Integrative computational design and construction: Rethinking architecture digitally

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Abstract

Increasing the construction capacity, while at the same time significantly reducing harmful emissions and consumption of nonrenewable resources, and still providing a liveable and affordable built environment, provides a great challenge for future construction. In order to achieve this, both the productivity of construction processes and the energy and resource efficiency of construction systems have to be improved in a reciprocal process. Digital technologies make it possible to address these challenges in novel ways. The vision of this Cluster of Excellence IntCDC at the University of Stuttgart and the Max Planck Institute for Intelligent Systems is to harness the full potential of digital technologies to rethink design and construction based on integration and interdisciplinarity, with the goal of laying the methodological foundations to profoundly modernize the design and construction process and related building systems by adopting a systematic, holistic and integrative computational approach. One key objective is to develop an overarching methodology of “co-designing” methods, processes and systems based on interdisciplinary research encompassing architecture, structural engineering, building physics, engineering geodesy, manufacturing and systems engineering, computer science and robotics, and humanities and social sciences. In this way, the Cluster aims to address the ecological, economic and social challenges and to provide the prerequisites for a high-quality and sustainable built environment and a digital building culture.

KEYWORDS

co-design, digital building culture, digital technologies, integrative computational design and construction, interdisciplinary research

The challenge for building in the future is to build more, while emitting fewer pollutants and using fewer nonrenewable resources, and still create a high-quality and liveable built environment. In a mutually influencing process, both the productivity of the building process and the energy and resource efficiency of the building systems must be improved. Digital technologies offer new approaches to solving these challenges.

The aim of the Cluster of Excellence Integrative Computational Design and Construction (IntCDC) at the University of Stuttgart and...
the Max Planck Institute for Intelligent Systems is to use the full potential of digital technologies to rethink planning and building in an integrative and interdisciplinary approach and thereby laying the methodological foundations for a comprehensive modernisation of building design. A central objective is the development of an overarching methodology of “co-design” of methods, processes and systems, based on interdisciplinary research between the fields of architecture, civil engineering, engineering geodesy, production and systems engineering, computer science and robotics, as well as the humanities and social sciences. The aim is to identify solutions to the ecological, economic and social challenges and to create the conditions for a high-quality, liveable, and sustainable built environment as well as for a digital building culture.

In order to limit man-made global warming to 2°C, as agreed in the 2015 UN Climate Change Conference in Paris, we must drastically reduce greenhouse gas emissions. Unlike mobility or industrial production, climate-relevant improvements in buildings can be achieved quickly and effectively. Research and development have therefore focused intensively on the energy optimisation of building operation in recent decades. Due to the continuously tightened legal framework conditions, a nearly climate-neutral building stock by the year 2050 seems realistic from today’s perspective. The focus is thus shifting from the operation of the buildings to the construction and disposal of the building structures and the CO₂ emissions and gray energy generated in the process.

In addition, there is a high demand for additional buildings. In 2050, the world population will be almost 10 billion people. To provide dignified housing for all, a living space roughly equivalent to today’s is needed over the next three decades. This enormous need does not only arise in Africa and Asia. In Germany, too, 400,000 housing units per year need to be built, mainly due to demographic change. Currently, not even half of this demand is being met. The productivity of the construction processes must therefore be increased considerably, but in fact it has been stagnating for decades.

The climate crisis and population growth pose unprecedented challenges for buildings. Productivity and resource efficiency must be reconciled with architectural diversity, because without cultural and social acceptance, the opportunities of industrialized building cannot be exploited. This will only succeed with leaps in technology, as we are seeing in other areas, such as electromobility or the energy transition. Instead, research and development in construction is all too often limited to incremental improvements of existing methods and processes.

Compared to all other industries, construction has the lowest level of digitalisation, even far behind agriculture and forestry. This is reflected, among other things, in the stagnating or even declining productivity of the construction sector for decades and the associated increase in the cost of construction services. Efforts to increase digitisation in the construction sector are currently focused primarily on building information modeling (BIM), which concentrates on increasing the efficiency and reliability of existing processes in the planning and operation of buildings, while production processes in prefabrication or on the construction site are not yet addressed. In addition, there is a steadily growing number of initiatives that call for and promote increased digitalisation of construction. However, the small-scale structure of the construction industry and a correspondingly fragmented research landscape favors incremental approaches that mostly follow a similar basic idea of digitalisation: Digital technologies are primarily used for the “computerisation” of existing processes and procedures in order to achieve a higher degree of automation of prefabrication and site-based construction. This, too, will only be a transitional step—automated building processes for predigital construction methods and building systems are created, but the full potential of digital technologies for integration and innovation cannot be raised. In order to fully exploit the possibilities of digitalisation, fundamentally new approaches for sustainable construction are necessary.

1 | THE CLUSTER OF EXCELLENCE ITCDC: INTEGRATIVE COMPUTATIONAL DESIGN AND CONSTRUCTION FOR ARCHITECTURE

The Cluster of Excellence ITCDC aims to harness the full potential of digital technologies for integration and sustainability in design, fabrication and construction. It aims to take the construction sector beyond the mere digitisation of established processes and the associated incremental improvements to sustainable innovations that can only emerge through highly integrative research in an interdisciplinary, large-scale research cluster.

With systematic, holistic and interdisciplinary research into integrative, computational planning and building, the Cluster aims to create the methodological foundations for a comprehensive, computerisation of existing processes and existing systems, but to develop entirely new approaches to design, engineering, manufacturing and construction so that the inherent properties/possibilities of digital technologies are seized and their full potential for industry-changing innovations in architecture and construction is realized.

This comprehensive goal requires interdisciplinary research in several fields ranging from architecture, civil engineering, building physics and geodesy, manufacturing and systems engineering, computer science and robotics to the humanities and social sciences. This approach, which transcends not only subject boundaries but also subject cultures, and the inclusion of investigations into the nontechnical aspects and barriers of digitisation that this makes possible, distinguishes the Cluster from comparable initiatives, such as the NCCR Digital Fabrication in Switzerland. In addition, the Cluster’s Industry Consortium, which represents all relevant facets of the construction industry, enables a direct and two-way exchange and transfer of knowledge.

It is expected that the comprehensive interdisciplinary methodological findings and research results of the Cluster will lead to integrative approaches to the use of digital technologies that will help to address the environmental, economic and social challenges that cannot be solved with current incremental approaches. In this way, the foundations will be laid for a high-quality, liveable and sustainable...
2 | CO-DESIGN AS AN OVERARCHING RESEARCH APPROACH AND METHODOLOGY

To unlock the full potential of digital technologies for future construction, the Cluster of Excellence follows an overarching research approach of “co-design” of the following research areas: A—planning and engineering methods, B—manufacturing and construction processes, C—material and building systems. A further research area D considers building culture, regulatory, social and ecological requirements and draws on historical experience with earlier approaches to digitalisation, modularisation and automation. In this area, for example, a holistic quality model is being developed to ensure the technical, ecological and social quality of co-design processes and products. Likewise, architectural-historical cross-references to the approaches of industrial and serial building of the 1960s and 1970s are examined and reflected upon to enable learning from history from the very beginning. E—building demonstrators will be used to test the architectural integration and validate the research results.

A research culture that examines the above-mentioned research areas A to D separately can be seen as the main barrier to innovation in the construction sector. Thus, we observe that digitisation in current research usually seems to be anchored either in the area of computer-aided design and construction methods, in the area of developing digital manufacturing and construction processes, or in the area of improving material and building systems. Consequently, research results are limited to one area and mostly work incrementally. Digital manufacturing for example, is being developed with a focus on automated production of existing building systems using known design and construction methods. Similarly, database-driven design (eg, BIM) is developed based on datasets of known, predigital building systems and associated established construction processes. To realize the full potential of digitalisation, it is essential to adopt a more integrative approach that conducts research in all these areas simultaneously and in a feedback loop.

Such comprehensive innovation cannot be expected from the construction industry itself due to the current business models and associated narrow perspectives of the various stakeholders in the sector. In order to advance the construction sector in a profound and comprehensive way, large-scale basic research is required to develop methods that enable future-proof innovations.

The research in the Cluster aims to establish an overarching methodology of co-design of design and analysis methods, manufacturing and construction processes as well as material and building systems (Figure 1). In this context, co-design is also understood as co-optimisation. Our definition of co-design is an integrative approach that transcends disciplinary boundaries and silos. Co-design is based on the simultaneous and feedback driven development of generative design methods for exploration, analytical methods for optimisation, monitoring methods to capture actual behavior, cyber-physical processes of digital prefabrication and robotic construction on the building site, and also considers multifaceted stakeholder perspective. As a result, new building systems are being created for the most important architectural applications, that is, multi-story and long-span buildings, building envelopes and the densification of the existing building stock, considering social needs and expectations, environmental impacts, regulatory requirements and historical experience. Specifically, work is currently underway on long- and two-axis spanning, multi-story timber building systems, long-span, high-performance, lightweight roof support structures made of fiber composites, as well as components made of graded concrete and façade elements made of biomaterials. In the later project phases, the focus will then be expanded to include the extension of existing building stock.

Therefore, our research approach is integrative, considering multiple disciplines and phases simultaneously, and inductive, developing a general methodology from the study of specific cases representative of the following research areas: A—planning and engineering methods, B—manufacturing and construction processes, C—material and building systems, D—cross-cutting social, environmental and humanities issues, and E—building demonstrators. Source: IntCDC University of Stuttgart
of important architectural applications. In contrast to the prevailing sequential integration in the form of a digital chain, the Cluster explores co-design as a methodology for the simultaneous and feedback integration of geometric, structural, mechanical, hydrothermal, acoustic properties, environmental, economic and social factors, aesthetic and spatial qualities, and possibilities of cyber-physical manufacturing and construction processes.

Current design approaches assume that the exact location, dimension, specification and quality of each building element can be precisely defined and then serve as a clear blueprint for construction. But already today, many construction projects have reached a level of complexity that makes it increasingly difficult to plan, manage and execute them in such a completely deterministic way. Co-design not only enables a much higher level of integration in the planning and development phase; the linking of methods, processes and systems also lays the foundation for behavior-based, sensor-driven, cyber-physical manufacturing and construction. Ultimately, this opens up opportunities for novel, feedback-driven, robust and semi-autonomous or autonomous construction processes that do not rely on fully preplanned models but still achieve the required performance and quality.

The long-term goal of the Cluster is to develop a co-design methodology that operates on successive levels: (a) a predictive layer that is located in the digital domain prior to any physical construction; (b) a combined predictive and empirical layer enabled by cyber-physical fabrication and design approaches; (c) a self-learning layer that uses artificial intelligence capacities to develop semi-autonomous or autonomous computer-aided design and robotic construction without the need for a comprehensive blueprint, corresponding global knowledge or centralized control.

3 | TWO CASE STUDIES SHOWCASING THE INNOVATION POTENTIAL OF CO-DESIGN

Initial work has already demonstrated in an exemplary manner how the simultaneous and feedback-based further development of methods, processes and systems through co-design in an interdisciplinary research environment can lead to significant innovations in the construction industry. The research and development on integrative, computational planning and robotic construction at the University of Stuttgart for example, was presented to a wider public with two pavilions at the Federal Garden Show 2019 in Heilbronn. The pavilion typology allows selected areas of research to be investigated in a targeted manner without immediately having to fulfill the multitude of functional, economic and legal requirements that make innovations in architecture so difficult. At the same time, however, it already requires real implementation on a scale that corresponds to that of a building. This proves whether an idea is so promising that it is worth being developed further for widespread use. The pavilion is therefore an important intermediate step from basic research at the university to practical application. The two BUGA pavilions are less to be seen as a direct model for general application and do not yet involve social science research. Their aim is rather to demonstrate the potential of the co-design method for digital planning and robotic manufacturing in timber and fiber composite construction. They allow the public to experience new, genuinely digital construction methods for a wide range of building materials. The Cluster of Excellence is building on this experience to further develop the full architectural, technical, ecological, social and economic potential of the co-design method.

3.1 | The BUGA wood pavilion: New possibilities in timber construction

A decisive key in the ecological transformation of the construction industry is the replacement of cement-based and metallic building materials with wood (which stores CO2) as comprehensively as possible. Therefore, numerous political initiatives have emerged in recent years at regional, national and European level to support timber construction. However, the current state of development limits timber construction to small and regular grids, relies on the use of numerous connecting details made of steel, and often requires access cores, edge beams and other components made of concrete or steel, so that timber construction cannot currently realize its full architectural, structural or ecological potential. The overarching goal of the BUGA wood pavilion is therefore to show how co-design-based research can open up new and expanded architectural and constructional possibilities. With the renewable and regionally available resource of wood, rooted within the building culture of the SME-based timber construction industry (Figure 2) the pavilion contributes to ecologically transform construction.

The co-design method created for this project generated the shape of each component for the pavilion according to the architectural design intent and the structural loading. Only the conception and development of the transportable robotic manufacturing unit to be used was also an integral part of the co-design. Only this highly integrative process made it possible to manufacture 376 different panel segments with 17,000 different finger joints in accordance with the diverse design requirements for the overall structure and its details with an accuracy of three tenths of a millimeter. Compared to solid wood segments, the hollow wooden segments significantly reduce weight and material, but also increase the number of components by up to eight times and lead to a more complex production process. The quest for greater resource efficiency therefore had to go hand in hand with automated robotic production workflows of the shell segments.

Load-adapted and thus material-efficient shell structures are virtually extinct in today’s building practice due to the high effort required for their manufacture. For the BUGA wood pavilion, a system was developed as an alternative to traditional shell construction methods in which a double-curved geometry is assembled from flat cassettes. This requires each of the pavilion’s 376 cassettes to have different dimensions, which in turn is only sensibly possible with computer-aided manufacturing. For this purpose, a transportable robotic manufacturing unit was set up in a timber construction
workshop.\textsuperscript{12} One robot grips and positions the components, while the second processes them, that is, applies the glue, sets the hardwood nails for temporary fixation, mills the edges and drills the holes. On average, the robotic assembly took 7.1 min per cassette. High-precision milling took another 30–60 min (Figure 3). The cassettes show a very favorable ratio of high bending stiffness to low self-weight. Therefore, only the three shell edges had to be supported at single points for assembly. The shell area, with a span of almost 30 m and a surface area of about 600 m\textsuperscript{2}, was completely erected without falsework by only two craftsmen in ten working days using cantilever construction. Robotic prefabrication thus shifts all work steps requiring knowledge and precision from the construction site to the workshop. The wood pavilion (Figure 4) can be seen as an application example and demonstrator of how robotic prefabrication opens up new perspectives for traditional timber construction. At the same time, it is a model for investigating the changed division of labor between people and machines and the associated organizational changes. The approaches and methods underlying planning, production and construction are being transferred to multi-story timber construction as part of the research in the Cluster of Excellence. To this end, two-layer hollow slab systems are being developed that allow for large spans and irregular support positions. These systems tie in with both the planning methods and the platform-based robotic construction setup (Figure 3) of the BUGA wood pavilion.
3.2 | The BUGA fiber pavilion: A genuine digital building system

The BUGA fiber pavilion pursued a different goal. Here, the aim was to use the example of fiber composites to show how fundamental and open-ended, co-design-based research can enable new manufacturing processes and construction systems (Figure 5).

Fiber composites have long had a firm place in many areas of technology, especially in aircraft design, shipbuilding and wind turbines blades. In construction, they are much less established. The main reason for this may be the complex formwork required which often-times comes with the usage of ecologically questionable resources, for example, PUR foams. In addition, fiber mats are usually placed into molds with a 0/90° orientation, so that a load-adapted fiber arrangement is only possible to a limited extent which leads to a considerable amount of material waste. The construction of elaborate molds is therefore only economically viable and ecologically justifiable for series production. In the construction industry however, it is usually a matter of one-offs or very small series, for which robust and simple processes are required, while high demands on precision, dead weight...
or performance, which are much more important in aviation, are of secondary importance. The transfer of manufacturing processes from other fields of technology is therefore not very promising; instead, new strategies adapted to the specific requirements of the construction industry are necessary. The overarching goal of the BUGA fiber pavilion was therefore to use the example of fiber winding to show how digital planning and robotic manufacturing enable additive processes that use significantly fewer resources and at the same time lead to completely new, high-performance building systems. To showcase this, readily available, well established materials, such as glass and carbon fibers as well as fossil epoxy resins, were used and deposited freely in space between two rotating winding frames by a robot arm (Figure 6). In the Cluster of Excellence's projects, the use of bio-based resins and natural flax fibers is being tested. In addition, the integration into ceiling and roof systems is being investigated, where a variety of other building requirements have to be met, for example, acoustic and fire regulations.

Another key research question is how coreless filament winding can be expanded toward on-site (pre)production. Only light and compact materials, such as fiber spools and resin barrels, would have to be transported to the construction site, where they can be used to manufacture long-span, high-performance composite components without emitting noise, dust or vibrations, so that the ecological balance of manufacturing can be further improved.

The BUGA fiber pavilion as an essential pilot project for the fiber composite research of the Cluster of Excellence consisted of over 150,000 m of spatially arranged glass and carbon fibers. The fiber composite structure was covered from the outside by an ETFE film, which provided protection from the elements. The individual orientation of the fibers and the resulting composite structure would hardly have been feasible with linear planning processes and conventional production technologies. Instead, the density and orientation of the fibers in each component were created using a novel co-design approach—a parallel and feedback-oriented development of planning methods and production processes. Shape, structure and architectural appearance were carefully coordinated considering manufacturing constraints.

The structural tests required for the building permit proved that the up to 5-m-long components of the BUGA fiber pavilion (Figure 7) can bear a compressive load of around 250 kN with a self-weight of only 70 to 80 kg.

4 | CO-DESIGN IN RESEARCH NETWORKS

The potential of simultaneous and feedback-based development of methods, processes and systems in an interdisciplinary research environment, which has been tested in the above-mentioned work, is now being comprehensively advanced in the context of the Cluster of Excellence with a broader scope of application, a deeper basis of basic research, stronger interdisciplinary anchoring and intensified industry exchange. This research addresses what we see as the most important types of buildings and the challenges associated with them within the framework of three research networks: multi-story building, long-span building and, in perspective, building in existing structures.

In doing so, the research networks provide common thematic vehicles to advance the researchers' work program. The networks facilitate productive research by bringing together related projects and researchers working on a theme, addressing a common key challenge and moving toward a common goal and building demonstrator. In other words, they form thematic co-design networks that address cross-cutting research challenges in an interdisciplinary way and ensure that the work is both relevant to key architectural applications and addresses key implementation conditions in their technical, environmental, building cultural and societal dimensions. In this way, the networks achieve interdisciplinary insights for the Cluster while enabling domain-specific research. They are flexible instruments to achieve our goal of establishing an overarching methodology of co-design through mutually inductive and deductive approaches.
4.1 | Research network multi-story building systems

This research network (Figure 8) focuses on the co-design-based development of methods, processes and systems for multi-story buildings, such as residential and office buildings, and represents the high integration challenge required in this context. Thus, the development of methods for exploratory design, optimisation and analysis, human-computer and human-robot interaction supported by augmented reality, as well as integrative data management are explored in this network in view of the particular challenges of this architectural application field, which includes divergent design drivers, multi-dimensional optimisation parameters, human-robot collaboration in fabrication, multi-layered data models and formats, and the associated multiple stakeholder perspectives—from the design and construction process to marketing and use. They also include the interrelation between spatial and constructive ordering systems, structural and building-physical performance as well as ecological, building-cultural and economic requirements. Methods development is directly related to the associated processes: we aim to increase the share of prefabrication processes of building elements and thereby regard structural framework and building technology integratively from the beginning. At the same time, we enable flexible adaptation to the use- and site-specific requirements of architecture. In this way, quality will be improved, work on the construction site will be minimized and time and cost control advanced. At the same time, control points are defined to ensure the monitoring and coordination of quality, safety and regulatory criteria. This is also relevant to support seamless collaboration between skilled workers and robots in prefabrication—from the development of suitable interfaces and visualization tools to necessary expertise. To this end, new methods of interaction in augmented reality integrate situated visualization—that is, visualization embedded in the real environment on site. Prefabrication interlocks directly with the development of cyber-physical construction and assembly processes on the construction site. The associated strategies of machine control are based on digital construction progress.
recording with a specific focus on the particular challenges of surveying, localization and navigation within construction sites for multi-story buildings. The focus here is on the assembly of prefabricated building elements for research into semi-autonomous construction, the development of software architectures for unified data management and investigations into the remaining necessities of manual activities.

The automated handling of heavy loads as well as the assembly of prefabricated elements for multi-story buildings is investigated using the example of a tower crane from the industrial partner Liebherr. There are many reasons why the automation of these construction processes does not yet exist in practice. From a technical point of view, there is a lack of suitable sensor technology that meets the extreme requirements for accuracy, robustness and economic efficiency. Compared to manufacturing processes in process engineering, for example, in automotive engineering, sensor concepts often fail due to the unstructured and unclear environment of the construction site, where a wide variety of processes run in parallel and sometimes under difficult weather conditions. In the course of the ongoing development of Internet of Things (IoT) applications and the associated miniaturization and cost reduction of sensor technology new imaging methods offer great potential for the efficient monitoring of the construction process. For this purpose, cameras and laser scanners are mounted on the carrier of the tower crane. This provides a good overview of a wide working area. By continuously analyzing the image data, objects on the construction site can be classified and thus the construction progress can be monitored. Among other things, this enables a quality check of the prefabricated construction elements during the ongoing assembly process, for example by comparing the nominal geometry with the three-dimensional measurement data reconstructed from the images. By applying state-of-the-art methods from the field of photogrammetry not only the construction progress is documented, but also an environmental model of the construction site is created in which transport processes can be planned and optimized in terms of process times or process safety. At the same time, these technologies also raise nontechnical questions. The research on operational acceptance in Area D of the Cluster of Excellence, for example, raises awareness of the fact that these forms of documentation are also relevant in terms of construction law and economics, which can both promote and inhibit their implementation.

In the environment of a digital construction site, the transfer from manual control of the crane to fully automated handling is essentially based on the application of cybernetic methods. Initially, the goal of partial automation is pursued by supporting crane operators with assistance systems. For example, the use of model-based control and regulation concepts for sway damping can increase the accuracy of load positioning to within a few centimeters. With suitable interfaces and visualization concepts, this can support the use of skilled workers without years of training, provided that questions of quality assurance and liability have been conclusively clarified.

On the other hand, assistance systems form the basis for new possible applications in assembly that go beyond simple logistical tasks. The combination of the planning of the transportation process in the digital environment and active sway damping, which ensures the desired subsequent behavior of the planned transport path, enables the independent transport of loads. In order to also take dynamic processes into account, the environment of the transported load is monitored so that the transport process can be stopped in the event of unforeseen obstacles and then replanned.

With the overriding goal of a higher degree of automation, new load suspension concepts are being investigated. These must be able to hold the transported load in a desired orientation despite a pendulum movement of the crane and to create additional room for maneuver in the course of positioning or assembly, for example by actively tilting the component. More flexibility in handling is to be achieved in particular by connecting further construction machines as well as cooperative load guidance. A crawler crane is used as the partner system, which operates from the ground. While the tower crane compensates for large forces in the vertical direction, the crawler crane can position components both vertically and horizontally. In combination with the newly developed load handling concept, this enables robot-based positioning in all six translational and rotational degrees of freedom.

Despite the desired automated assembly of prefabricated components, in the end we can only speak of a partial automation of construction. Therefore, integrative investigations into operability, adapted expertise and the best possible integration of machine and human skills in new forms of human-machine cooperation are imperative. Through the use of technology, not only is human-machine cooperation possible, but human capabilities can even be increased in a targeted manner. This can thus be a component for an appropriate design of workplaces of the future. The trend toward automation is happening gradually. Construction machines are already equipped with an ever-increasing number of sensors. The control hardware has also been developing in the direction of higher performance, a permanent connection to the internet for machine monitoring and tracking, as well as simple software updates over the air. These state-of-the-art favors further steps toward semi-autonomous to fully autonomous machines, which are certainly still a long way off. Complexity in this context is preferably focused on the software; in this context, many efforts have already been made in the consumer area to make it easier to use, which can certainly be transferred here. The main problem is the question of robustness, especially of sensor systems in the harsh environment of the construction industry. This criterion plays a decisive role in the selection of the sensor concept. Lastly, the economic efficiency aspect must certainly be considered, although this can easily be compensated for by efficiency increases in view of the limited costs for additional sensor technology and slightly increased hardware costs.

Construction systems for multi-story buildings are developed in direct feedback with the peculiarities of cyber-physical building processes. Special attention will be paid to the necessary flexibility and adaptability both in the initial design phase with regard to the local context of the building project and throughout the life cycle due to changing usage requirements, societal change and further technological developments. We will explore concepts of modularity, material
systems and interfaces that enable new forms of spatial reconfiguration while avoiding the architectural monotony that characterizes most current approaches to serial and modular building.

In the developed world, people spend 87% of their lives in buildings, the majority of which are multi-story structures. The demands on these structures vary not only over time, but also depending on contexts of use and cultural routines. These structures therefore represent a highly relevant field for the investigation of socio-technical options. They allow the consideration of social demands and building-cultural expectations, but also economic, entrepreneurial and regulatory framework conditions as an integral part of the investigation. They also provide an important framework for exploring the historical embeddedness and reflection of the Cluster of Excellence, particularly on the successes and failures of mass-produced, large-scale, multi-story building developments of the 1960s/1970s. In view of the sheer volume of global multi-story construction and its impact on the environment, the developments are evaluated ecologically and the quality and safety demands are used as an occasion for research on the necessary development and adaptation of regulatory concepts, legal frameworks and technical standards.

The research network’s investigations are focused on a common, multi-story building demonstrator that enables scientific assessment, architectural validation and social studies.

4.2 Research network long-span building systems

The second research network (Figure 9) explores co-design-based development of methods, processes and systems for long-span buildings, which include large public, cultural, sports and infrastructure buildings. It also serves as a challenge for achieving high performance of building systems, as structural and material efficiency play a critical role in the economic feasibility, environmental sustainability and architectural articulation of long-span building systems. Therefore, we aim to directly link exploratory computational design optimisation and visual analytics methods. This applies both to novel, high-performance building systems and their efficient construction through end-to-end 4D modeling (spatial dimensions related to time) and the use of artificial intelligence and exploratory data visualization. Visualization methods are already successfully used in many areas of industrial production, but 4D modeling in construction brings special challenges. One goal is to take also into account the specific characteristics of advanced manufacturing and material technology to adapt to forces at multiple scales. This integrates (a) local, graded material composition, (b) regional, force-adaptive system segmentation, connections and interfaces, (c) global shape finding and topology optimisation.

The development of design and construction methods is put in direct feedback with the development of cyber-physical prefabrication processes (B.1) for high performance building components that allow multi-scale geometric and material differentiation for optimized load adaptation. Within a coupled cyber-physical system of prefabrication and on-site assembly, large-scale robotics processes and systems are investigated with regard to the construction of long-span building structures. In applications with large spans, efficient on-site assembly presents a particular challenge. As an extension of the camera-based construction process monitoring considered in the first research network, sensor concepts from the field of geodesy are used (total stations; laser scanners; GNSS receivers, levelers, and geotechnical instrumentation). These enable more precise localisation and positioning in the sub-millimeter range, which is particularly necessary for the automated assembly of impact-prone fiber composite elements. Since these sensor systems require continuous visual contact for position determination, novel distributed measurement concepts and sensor data fusion methods are being investigated to ensure uninterrupted tracking of moving objects. Analogous to the research on tower crane automation, the essential goal is a mostly autonomous assembly. The target platform is a crawler crane. The research focuses on the development of automation and control concepts in contact...
situations of construction and assembly processes. Even if high-performance components enable optimized load adaptation, a corresponding construction method is susceptible to structural damage as long as the intended shape has not been achieved and the building is still under construction. Methods for precise position and force control as well as model-based assistance functions for vibration damping and path planning based on these can minimize this risk. If these are also applied in cooperative assembly processes in which, for example, two crawler cranes or another tower crane work together, the basis for innovative construction systems is created. A concrete example is a possible reduction in the scaffolding or temporary support structures typically required by seamlessly compensating for changing structural conditions and associated deflections. These can be planned for in the design phase when designing the construction system, taking robot-based assembly into account. In the actual construction process, error-free realization is aimed at through the targeted automation concept; at the same time, however, necessary interfaces for safe and flexible use under different construction conditions are co-developed. Even if an ever-higher degree of automation is aimed for, humans and their perceptive and cognitive abilities remain an important component of the cyber-physical construction process. This requires effective methods that allow skilled workers to actively intervene in the construction process without endangering their own safety. In this context, new approaches to teleoperation as well as to load-bearing by means of haptic perception are being investigated. The great challenge here lies only partly in the interpretation of the sensor results, but mainly in the way they are transmitted to the people steering or controlling. The essential goal is to create a realistic impression of digital reality. For this purpose, a wear-able, haptic user interface is being developed that captures human movement via inertial measurement units. In this way, the dominant arm can control the direct movement of the crane and the nondominant arm can initialise predefined movement and assembly sequences, for example for an automated execution of simple, repetitive sequences. The forces transmitted in the assembly process are fed back via haptic feedback. A new gripper and load-bearing concept provides the necessary sensor technology as well as flexibly adaptable actuator technology that can adapt to a wide variety of shapes of prefabricated components. Here, too, it can be seen from the development of the rapidly growing market with mini cranes and small manipulators that considerable increases in efficiency are already possible today for certain tasks, such as façade construction. This development will certainly become more widespread in the future.

The developed monitoring, sensing and machine control approaches form the basis for our investigations of semi-autonomous to fully autonomous processes for long-span construction. The use of robots plays a crucial role for these processes, in particular methods are needed for the processing of sensor data in real time, for the integration of simulation, but also for the haptic user interfaces to control the cyber-physical platform.

A critical factor for long-span structures is dead weight. In coordination with design/engineering methods and manufacturing/construction processes, we are developing novel, high-performance, lightweight, long-span building systems (C.2) based on wood-based materials and fiber-reinforced composites for this purpose. The grade purity of the building materials and the monitoring of environmental impacts play an important role. A long-span building demonstrator will provide a vehicle for linking the network's research activities and evaluating its scientific results, and will also allow the associated architectural features to be studied.

4.3 | Research network building in existing contexts

The network Building in existing stock (Figure 10) will prospectively expand the findings of the first two networks to include the specific requirements of a co-design-based development of methods, processes and systems for building in existing contexts. Building in the

FIGURE 10 Research network building in existing building stock.
Source: IntCDC University of Stuttgart
space between or on top of existing buildings presents a particular challenge in terms of adaptability to the typically complex context of existing buildings, but also to the expectations of their users. The further densification of urban structures in the developed world is a central task in order to meet the enormous demand for inner-city living, minimize the need for additional transport infrastructure and reduce environmental pollution and land consumption. For example, in Germany alone, vertical expansion of the urban building stock could realize additional 1.5 million housing units, saving the equivalent of up to 250 million m² of undeveloped land, which is crucial to the government’s goal of halving land consumption by 2030.

The existing building stock usually represents a complicated interface situation with regard to geometric boundary conditions, load-bearing capacity of the existing building stock, requirements for suitable building-physical properties, existing usage patterns and new usage goals. This is to be met by co-design-based analysis, planning and optimisation methods that favor integrative and also participatory forms of planning and building with the extended building information modeling based on an automated digitalization of the building stock. On the one hand, this requires adaptive data management strategies in order to be able to integrate the multi-layered information. On the other hand, feedback from the different groups of people involved should be taken into account; visualizations and corresponding visual analysis methods can play an important role here (see Reference 35 for the example of urban data).

Building in the urban environment also comes with challenges in terms of site set-up and impact on the urban environment. This forms the starting point for the development of external cyber-physical prefabrication processes of building components and robotic on-site platforms of large-place special demands on the monitoring, detection and control processes. Traditional craft knowledge and manual labor go hand in interventions on existing buildings and are now complemented by new forms of human-machine interaction in robotic construction, which are being investigated for their social, professional and ethical implications. In the context of existing building, the vision of autonomous robotic systems is still the furthest away, given the unstructured environment and the variety of different scenarios. Nevertheless, it is worth considering assistive manipulators in this field for the future.

Horizontal or vertical extensions to the existing building stock place particular demands on the development of co-design-derived building systems, which must geometrically adapt to the existing boundary conditions and ensure lightweight construction to minimize the impact on existing foundations, as well as being effectively insulated acoustically and hygrothermally. The building systems should be prefabricated as far as possible to reduce noise, dirt, traffic and other impacts on the surrounding environment. A building demonstrator will also be used for this application as a checkpoint of research convergence, scientific evaluation and to assess architectural features and social acceptability.

5 | OUTLOOK

Digital technologies can fundamentally change the planning and building of the future. More efficient buildings and more sophisticated architectures can be expected as a result of more integrative, feedback-oriented and coordinated planning and construction processes, which at the same time make more responsible use of ecological resources. Digital approaches thus promise to solve many problems of the construction industry at the same time. They can contribute to overcoming the productivity, skilled labor and profitability crisis, but also the resource and sustainability crisis, as well as the confrontation culture emblematic for the construction sector. A new building culture that can better respond to the demands of the 21st century can be imagined through new planning methods, new ways of thinking, building materials, building processes and systems, and also through new working conditions on the building site and in prefabrication. A major challenge for this lies in the development of suitable interfaces to create universal interoperability and enable versatile monitoring and optimisation processes, so that building systems communicate with designs, robots with construction plans, construction workers with architects. This interoperability is also important to ensure that construction processes and structures remain comprehensible and flexible for all sides today and in the future, and that design processes can be corrected and calculations adjusted. In contrast, the linearity of today’s approaches still imposes limits on architecture and construction technology. Mature, integrative computational processes can leave these limitations behind. In addition to the technical challenges, the nontechnical challenges and obstacles also play a decisive role. Which possibilities are taken up and further developed also depends on legal, economic and political frameworks as well as societal expectations and demands. Finally, the future of construction will also be shaped by the—especially digitally driven—concentration processes in international competition and accelerating standardization, which do not always match the new possibilities in construction technology. Also, for this reason, the considerations in the Cluster do not end with the developments in building technology, but include the requirements of the application contexts and consider the scope for action of the building professionals.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable - no new data generated.

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