1 Advanced Construction and Building Technology

A society's well-being and cultural evolution can be achieved through sufficient personal income. A nation therefore has to be efficient and achieve further productivity and economic growth. Where there are no or limited natural resources to be exploited and sold, high income can come only from sophisticated technology. Affordable and efficient socioeconomical and sociotechnical processes are further required as a result of demographic changes. As an example of success based on research and innovation, the "Made in Germany" label is internationally famous for its cars, machines, industrial facilities, and medical and environmental technologies. It illustrates how future wealth can be generated only by innovation leaps and radically new types of value design and engineering.

Around the world, a substantial amount of investment is allocated in the built environment, infrastructures, and facilities, signifying the strategic importance of the construction sector. Analysis (see Section 4.1) shows that productivity in the construction industry has been declining for decades worldwide. The construction industry has one of the lowest capital stocks compared to other industries, as well as low capital intensity; research and development (R&D) spending is also extremely low. Both the advancement of manufacturing technologies, as well as the development of new products, have been stagnating for decades. Furthermore, construction defects, improper working conditions, and low attractiveness of the construction field for younger generations, as well as the tremendous consumption of raw materials and energy by the construction process and building products, present challenges for which the conventional construction and architecture industries currently do not have solutions. In high-wage countries, as well as on a global scale, the natural aging of societies will continuously worsen the situation by reducing human capital, as well as the ability for change and economic growth. Börsch-Supan, a German macroeconomist, sees a solution for furthering productivity and economic wealth, predominantly via supplementing human capital by capital intensity and nonlinear advances in machine technology and productivity (Börsch-Supan et al., 2009).

Whereas the general manufacturing industry, discusses under notions such as "Industry 4.0" (see, e.g., Jopp, 2013) or "Cognitive Factory" (see, e.g., Zäh et al., 2009), phenomena such as hyperflexible and intensively automated manufacturing systems (considered as the fourth industrial revolution) in which highly autonomous, flexible, and distributed but networked automation and robot systems cooperate in

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producing in near real time individualized and complex products with incredible efficiency, in the construction industry productivity and change have been stagnating for decades. Change in the construction industry occurs extremely slowly on the one hand because of the characteristics of the products, their complexity, extremely long life cycle, diversity, their dimensions and materiality, and fixed-site nature but also has roots in low R&D spending and the reluctance to adopt new strategies and technologies. In parallel to the marginal improvements in conventional construction, since the 1970s, scientists, R&D departments, and innovative companies have been supported by universities, associations, and governmental institutions to work consistently on a type of disruptive change, a new set of technologies and processes that will change the process and idea of construction in a fundamental way and that can be summarized under the term "automated construction".

In contrast to conventional construction, automated construction is capital intensive and machine centred with a potentially unlimited performance and is able to manufacture in "real time" (Linner, 2013). As automated construction necessitates a complementary and also disruptive change in the whole industry (products, processes, organization, management, stakeholders, business models, etc.) to be able to fully unfold its potential, it can be considered as a rather complex type of innovation or change. Changes of such complexity take time, sometimes decades. However, now after nearly 40 years of technical development and experimentation in the field, an increase of activity has resulted within companies, research institutes, associations, and governmental institutions. This indicates that the new technology is gaining acceptance, and its adoption level is finally heading towards a growth phase.

1.1 Robot Technology Becomes Ubiquitous

> The end of the information age will coincide with the beginning of the robot age. However, we will not soon see a world in which humans and androids walk the streets together, like in movies or cartoons; instead, information technology and robotics will gradually fuse so that people will likely only notice when robot technology is already in use in various locations. Ishiguro (2012)

Robotic systems are advanced machines characterized by capabilities, such as re-programmability, autonomy, flexibility, and situational awareness. By observing advances within robot technology, it is feasible to predict that it will experience a development similar to that of the personal computer during the 1990s. Experts and masterminds, such as, for example, Bill Gates, announce the era of robotics and estimate that robotics will be part of our everyday lives. The South Korean government recently announced that it supports heavily the development of robot technology, with the goal of establishing at least one robot system in each household. Recently Google acquired key players of the robot hardware and artificial intelligence development field (e.g., Boston Dynamics, Shaft Inc. and Nest) to be able to expand in the near future into the service robotics and home automation domain. Furthermore, around the world governments discuss the implementation of new laws and regulations that would provide the basis for large-scale deployment of autonomous vehicles and aerial systems in the public space. As early as in 1961 Joe Englberger wondered whether relating robotic technologies to only product manufacturing applications makes any sense. "The biggest market will be service robots" (Englberger, 1989) asserted Englberger, who started the industrial robotics era, when his firm (Unimation) delivered GM's first robot.

Currently robots are becoming more user friendly, less expensive, task adaptable, smaller, more widely distributed, and seamlessly integrated into work processes and devices. Individuals today are able to acquire modular kits of open source robot hardware, and interface robot systems directly to a computer via USB devices. Furthermore, there are examples of robots that have become invisible and complex types of such robots consist of a network of interconnected, distributed, and sometimes invisible sensor and actuator systems (including mobile phones or appliances). This means that individual devices functioning as machines can now cooperate as a network to manipulate or achieve goals (by manipulating energy flows as smart grids do) autonomously as a robot system.

With the continuous evolution within the field of robotic research, new technical capabilities (modularity, lightweight concepts, wearable robot technology, and social robot technology) have been explored and combined with existing manipulation-oriented automation and robot technology. Over time, the ability of robot systems has grown, allowing them to work more and more in unstructured environments comparable to those in which human beings operate. This evolution leads to the fact that robot technology, apart from the classical manufacturing industries, can now be introduced and deployed in numerous fields, such as aircraft production, farming, the construction industry, and health care sector.

New capabilities not only extend the application area of robotics, but also allow for new application scenarios in factory-like environments. Robot systems are now more dexterous and adaptive, therefore building a basis for the production of customized and even personalized products. Faster product life cycles, and the increasing demand for flexible production systems able to produce customized products, has also led robot systems towards refined modularization, plug-and-play capabilities of subsystems, open source approaches, concepts for self-configuring and self-organizing strategies, and cellular approaches.

In short, it can be said that automation and robot technology are becoming ubiquitous and step by step pervading our life on earth. Table 1.1 lists thematic fields into which automation and robotics are currently advancing as well as approaches and systems within those fields. Along with Figure 1.1 it shows that robot technology can penetrate nearly all fields of professional and private life. It can be assumed that coordinated and consequent establishment of automation and robotics in several thematic fields in parallel will lead to complementarities and synergies and make robot systems even more efficient.

In our book series the focus is on but not limited to automated/robotic construction. Automated/robotic construction cannot be considered or introduced without strong cross links and even complementary changes in many of the other thematic fields mentioned. The future success of automated construction depends in particular on advances in the transportation field (e.g., the delivery of large and complex components or equipment by robotic airships would be advantageous as well as robotic material transport and logistics solutions) and on new products and business models to be generated. The underlying basic technologies and concepts are the same, and a close collaboration between developers in the various thematic fields

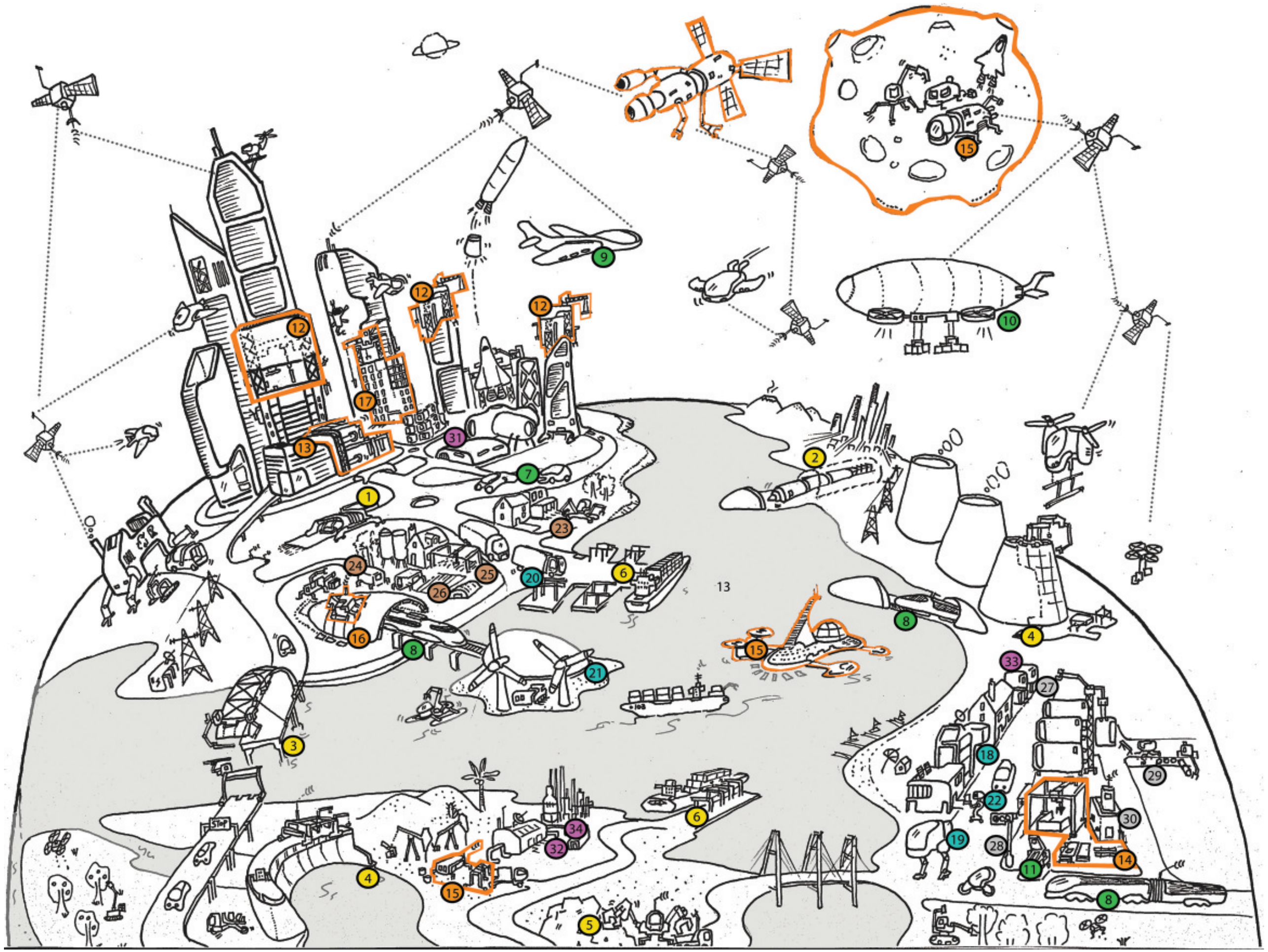

Figure 1.1. Automation and robot technology becomes ubiquitous and step by step pervades our life on earth. In our volume series the focus is set, but not limited to, automated/robotic construction. (Drawing by W. Pan, Chair of Building Realization and Robotics)

Table 1.1. *Thematic fields into which automation and robotics are currently advancing*

Thematic field		Systems and approaches
Automated/Robotic Infrastructure Production	1	Automated road construction
	2	Automated tunnelling (i.e., by tunnel boring machines)
	3	Automated bridge construction
	4	Automated con- and deconstruction of dams, power plants, etc.
	5	Automated mining
	6	Automated container port
Automated/Robotic Transportation Systems	7	Autonomous cars
	8	Autonomous public transport (metro, train, etc.)
	9	Autonomous air travel
	10	Automated logistics
	11	Advanced micro-mobility (i.e., Cyberdyne's HAL or Toyota's i-Real)
Automated/Robotic Construction	12	Automated construction of vertically oriented buildings
	13	Automated construction of horizontally oriented buildings
	14	Housing production
	15	Novel construction markets accessible through automated/robotic construction: construction in space, sea and deep sea, desert, Arctic areas, etc.)
	16	Automated building servicing and maintenance
	17	Automated de-construction and re-customization
Automated/Robotic Environments	18	Home and office automation
	19	Assistance technologies
	20	Networked production facilities and supply networks
	21	Intelligent energy generation and distribution
	22	Service and household robotics
Automated/Robotic Farming and Food Production	23	Computer-aided/robotic farming
	24	Robotic milking stanchions
	25	Automated food production facilities
	26	Customized food
Automated Robotic Town Management	27	Smart grids
	28	Automated/robotic traffic control
	29	Automated/robotic infrastructure inspection and maintenance
	30	Automated supply management (water, gas, goods, food, etc.)
General Manufacturing Industry	31	Digital/cognitive factories
	32	Mass customization
	33	Mini factories, cloud manufacturing
	34	Cellular logistics

will be unavoidable to be able to distribute the development and production cost of the technology.

1.2 The Origins of Automated Construction and Its Disruptive Nature

The individual development of conventional construction and automatic construction, as well as the interrelation of the course of development of both, can be described in an abstract way by an S-curve framework. Individual S-curves can

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describe the life cycle of innovations and in particular new technologies. S-curves, in general, represent the development of a product or technology over time. In relation to the technical adoption rate or to a performance index, it allows a way of subdividing its life cycle into three phases:

1. Phase A (Innovation Phase): no knowledge, first trials, huge amount of R&D spending and relatively low or no outcome, technological and organizational problems, development of prototypes that are difficult to commercialize
2. Phase B (Growth Phase): knowledge increases; overcoming of technical and organizational obstacles; development of complementary infrastructure, products, and services; new business models; increased adoption by customers; rapid growth through synergies
3. Phase C (Maturity Phase): technology reaches technical, organizational, and economical limits, leading to stagnation.

An overlay of S-curves can be used to describe the relation between the stagnation and technical limits of one technology and the initiation, development, and growth of new strategies and technologies that are at the beginning inferior to the existing technology but gain in importance, performance, and adoption rate over time. In Figure 1.2 this concept is applied to construction. Conventional construction is supplemented by a new technology, automated construction, which at the beginning phase, where we still are, is inferior in performance owing to technical, organizational, and economical obstacles and missing integration with the economic environment still dominated by the mature technology (conventional construction). However, over time the new technology will outperform the conventional one.

According to Foster (Foster, 1986; Foster & Kaplan, 2001; Foster worked more than 20 years in a leading position at McKinsey) the performance of an industry or business is limited by the nature of its core technologies. Signs that the technology reaches its limits are an increase in management issues and conflicts and a decreasing rate of performance improvement. When core technology reaches limits, major improvements of performance (10, 20, 30, 40 times) can be achieved only by technological discontinuity. In particular in this volume (**Volume 1**) we show that there are numerous signs that conventional construction technology is reaching its limits (constant productivity, increasing rate of construction defects, inability to cope with highly complex buildings, extremely low R&D spending, etc.). Our volume series (**Volumes 1–5**) shows readers the potentials and higher limits of automated/robotic construction, explains the new core technology and its applications in detail, and identifies current strengths and weaknesses of the technology to build a solid basis for taking it further in the future.

In business science, innovation, and management research, it is a well-known principle that productivity losses, limitations, and stagnation can be overcome effectively by change, innovation, and openness to discontinuity. One can reference Kondratieff's economic cycles (see, e.g., Mager, 1986), Fujimoto's concept of evolutionary learning capability which he sees realized at Toyota (Fujimoto, 1999), and the concept of jumping the S-curve as a method for major firms to stay on top over decades or even centuries (Nunes & Breenes, 2011). Eventually the survival of individual firms and even professions over longer periods of time is possible only if changes are made. This includes major system changes that allow for even broader value creation possibilities. In the words of Nunes and Breenes (2011), it is now time

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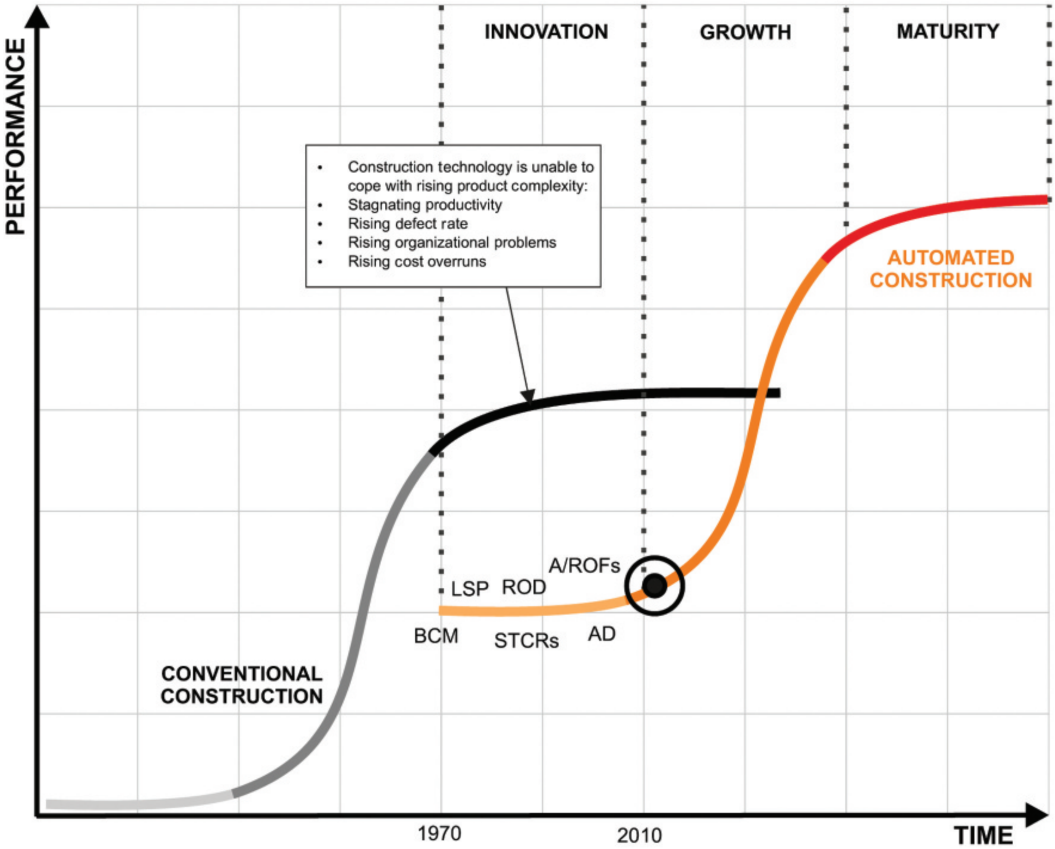

Figure 1.2. Foster's (1986) S-curves applied to future development of construction industry and technology (Drawing by B. Georgescu, Chair of Building Realization and Robotics). BCM = building component manufacturing; LSP = large-scale prefabrication; STCRs = single-task construction robots; ROD = robot-oriented design; A/ROFs = automated robotic on-site factories; AD = automated deconstruction.

for the construction industry to jump the S-curve and change the notion of labour-intensive construction into a notion of capital-intensive manufacturing to keep up with growing product complexity and customer demands. The change to automated construction would create a major system change that is similar to the change from arts-and-crafts–based production to industrial production that has already taken place in other industries that manufacture comparably complex products, such as the shipbuilding, automotive, and the aircraft industries (see also Chapter 5).

In the 1970s, analysis indicated a significant decrease in growth of productivity in the construction industry compared to that in the general manufacturing industry (see in particular Section 4.1). This led to the birth of the notion of automated construction as an alternative to conventional construction through the influence of the first robot boom in Japan. The breakthroughs of building component manufacturing (BCM) and large-scale prefabrication (LSP), and the start of intensive R&D in the field of relatively simple single task construction robots (STCRs) characterized this initialization phase. In the 1980s, with productivity in conventional construction still stagnating (in Europe, the United States, as well as in Japan; see also Section 4.1) and building products (e.g., in the form of high-rise buildings) becoming more complex,

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research in automated construction was intensified, which led to the development of automated/robotic on-site factories. In the next decades, about 30 systems were developed, some of them as prototypes and some as commercially applied systems.

Although automated construction in the described phase (from the 1970s to present) remained to a large extent in a prototype and experimentation phase and accompanied by technical, economical, and organizational problems and a still relatively low adoption rate, the phase can be described as the classic initiation and innovation phase by an S-curve diagram (Figure 1.2). The low adoption, technological obstacles, and high cost of implementation compared to the benefits at present characterize this phase in the innovation cycle. However, these characteristics shall not be interpreted negatively, but rather be acknowledged as part of the innovation process. The period from the 1970s can be seen as an experimental phase in which different types of automated construction were identified, developed, and evaluated. Strengths and weaknesses of different, alternative approaches were identified and the first tools for managing and co-adapting products and organizational structure in the form of robot-oriented design (ROD) were developed.

In a next phase (Phase B, Growth) the application field of automated construction can be extended (e.g., with the development of systems for horizontally oriented automated on-site construction and approaches to automated deconstruction which is already underway). Furthermore, concepts for robot-oriented design and management can be taken further, providing the basis for a co-adaptation of products, processes, organization, management, stakeholders, and business models to the new manufacturing technology. This in turn would provide a basis for more rapid adoption and in effect to create (exponential) growth. In this growth phase and with the co-adaptation of products and the surrounding infrastructure, automated construction can then unfold its full potential and boost its performance. This co-adaptation process has already achieved significant relevance in major technologies that most individuals take for granted, for example, in automotive technology (which took off once the surrounding infrastructure with roads was established) and PC technology (which took off after the development of compatible software, new interface technologies such as the mouse, and finally the emergence of the Internet). Chapter 3 therefore contains a detailed explanation of the role of complementarities of products, organization, informational aspect, and machine technology in construction.

The growth in Phase B will be stimulated further by the performance limits of human-centred, conventional construction, which will become more obvious in light of growing product complexity, increasing pressure on productivity, and demand for affordable individualized building products. Already now the growing rate of construction defects, decrease of productivity, increasing organizational complexity, and rising amount of disastrous cost overruns of major projects indicate that the limits of conventional construction technology have been reached. In contrast, unlike human labour, machine technology (and with it its modern variants such as automation and robot technology) is consistently a highly accurate and reliable means of production that guarantees time, cost, and quality also for extremely complex products (see the detailed analysis of the aircraft building, automotive, and shipbuilding industries in Chapter 5), and that naturally, unlike the human being, is potentially "unlimited" in terms of capacity and capacity improvement. Automation and robot technology, due to programmability, inbuilt flexibility, and modular approaches, can now be adjusted (or can adjust themselves) to product variations and even completely different products to be manufactured within short- and long-term time frames. The advances in manufacturing technology, as well as in automation and robot technology during the last decades, have been enormous, providing a rich ground for technological transfer. These concepts allow automated construction to begin to thrive on a relatively high technological level. In particular in developed countries, advances in the field of automation and robot technology will grow in importance for industrial development and add to the pressures to transfer this technology into construction. A factor to consider in light of all of these facts is that in key economies population decline and ageing threatens economic productivity and growth.

All in all, it can be said that change is on the way and that it is only a matter of time until the currently inferior automated construction technology will improve further and eventually create synergies with the surrounding developments and infrastructures and finally outperform the conventional way of building. As the technology itself as well as the complementary changes in construction are complex, the series The Cambridge Handbooks on Construction Robotics systematically represents, examines, explains, and summarizes the inventions and developments in automated construction in the described innovation phase (1970s to present).

1.3 The Mission and Structure of the Series

Automated and robotic construction is covered in a holistic way in this series, with the intention of extending the traditional core competencies of design and building, broadening the activity area of future graduates and professionals, and creating new employment opportunities in light of the changes taking place and the expected transition of automated construction technology into the adoption and growth phase (see Section 1.2). The growing activity in the professional field, increased interest of researchers and students in the field, and a large number of requests to the authors for consultancy motivated the authors to systematically outline the related developments, technologies, and strategies in a book series. Furthermore, the intensification of R&D activity at top research facilities worldwide (University of Cambridge, University of Oxford, Harvard University, National University of Singapore, Oulu University, Korea University, Sungkyunkwan University, ETH Zürich, and various universities in Russia) to which the department of the authors provided assistance and support gave a new perspective on the comprehensive knowledge basis needed in this field. The knowledge gained from this experience represents the fact that there are still massive knowledge gaps and that the interrelations with other professional fields and the complexity of the innovators and changes ahead are still lacking in systemic explanation.

The Technische Universität München (TUM) within the Bavarian high tech cluster functions as an incubator for the development of advanced and sociotechnically integrated and building-related technologies. In the master course Advanced Construction and Building Technology (M.Sc.), which the chair has been coordinating since 2011, researchers and students from nearly all professional backgrounds (architecture, industrial engineering, electrical engineering, civil engineering, business science, interior design, informatics, mechanical engineering) are brought together. This broad range of professional backgrounds will build the basis for the necessary co-adaptation and complementarity of products, organization,

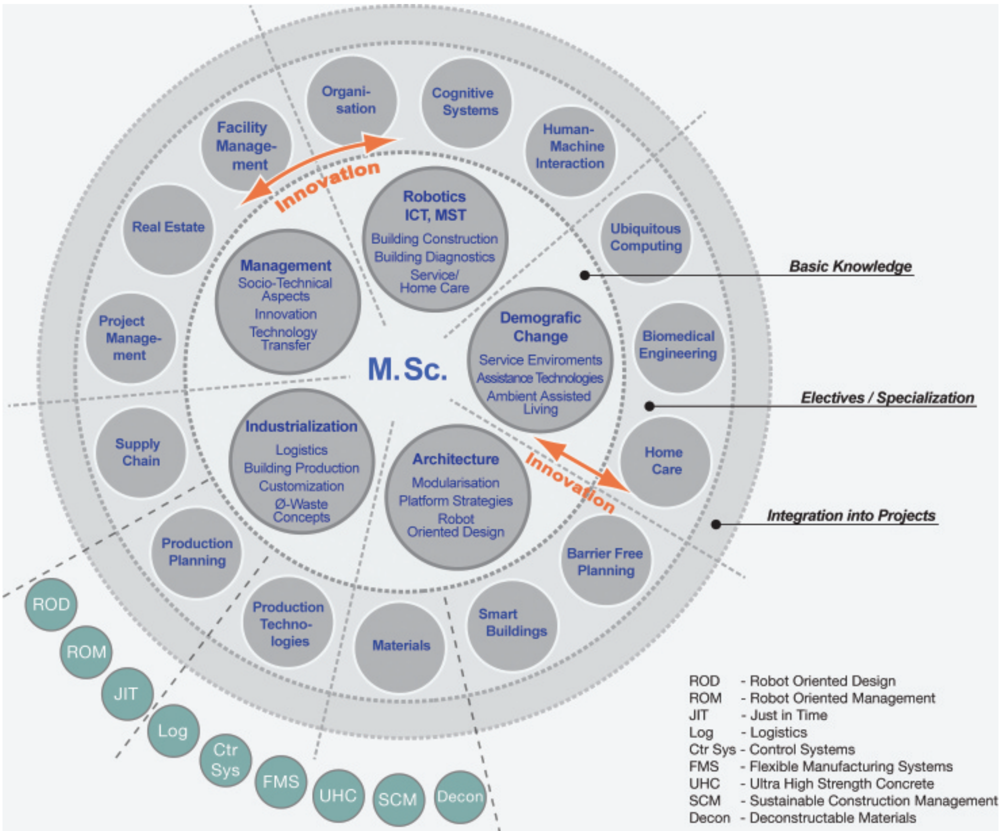

Figure 1.3. Complementary knowledge in multiple knowledge fields is necessary to work with the complex changes that construction and building will undergo on the way from a crafts-based low-performance to a machine-based high-performance industry. (Drawing by B. Georgescu, Chair of Building Realization and Robotics)

informational aspect, and new machine technology in construction in the upcoming growth phase (see also Section 1.2).

The mentioned master merges management competency (construction management, technology management, innovation management) with competency in advanced technologies (production technology, information and communications technology [ICT], microsystems technology, mechatronics, automation, robotics, personal assistance technology) and applies it to solve future challenges of our society by considering all phases of a building's life cycle (development, planning, construction, use/performance, de-construction/end-of-life). The students who take the master course acquire complementary knowledge in multiple knowledge fields to prepare them to manage the complex changes that construction and building will undergo on the way from a crafts-based low-performance to a machine-based high-performance industry and become actors, consultants, or leaders in that change on the governmental, institutional, R&D or enterprise side.

The authors of this series define architecture as a service to society, economy, and ecology and construction as a machine technology–based production process that produces advanced "products" on the basis of the latest manufacturing technologies and strategies. Based on intensive studies of the economic and technological development in general manufacturing industry, the authors believe that the delivery of future high-tech environments/buildings (representing the "products" in construction industry) at reasonable cost is dependent on highly efficient production methods. The authors follow and promote the philosophy that only frontier engineering sciences are able to breed these innovations. These innovations are, furthermore, driven and amplified by globalization, closed loop resource utilization, transformation of technological potentials, and environmental and demographic challenges.

The future construction sector will expand to new business fields by transferring and absorbing advanced technologies from various disciplines (see Figure 1.3). Its success will depend on the ability to "manage" innovation and to improve the complete value chain according to automation and robot technology demands. Automation and robotics in construction will create new markets, qualifications, skills, and professions. Even though architecture, engineering and construction are the focal points of the mentioned master course, it cross links considerably with other disciplines and faculties in order to foster augmented skill formation for the qualification of the next generation of engineers.

Key topics of the Cambridge Handbooks on Construction Robotics series comprised of five volumes are introduced shortly on the following pages. Figure 1.4 outlines the structure of the Cambridge Handbooks on Construction Robotics series graphically.

1.3.1 Volume 1: *Robot-Oriented Design – Design and Management Tools for the Deployment of Automation and Robotics in Construction*

In this volume, design, innovation, and management methodologies that are keys for the realization and implementation of the advanced concepts and technologies presented in **Volumes 2, 3, 4,** and **5** are explained. Robot-oriented design and management enables the efficient deployment of advanced construction and building

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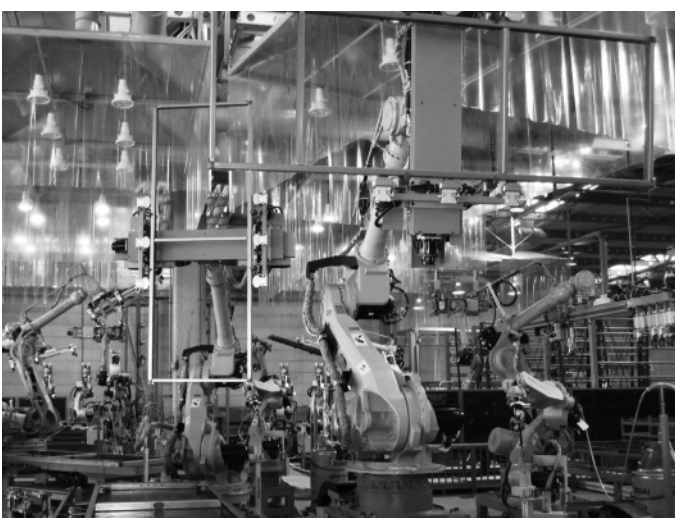
technology. It is concerned with the co-adaptation of construction products, processes, organization, and management and automated or robotic technology, so that the use of such technology becomes applicable, simpler, or more efficient. It is also concerned with technology and innovation management methodologies and the generation of life-cycle–oriented views related to the use of advanced technologies in construction and building context. The concept of ROD was first introduced in 1988 in Japan by Bock (1989) and later served as the basis for automated construction and other robot-based systems around the world. It was developed for improving the construction sector and adjusting conventional construction processes and component design to the needs of the novel tools. In **Volume 1**, technologies relevant to understanding approaches outlined in **Volumes 2, 3, 4,** and **5** and the application of related technical, organizational, and economical concepts and parameters are introduced.

1.3.2 Volume 2: *Robotic Industrialization – Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication*

In this volume, concepts, technologies, and developments in the field of building component manufacturing (BCM) based on concrete, brickwork, wood, and steel as building materials and LSP holding the potential to deliver complex components and products are introduced and discussed. BCM refers to the transformation of parts and low-level components into higher level components by highly mechanized, automated, or robot-supported industrial settings. The definitions of components are interpreted differently by different industries and even by individual companies. However, the definitions of components share as a common element, that they are considered as more or less complex combinations of individual preexisting parts and/or lower level components. Pure BCM can be distinguished from the transformation of raw material into parts (production of bricks or simple concrete blocks).



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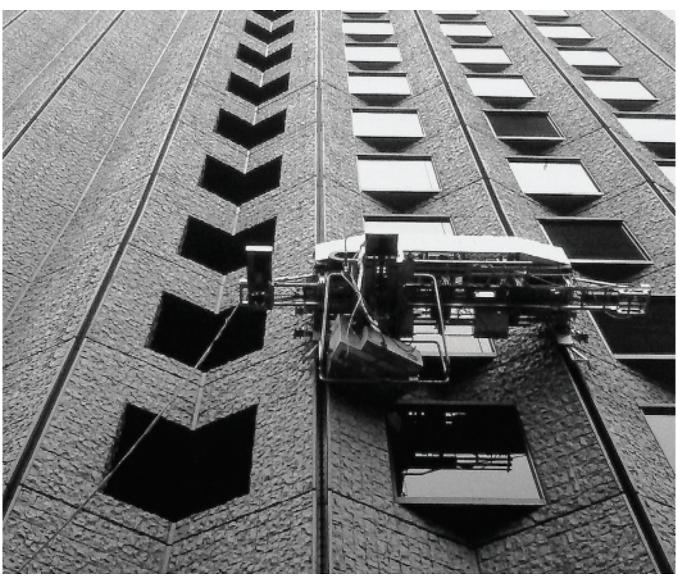
Also, component manufacturing can be distinguished from the manufacturing of highly complex modules or units. BCM is clearly distinguished from the manufacturing of high-level building blocks, such as building modules (prefabricated bath modules or assistance modules which can also be referred to as building subsystems) and building units (such as the LSP of fully finished building sections, delivered for example by Sekisui House, Sekisui Heim, Toyota Home, Misawa Hybrid). For highly automated LSP, according to the OEM model (see Section 4.3), component manufacturers represent Tier-1 or Tier-2 suppliers. Tier-1 suppliers would deliver components directly to companies such as Sekisui Heim or Sekisui House, whereas Tier-2 suppliers would supply the suppliers of the bath or assistance units. For automated/robotic on-site factories, component manufacturers again represent Tier-1 or Tier-2 suppliers. BCM and the LSP industry can reduce on-site complexity (task variability, complexity and amount of operations on the construction site) and build the supply backbone in an OEM-like industry structure, which can be considered as a prerequisite for the successful implementation of automated/robotic on-site factories. The image above shows the automated assembly of steel frames in a factory of Sekisui House.

1.3.3 Volume 3: *Construction Robots – Elementary Technologies and Single-Task-Construction Robots*

After the first experiments in large-scale industrialized, automated, and robotized prefabrication of houses were conducted successfully in Japan, and the first products (e.g., Sekisui M1) also proved successful in the market, the main contractor, Shimizu, in 1975 set up a research group in Tokyo for construction robots. The goal was now no longer the mere shifting of complexity into an off-site structured environment (SE) as in LSP, but the development and deployment of systems that could be used locally on the construction site to create structures and buildings. The focus initially was set on simple systems in the form of STCRs that can execute a single, specific



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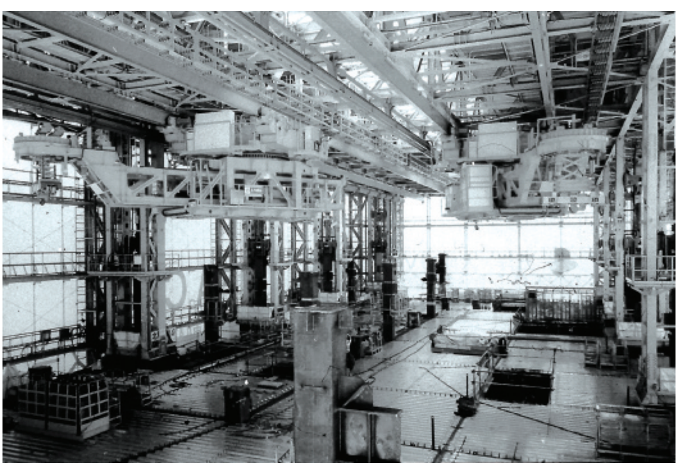
construction task in a repetitive manner. The fact that STCRs were task specific made them initially highly flexible (they could be used along with conventional work processes and did not necessitate that the whole site be structured and automated), but also represented a major weakness. As they were, in most cases, not integrated with upstream and downstream processes, demanded safety measurements, and hindered parallel execution of work tasks by human workers in the area where they were operated, productivity gains were often equalized. Above all, the setup of the robots on-site (equipment, programming) was time consuming and demanded new skills. In addition, the relocation of the systems on-site was, in many cases, complex and time consuming.

The evaluation of the first generations of developed and deployed STCRs and the identification of the aforementioned problems led step by step from 1985 onwards to the first concepts for integrated automated/robotic sites (**Volume 4**). Concepts for integrated automated construction sites "integrated" STCRs and other elementary technology as subsystems into SEs set up on the construction site. The development of STCRs, elementary technology, and a concept for structuring on-site environments by ROD was analysed and supported by one of the authors (Bock) in Japan from 1984 to 1989 (see also Bock, 1989). As the development of STCRs created the basis for, and paved the way for, integrated automated/robotic construction sites from the 1990s onwards, the development is reviewed in this Volume. As the development of STCRs, parallel to or as subsystems of integrated automated construction sites, continued up to today, about 150 STCRs have been identified, analysed, and categorized. Furthermore, the conceptual and technological reorientation towards integrated automated construction sites initiated by Waseda Construction Robotics Research (WASCOR) Group (joined by researchers of all major Japanese construction firms) and detailed technical descriptions of the automated equipment and robots is shown.

1.3.4 Volume 4: *Site Automation – Automated/Robotic On-site Factories*

The approach of setting up SEs on the construction site in the form of automated/robotic on-site factories can be considered as a logical expansion of BCM,



LSP (**Volume 2**), and STCRs (**Volume 3**) technology and the consequent implementation of automation and robot-oriented design and management tools (**Volume 1**). In **Volume 4**, all worldwide conducted approaches following the direction to an on-site factory approach are outlined. Thirty different systems are outlined, resulting in an application of automated/robotic on-site factory technology about 60 times. The outline is split for each system into a more technical part and a part that focuses on parameters related to productivity, efficiency, and economic performance. All systems were analysed systematically (based on the same frameworks) and 13 categories were set up (10 categories for construction and 3 categories for deconstruction). One of the main ideas for setting up automated on-site factories was to integrate standalone or STCR technology into structured on-site environments to networked machine systems and to improve organization, integration, and material flow on the construction site, apart from the possibility to integrate off-site manufactured components. **Volume 4** also discusses the building typologies for which automated/robotic on-site factories are an applicable approach, and how and to what extent those systems can be made technologically flexible to be able to manufacture a variety of different buildings (products) on the basis of industrialized, automated, and flow-line like stable factory processes.

1.3.5 Volume 5: *Ambient Robotics – Automation and Robotic Technologies for Maintenance, Assistance, and Service*

For a long time the focus of innovation in the area of automation and robotics in construction has been laid on the industrialized and rationalized off-site or on-site construction as well as on related processes, building systems, management and logistic tools, and high-tech construction and prefabrication. However, today, in particular the complexity of buildings is rising rapidly owing to new paradigms such as ubiquitous computing, the demand for energy efficiency, and emerging assistance

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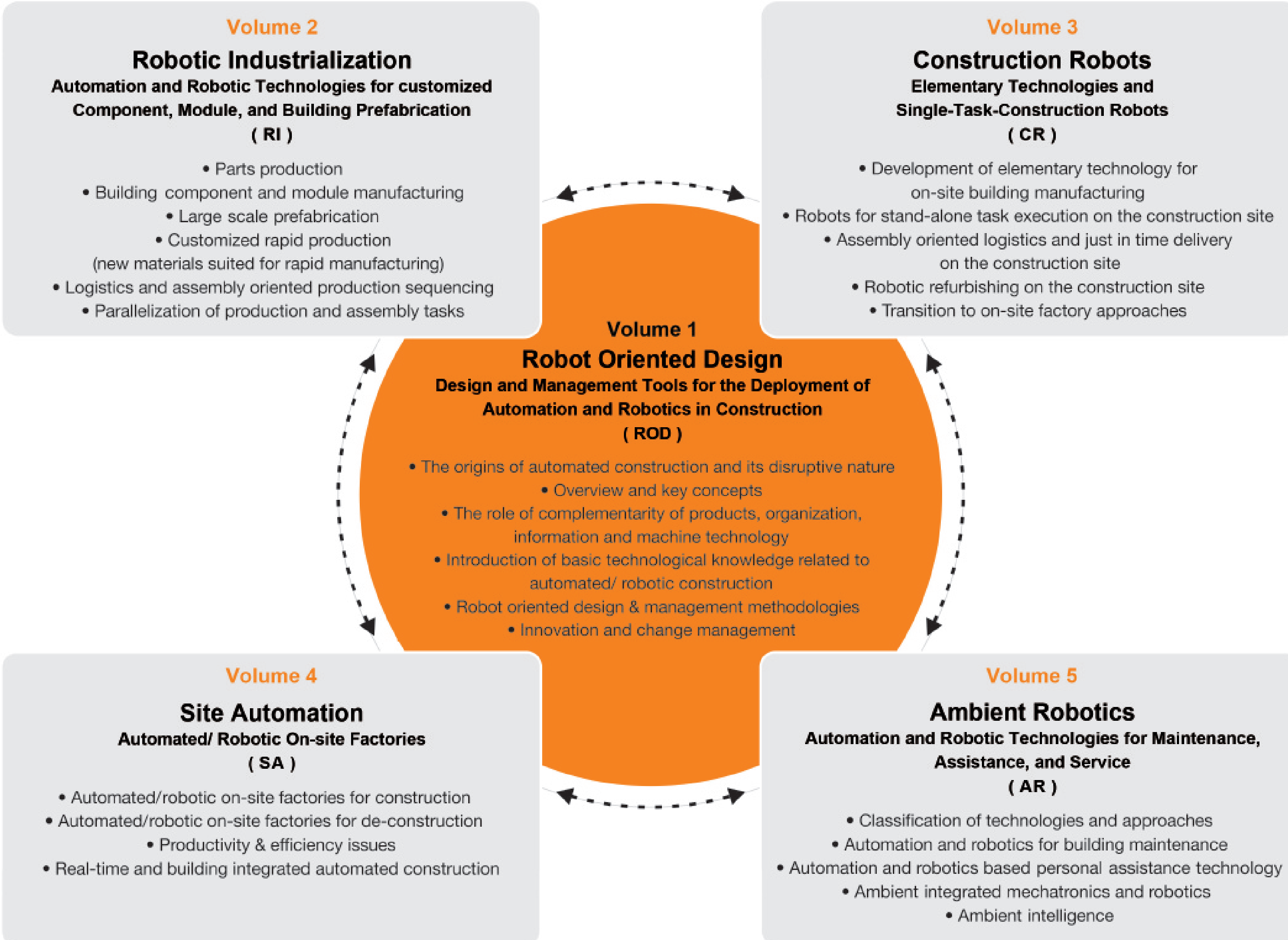

Figure 1.4. Thematic fields covered by the Cambridge Handbooks on Construction Robotics books.

technologies. Buildings become integrated with a multitude of new subsystems and extend their performance to areas that have formerly not been considered as part of the construction and building industry. With the integration of microsystems technology, mechatronics, service robotics and robotic features into buildings, and because of the tendency towards more and more integration of users in early design phases, buildings can become not only more intelligent, but they can also be much more personalized to the inhabitants' needs and could further serve as platforms for a multitude of commercial services. These changes could have a tremendous impact on the whole value chain and are likely to transform building structures, construction technologies, and business models. Therefore, it is necessary to anticipate future developments accompanying the new performance scope of "robotic" buildings and to create relations to automated/robotic construction. **Volume 5** outlines and discusses all of these aspects.