction (Figure 5): (1) particle-bed based selective solidification processes and (2) deposition processes.[9,10]

In particle-bed-based selective solidification processes, thin layers of bulk material are selectively solidified and joined with the layer underneath by locally limited application of a liquid or energy.[11,12]

The main advantages of these processes are their high resolution and a great freedom of form. Therefore, these technologies are particularly suitable for the fabrication of geometrically complex structural elements (Figure 6). The particular challenges here are to further improve the material properties, to scale up to the large scale, and to increase the building rate. The particle-bed-based processes include selective cement activation (SCA) (project A01) and selective paste intrusion (SPI) (project A02) for concrete,[11–17] laser powder bed fusion (LPBF) (project A06) for steel and individual layer fabrication (ILF) (project A08) for wood.[18] The research on these projects is carried out in cross-location teams in Braunschweig and Munich.

In deposition processes, on the other hand, parts are built up successively by depositing suspensions (eg, fresh concrete) or molten solids (eg, steel). The deposition processes have advantages in respect

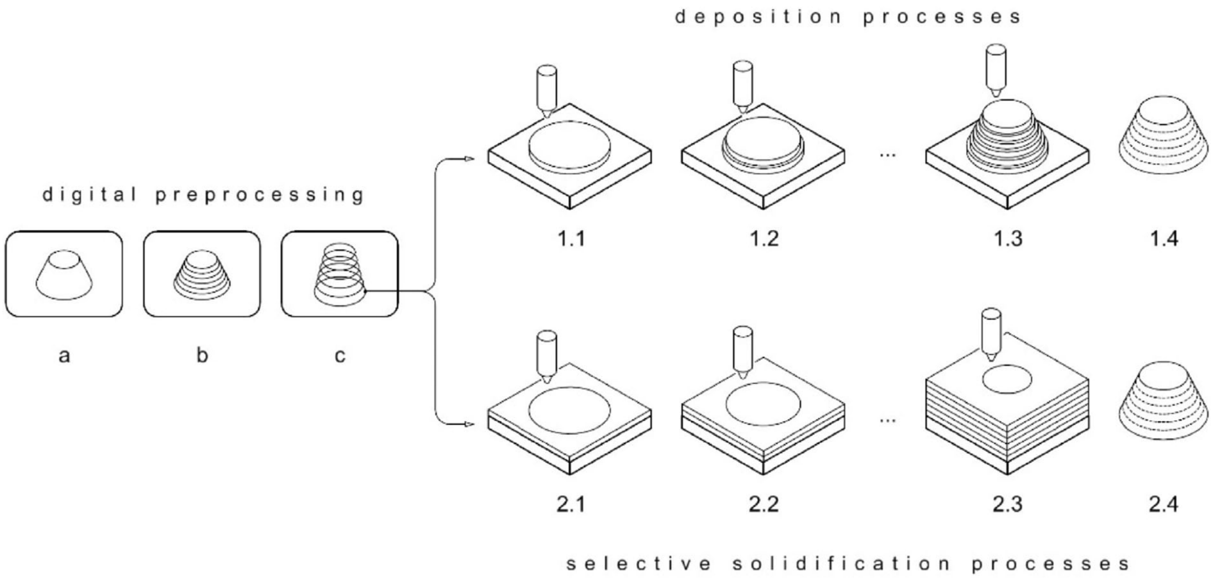

FIGURE 5 Process steps of AM processes: (A-C) digital preprocessing, (1.1-2.4) physical fabrication process, (1.1-1.4) by depositing of material and (2.1-2.4) by selective solidification of material (pic: K. Henke, TUM)

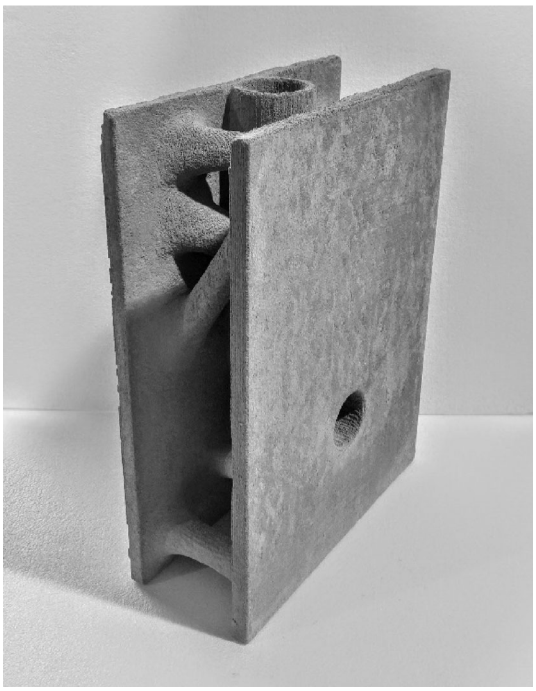

FIGURE 6 Wall-element with integrated tube, additively manufactured by selective cement activation at the AMC-lab of TUM (pic: D. Talke, TUM)

of construction speed. However, they still show weaknesses in terms of geometric freedom and surface quality. From this group of processes in the TRR 277, extrusion (project A03) (Figure 7A)[19] and shotcrete 3D printing (SC3DP) (project A03) (Figure 7B)[20–22] are being investigated for concrete as well as wire and arc additive manufacturing (WAAM) (project A07)[23] for steel. Research projects addressing deposition processes are located at both TRR 277 sites.

A cross-project topic of particular importance is the integration of reinforcement in the AM of concrete elements. All projects in the TRR 277 network that research AM with concrete (projects A01, A02, A03, and A04) are therefore investigating strategies for the implementation of reinforcement in the manufacturing process.[8,24,25] In addition, reinforcement integration is the central subject of project A05. In this project, a fundamentally new strategy for the integration of carbon fiber reinforcement is pursued, which employs a cooperative, robot-assisted process.

Further topics to be addressed in this focus area of the TRR 277 are gradient materials, for example, the gradation of lightweight concrete properties, as well as the combination of AM technologies with conventional construction techniques or with industrially available semi-finished products, for example, concrete ceiling slabs with 3D printed ribs (Figure 8A) or 3D printed strengthening of industrially available steel sheets (Figure 8B).

4.2 | Focus area B computer-aided modeling and process control

The aim of the TRR 277 focus area B "computer-aided modeling and process control (*Modeling and Control)*" is to support the newly researched manufacturing methods and processes of focus area A with the modeling of process simulations and the development of control systems. Nonlinear material behavior in AM processes with steel or concrete require innovative approaches in simulation with different resolutions and scaling in order to calculate processes such as material discharge from nozzles, material application, or the temporal behavior of the material from the liquid to the solid state and to be able to integrate them into control loops. The modeling and simulation of the selective laser melting process (project B01, Figure 9A) provide the basis for automated reinforcement production. The greatest

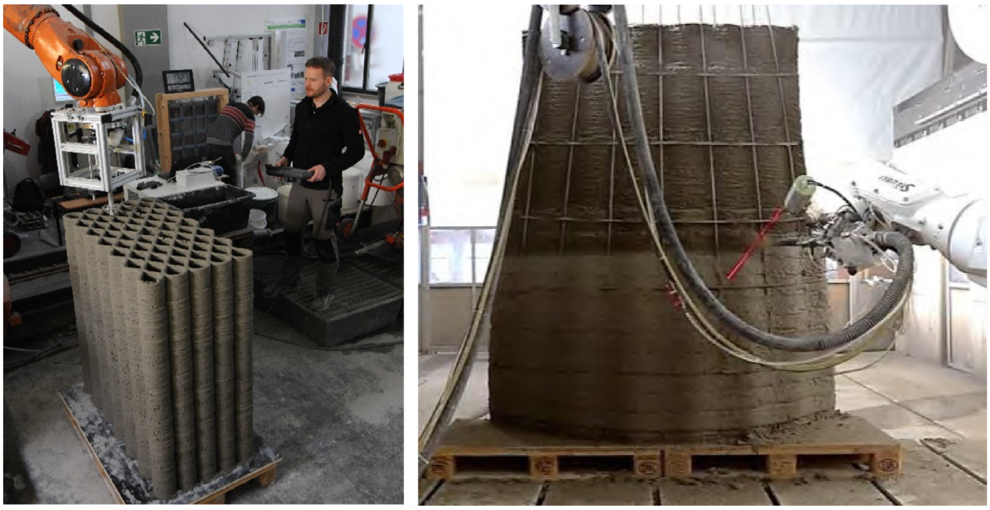

FIGURE 7 Additive manufacturing by extrusion of lightweight concrete at TUM, left (pic: K. Henke, TUM) and B, reinforced double-curved wall element, manufactured in shotcrete 3D printing process at TU Braunschweig, right (pic: ITE, TU BS)

FIGURE 8 Concreted floor slab element with ribs printed in the SC3CP process, left (pic: ITE, TU BS), and sheet steel with printed strengthening lines in the WAAM process, right (pic: ITE, TU BS)

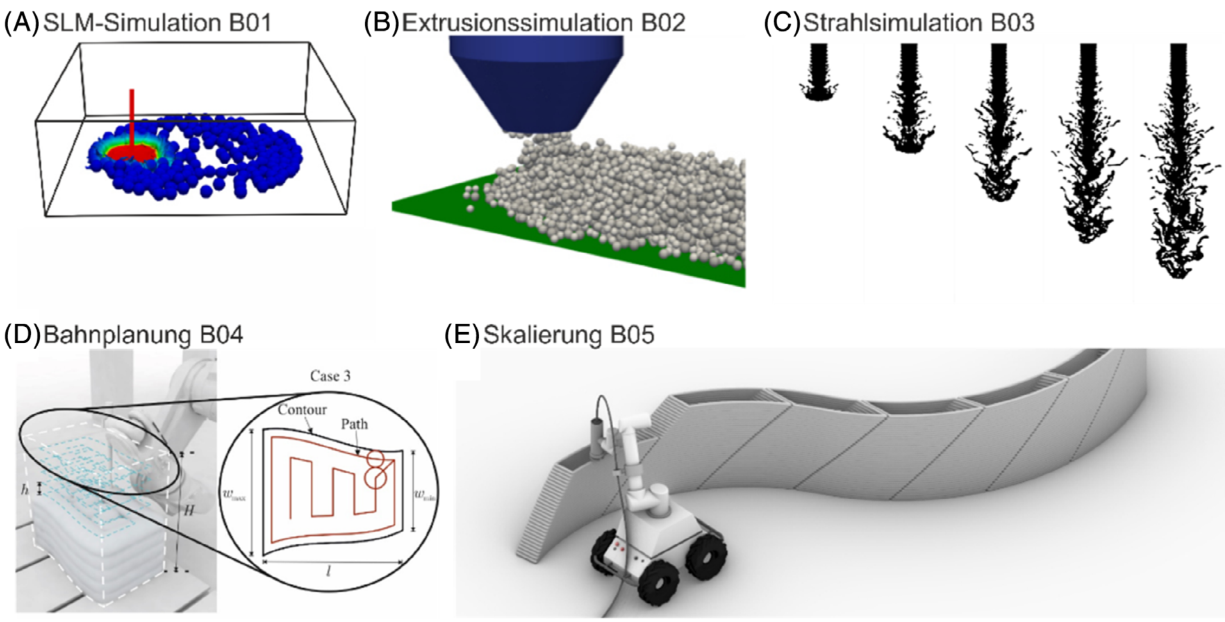

FIGURE 9 Components of the digital process image for the development of control concepts for the additive production of large scale and reinforced concrete components (pic: L. De Lorenzis, ETH; J. Fottner, TUM; M. Krafczyk, TUBS; K. Dörfler, TUM; A. Raatz, LUH)

challenge here lies in the adjustment and prediction of the component strengths generated. Complex simulation methods are also being researched for material application for extrusion processes using discrete element modeling (project B02, Figure 9B) and for 3D shotcrete printing using multiphase and multicomponent LBM-DEM methods (project B03, Figure 9C).[26]

In particular, the resulting modeling of fresh concretes during the mixing process and the material application provide an essential contribution to predicting the final contour and the final component properties. In order to subsequently guarantee a consistent component quality during production, the resulting simulation models must be optimized with regard to their computing time and transferred into path planning and control concepts (project B04, Figure 9D).[27] Advances in robotics and the latest optimisation methods make it possible to explore these control loops for robots with an extended degree of freedom and thus to operate with coordinated motion sequences with high precision in enlarged installation spaces, in favor of the realization possibilities of individualized and large-scale products.[28] The transfer of the developed concepts to mobile robots further provides the possibility for flexible on-site production without restrictions regarding the available working space (project B05, Figure 9E).[29] Furthermore, the collaboration of multiple mobile units within a network is carried out, whereby the use of various tools should lead to time-optimized simultaneous production and post processing.

4.3 | Focus area C design and construction

Focus area C "*Design and Construction*" addresses the implementation of AM in the entire digital process chain, from planning to construction (Figure 10).

In total, focus area C consists of seven projects, four of which deal with planning-related issues and three of which investigate implementation-related issues.

The projects in the area of "Design" address topics relevant to design and planning and deal, for example, with research into methods of structural optimization (project C01), form optimization (project C02), the functional integration of aspects of building physics (project C03), as well as the conception and development of novel, computer-supported decision-making aids for the selection of adequate AM fabrication methods.

Further projects in the area of "Construction" address topics of construction and investigate aspects of the force-fit joining and assembly of printed elements (project C05), as well as the target-performance comparison of printed components and larger structures produced using the AM process (project C06). Furthermore, aspects of the changing qualification requirements for skilled workers in the construction industry, as well as aspects of the quality assurance of AM products and the changing building regulations in the course of the implementation of AMC, are examined (project C07).

4.4 | Networking of the projects in the TRR 277

The methodological basis and unifying element of the three focus areas A, B, and C is the collaborative work on cross-project physical demonstration objects from focus area A with assigned digital twins. Each project in focus areas B and C is linked to the digital and real demonstrators of at least one A project. This integrated planning and execution process along the AM process chain to be investigated can be exemplified by a structural node element printed in project A01 (Figure 11).

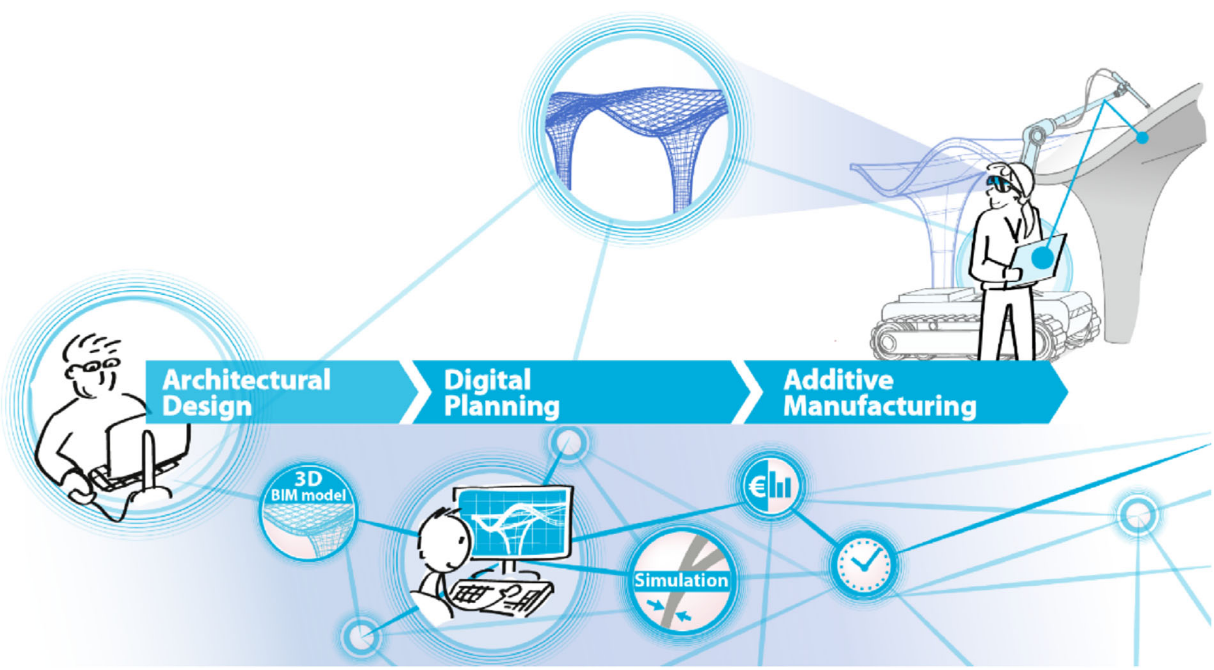

FIGURE 10 Integration of additive manufacturing technologies into the entire digital process chain from planning to construction site (pic: TRR 277)

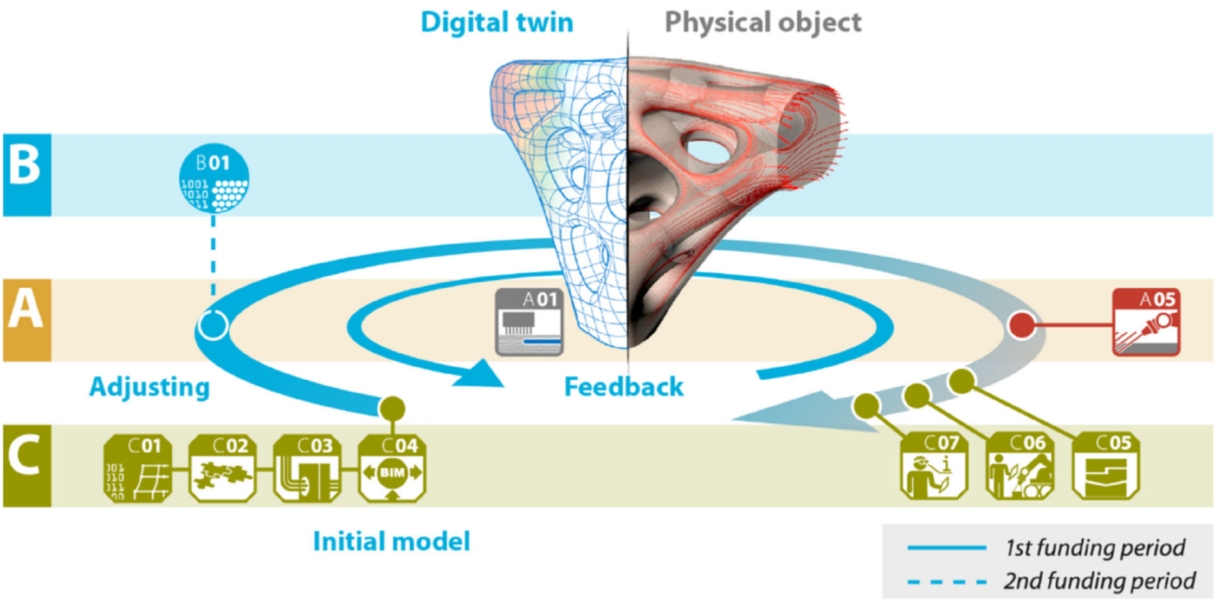

FIGURE 11 Conceptual idea of demonstrator A01 and corresponding interactions between A, B, and C projects (pic: TRR 277)

FIGURE 12 Germany's first 3D-printed house in Beckum, Westphalia, under construction. The tests for material approvals (ZiE) and the construction project-related type approval (vBG) were carried out at the Technical University of Munich. (pic: D. Weger)

The initial shape and topology of the node are generated by projects C01 and C02. Furthermore, geometric constraints resulting from the integration of additional functionalities such as component core activation, acoustic functionalities, or building service components, will be defined in project C03. The digital twin of the node is then used to merge the geometry data and relevant material and manufacturing data for production into a BIM model developed by C04. The AM process of the node is a synthesis of the knowledge gained in A01 about the SCA technique and the integration of individualized, prefabricated fiber reinforcement investigated in A05. While the aspects investigated in projects C05 to C07 are subsequent to the actual manufacturing process, they are nevertheless integrated. In project C05, the subtractive precision finishing of structural joint details, so-called "dry joints," is being investigated. Applied appropriately to the node, a connection to a conventional semi-finished product or to a printed structural element can be realized. Project C06 addresses target/actual comparison by means of photogrammetry and optical 3D measurement techniques at different scale levels of the component and the structure as well as the subsequent feedback of this information into the production process. For example, if dimensional deviations are detected at the node, these defects can be compensated for by adjusting the production of the subsequent components. Accompanying the entire process sequence, project C07 is investigating both the necessary changes in building regulations and new professional qualification concepts for AM in the construction industry through observational studies.

5 | SUMMARY AND OUTLOOK

The DFG Collaborative Research Centre TRR 277 AMC of the two universities TU Braunschweig and TU Munich wants to set the foundations to provide AM as a digital key technology for the construction industry. The fact that the technology has enormous potential to increase productivity and resource efficiency in the construction industry is already demonstrated by the first prototype 3D-printed houses in Germany, such as in Beckum (Figure 12).

In addition to the environmental and economic benefits, AM technology offers the opportunity for new design strategies in architecture and engineering. The interdisciplinary research teams of the TRR 277 are investigating novel design-driven AM approaches following the control of the flow of forces and with an efficient use of material. The integration of other functions, especially from building physics and technology, can also create novel design strategies in the future and lead to individualized architectures becoming economically feasible.

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