Introduction

In this volume, concepts, technologies, and developments in the field of building component manufacturing (BCM, outlined in Chapter 2) based on concrete, brick-work, wood, and steel materials, as well as building module manufacturing (outlined in Chapter 3) and large-scale prefabrication (LSP, outlined in Chapters 4 and 5) with the potential to deliver complex components and products, are introduced and discussed. BCM refers to the transformation of materials, parts and low-level components into higher level components through the use of highly mechanized, automated, or robot-supported industrial settings. The definitions of components share a common element; they are, more or less, a complex combination of individual preexisting basic elements, parts and/or lower level components. BCM should also be distinguished from the manufacturing of more complex modules (e.g., prefabricated bath modules) or units (products of LSP companies, e.g., prefabricated three-dimensional building sections as manufactured, for example, by Toyota Home and Sekisui Heim).

For highly automated LSP, according to the original equipment manufacturer (OEM; see also Section 1.1) model, component manufacturers (BCM companies) represent Tier-1 or Tier-2 suppliers. Tier-1 suppliers deliver components directly to LSP companies such as Sekisui Heim, whereas Tier-2 suppliers would, for example, provide them to the suppliers of the bath or kitchen modules (building module manufacturers). For automated construction sites utilizing singe-task construction robots (STCRs, see **Volume 3**) or automated/robotic on-site factories (see **Volume 4**), low- and high-level components manufacturers (BCM, manufacturers of modules, LSP) again represent Tier-*n* suppliers.

In automotive manufacturing, for example, the Smartville factory (Volume 1, Section 4.3.4) demonstrates that the delivery of well prefabricated, high-level components to the final integrator and assembly line considerably reduces task variability, the amount of necessary assembly operations, organizational complexity and lead times and increases significantly the possibility to automate. Well-designed basic elements/parts/components are able to foster the creation of a structured environment (SE) in the receiving value added step. Therefore, as outlined in Volume 1, Section 6.3, in automated/robotic construction the whole value chain has to be considered, as each value added step holds the potential for prestructuring and simplification of processes (major success factor for efficient automation/use of robotic technology)

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for the subsequent value-added steps. So, for example, the process of transformation of raw materials into basic elements by additive manufacturing holds the potential to create basic elements that are directly customized/optimized for the automated processing by a certain machine into complex parts or low-level components in a subsequent value added step. The manufacturing of parts or low-level components then can (e.g., through the embedding/imprinting of compliant joints, guiding elements, and sensors/tags for guiding the end-effectors picking them; see also Volume **1**, Section 6.5) can simplify/foster assembly by a robot system into more complex components as, for example, walls or panels or units. Similarly, the module manufacturing and LSP industries can through the delivery of manufacturing optimized modules, panels and units reduce on-site assembly complexity (amount and variety of tasks) and thus foster the efficient use of robots operated on partly automated construction sites (SCTRs) or within highly automated/robotic on-site factories. Furthermore, BCM, module manufacturing and LSP are able to insert functionality in components (e.g., sensor elements, microsystem technology) that is able to foster features related to ambient robotics (Volume 5) as, for example, robot-enabled maintenance, recustomization, and other building integrated life-support services.

1.1 OEM Model and Manufacturing Strategy

In industries in which highly complex products are manufactured (automotive, aircraft, and in particular, building industry; see also **Volume 1, Chapter 5**) individual components are often so complex that a supplier must rely on other suppliers, thus leading to the OEM model (Figure 1.1; for more details, see **Volume 1**).

The concept of prefabrication, to which the aforementioned concepts belong, becomes increasingly important in our industrialized economies. In recent years, there has been an increase in the use of prefabrication, not only in building construction, but also in other industries such as automotive manufacturing, engine construction, and food supply. Time plays a big role in today's society and is a factor in many areas of various markets. The goal of prefabrication should be to improve the efficiency and performance of a product. The term efficiency (see also **Volume 1, Section 4.1**) encompasses many aspects, as the goal is not limited to pure cost reduction, but more so to the upholding of quality while saving time through the shortening of building phases, and reducing failure cost. The money saved is then available for the end-user, system operator, contractor or machine supplier – for example, to be reinvested into research towards superior product performance and thus to trigger a performance multiplication effect (PME; a basic concept in automated/robotic construction, discussed throughout **Volume 1**).

A well-planned manufacturing strategy is the key to successful prefabrication. A manufacturing strategy can be classified into hard and soft items. Hard items comprise decisions such as production capacity, factory network, selection of production technology, and vertical integration. Conversely, personnel/labour management, supplier management, production plan control, costing, and general management can be classified as soft items. The materials used determine both hard and soft production items. Brickwork, steel, concrete, carbon fibre composites, wood – every construction material that determines the primary and secondary structure of a building – has specific requirements and potentials. In addition, depending on



Highly complex prefabricated sections of buildings

Complex prefabricated elements (e.g., prefabricated bath cells)

Simple prefabricated elements

DEM-like integration structure in automated/robotic construction

(e.g., prefabricated wall elements)

Transformation of raw materials into

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Figure 1.1. OEM model. OEMs rely on suppliers, called Tier-*n* suppliers, according to their rank in the supply chain. The model explains the general flow of material as well as the flow of information during manufacturing of the product and its subcomponents (Authors' interpretation based on Kurek, 2004). In an OEM-like integration structure, well-designed building components are able to foster the creation of a structured environment (SE) in the receiving value added step. Therefore in automated/robotic construction the whole value chain has to be

Prefabrication/pre-assembly

Pure production

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the material and local area, various construction types have been developed that must be synchronized with a specific manufacturing strategy. BCM and LSP refers to the transformation of materials, parts and low-level components into higher-level components through highly mechanized, automated, or robot-supported industrial settings and manufacturing systems. The term "manufacturing" is used in this volume (as well as in the other volumes in the series) as an umbrella term that covers both production (a process or set of processes that transform raw material into treatable basic elements, parts or low-level components) and assembly (a process or set of processes that joins various basic elements, parts and low-level components into medium/high-level components). Thus, BCM covers the transformation or preparation of individual materials and parts as well as their combination with other elements in a factory or factory-like, structured environments.

1.2 Analysis Framework

The analysis framework used in this volume was set up to enable identification and analysis of the relationship and interplay of products (and product performance), manufacturing strategies, manufacturing layouts and manufacturing technologies related to the factory-based off-site manufacturing of buildings. The previously identified (see Volume 1, Chapter 4) and discussed relevant topics in the areas of modularity, technology, and organization in manufacturing, automation, and robot technology form the basis for the analysis and outline in this volume. Furthermore, the possibility of supporting automated and robotic processes through robot-oriented design (ROD, see also Volume 1, Chapter 6) and generating customized/personalized (or better, industrially and robotically customized/personalized) products by industrialized and highly automated manufacturing systems is analysed. In addition, the analysed manufacturing strategies are related to the greater context of the construction industry (current situation, market shares, and history) as well as emerging topics (e.g., end-of-life strategies) and innovations. Concepts, technologies, and developments in the field of BCM, module manufacturing, and LSP described in this volume are analysed by the framework outlined in Table 1.1.

In general, it can be said that both wood and steel off-site manufacturing methods allow for generating higher level components, and thus higher added value when compared with brickwork and concrete off-site component manufacturing. As the large-scale off-site component manufacturing on basis of steel panels (e.g., Sekisui House) or three-dimensional steel units (e.g., Sekisui Heim) shows, steel structures allow for the generation of a carrier element, carrier frame or template that can be equipped in production line–like, automated SEs with various other parts and components. Furthermore, steel is a material that is easily processed (because of its weight and density) with high precision in an off-site SE. The use of automated systems, robots, and end-effector tools for the processing of steel in SEs has been almost perfected since its large-scale introduction by Henry Ford in a multitude of industries (see **Volume 1**), allowing for a large array of strategies, processes, and technologies to be implemented. This is considered advantageous for the restructuring of the construction industry according to an OEM model with on-site factories (**Volume 4**) as the final integrator of high-level building components.

Organization of this Volume

Table I.I. Analysis tramework	Table 1.1.	Analysis	framework
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Field of analysis	Analysed factors	
Current situation and market shares	Industry shares Manufacturing volumes Raw material consumption	
History	Timeline Beginning of industrialized manufacturing Key persons and periods	
Range of products	Classification based on geometry Classification based on complexity Classification based on function	
Manufacturing methods	Workshop and group-like manufacturing methods Flow–line like, chain-like, and production line–based manufacturing General strategies	
Factory layouts	Comparison of various organizational settings and layouts Modularity	
Subsystems, end-effectors	Subsystems (e.g., assembly lines, logistics systems, crane systems, handling devices, warehouse systems) Subsystems (e.g., welding, bolting, material gripping, material distribution, material orientation, measuring)	
Possibility for industrial customization/personalization	Possibility to customize product by modular approaches Possibility to customize products by automation and robot technology	
Emerging topics in the field	Innovations in the field resulting from new manufacturing methods, technologies, and materials	
End-of-life strategies	Reverse logistics Remanufacturing Recycling	

1.3 Organization of this Volume

The rest of this volume is organized as follows. Chapter 2 focuses on the manufacturing of lower-level components, typically composed of ceramic/brickwork, concrete, wood, steel, glass, and polymers as basic ingredients (building component manufacturing, BCM). Chapter 3 provides examples of the manufacturing of mid-level components (building module manufacturing; e.g., manufacturing of building modules, prefabricated bath modules, or assistance modules, also referred to as building subsystems). Chapters 4 and 5 (large-scale prefabrication, LSP) deal with the off-site manufacturing of complete buildings composed of low-level components, mid-level components, and very high-level components (units). In particular, they focus on systems and kits that are produced (using automation and robot technology) in larger quantities (large-scale).

It must be said that the Japanese LSP industry is far beyond that of other countries in terms of quantities produced, manufacturing technology, and organization, and for this reason, it is described and analysed in detail in a separate chapter (Chapter 5). Japan has the most successful housing prefabrication industry in the world, and has maintained this position for about 40 years. Today, the Japanese

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LSP industry manufactures approximately 150,000 entirely prefabricated housing units per annum, with a continuously increasing degree of quality and embedded, advanced technologies. A peak maximum production was reached in 1994, with approximately 600,000 prefabricated housing units. Apart from the large and consistent market share, it is remarkable that the industry supplies higher market segments (rather than the typical lower market segments) with fully customized, earthquake-resistant, high-tech buildings. To be able to provide outstanding quality, almost all manufacturers use automated machines and robot systems in their factories and organize their means of production along a production chain or even production line. The average salaries paid by Japanese prefabrication companies are among the highest in the Japanese general industry. Most Japanese prefabrication companies have no strong roots in the construction industry but rather originate from multinational chemical, electronics, or automotive companies. Currently, the Japanese LSP industry advances directed towards adding and emphasizing complex additional functions and services playing a major role in the country's disaster prevention and disaster management strategy, and developing and delivering (in the role of a kind of super-OEM) entire "smart" cities that are sustainable, affordable, and assistive. Japan's prefabrication industry currently changes the notion of buildings recognized as simple "construction" products towards the notion of buildings recognized as complex high-tech products with completely new, service-oriented value creation potentials – and its advanced manufacturing capability is the backbone for this evolution.

In sequentially proceeding from manufacturing of basic elements, parts and lower-level components to mid- and high-level components, the order of chapters in this volume strictly follows the organizational structure considered as optimal for the deployment of automated/robotic construction, reflected by the OEM model (Section 1.1) and outlined in depth throughout **Volume 1**.

2 Automation and Robotics in Building Component Manufacturing

Building component manufacturing (BCM) is to be distinguished from the manufacturing of medium/high-level building blocks, such as building modules (Chapter 3) and large-scale prefabrication (LSP, see Chapters 4 and 5). This chapter deals with the BCM of parts, assemblies and lower level components and outlines machine systems and manufacturing processes with a particular focus on automation and robot technology. The components and manufacturing systems outlined are based on the processing one of four main materials: ceramic, concrete, wood, and steel. Each is discussed in a separate section. The sections are structured to acquaint readers with the entire manufacturing process, from the processing of raw materials to the production of parts and, finally, to the assembly of those parts into components. The necessary manufacturing methods are outlined to provide an understanding of the basics, identify the specific properties, and describe the variety of processing methods for each material. The chapter focuses on the specific automated machinery, robot systems, end-effectors, jigs, fixtures, workflows, and process layouts necessary within each material category to make, handle, assemble, and process elements and parts into components.

Roughly similar manufacturing methods are used within all of the four material categories in the production and assembly of building components. First, the materials (with the exception of wood) are obtained from a mixture of various basic substances. To achieve permanent union of the mixture of these substances, a transformation process (e.g., curing or hardening process) is required and specific thermal, atmospheric or pressure conditions must be created. Next, thanks to processes such as, for example, extrusion and moulding, the mixed material can be brought into the required form (e.g., basic, raw parts such as bricks, steel bars, and profiles). Since the described transformation of raw materials into parts doesn't take into account the specifications of the future use, further treatment, manipulation and assembly of these simple elements with other elements is required to produce building components with specifications, features, performances and connectors that allow its use in a larger, more complex, modular systems of components, modules, units and buildings.

The process of manufacturing a specific component is beyond raw material transformation completed in many different steps. Briefly stated, these could include cutting, machining, bending, coating, and assembling of elements. Each building

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component may contain several single elements to be able to offer the desired functions. In BCM (in contrast to conventional construction, where in many cases components are built on the construction site; see Volume 1, Section 6.5.5) the manufacturing processes take place off-site, in a structured environment (SE) of a factory, and require a specific manufacturing layout for each material. In this SE advanced manufacturing methods can be used to produce and if necessary customize or personalize the components. In SEs, emerging techniques, such as flexible automation, modular manufacturing systems, flexible jigs/fixtures/end-effectors, robotic systems and the various forms of 3D printing, are ameliorating the industrial production of building components and provide completely new ways of customizing/personalizing components either for subsequent assembly processes (e.g., assembly in LSP [Chapters 4 and 5], processing by STCRs [Volume 3] or processing by automated/robotic on-site factories [Volume 4]) or the use phase of the building and the customer. Each of the following sections outlines the cutting edge manufacturing technology in each of the four BCM component fields (brickwork/ceramic, concrete, wood, and steel) and makes the reader familiar with manufacturing processes, layouts, and equipment.

2.1 Brickwork- and Ceramics-Based Components

In this section, the concept of a brick refers to the volumetric unit of construction that comprises brickwork building components such as walls and slabs. It also refers to any construction techniques that may emerge from this, not necessarily to the classic clay-based brick. The material could be any kind that is used in the brick element production phase: clay, adobe system, concrete, lime, sand, aggregate, and so on. Advanced machines, automated processes, and robot systems play a large role in the production of low-level parts and components as well as in the assembly of parts and low-level components into higher-level components (e.g., complete wall or ceiling components). Brickwork structures can be preassembled using SEs, advanced machines, automated processes, and robot systems, either off-site or onsite. It is therefore shown in this section that machine systems, logistical aspects, and designs of parts and components must be adapted to the specific use case. An overview of brick and ceramic component manufacturing is also provided. First, traditional brick element fabrication and manipulation techniques are introduced. Next, modern automated or robotic techniques for brick working are described. It should be said that brick and ceramics are one of the oldest construction materials, and some of the original technology may have been diluted in the current field of construction. The latest robotic extrusion and moulding systems have opened up new methods for creating new industrially customized/personalized products from these historic materials. In extensively rewritten and expanded form, Bock and Linner (2009d) builds the basis for Section 2.1.

2.1.1 History and Techniques of Brick and Ceramic Parts Production

Throughout history, brick and ceramic elements have been successfully used as building materials around the world. What are the main factors contributing to this success? Bricks and ceramics are composed primarily of inexpensive and abundant materials such as clay, sand, and lime. Ceramic is defined as a crystallized nonmetallic

Brickwork- and Ceramics-Based Components

material (Carter et al., 2013). The crystallization is done through a heating process. Today, a large majority of brick elements are ceramic, although the primitive dried brick, adobe, or mud brick was left to dry without creating a ceramic composition (Schmandt-Besserat, 1977; Stordeur et al., 2007). These bricks don't have an inner crystalline structure, and so they are not considered ceramics. In the very beginning, components used to be manually mixed and moulded with some water. When drying, normally outdoors and under the sun, there was no chemical reaction or liaison between the sand and lime. Once the adobe had been placed in a wall, if it was in contact with a large quantity of water, dried brick elements could become diluted. To improve the inner structural composition, ceramic and fired brick production was introduced (Khan et al., 2013). The elements were fired in kilns to achieve a crystalline nonmetallic substructure that made the element more stable. The more it was vitrified, the easier the material was shaped in fine forms. In that sense, porcelain is considered a highly vitrified type of ceramic (Carbajal et al., 2007). The brick manufacturing technique was further improved by the tunnel kiln (hereafter referred to as a kiln brick) in which the bricks travel through a type of linear oven (Ritchie, 1980). Another step towards the industrialization of brick manufacturing was the development of extruded bricks (Händle, 2007). A clay, sand, and lime mixture is pushed through a die and the profile created is cut to the required measurement. This way, the intended form is shaped much faster than using moulds. Special materials such as quartz, crushed flint, and siliceous sand are added to the initial ingredients. These materials are shaped with water and, to combine the sand and lime chemically, the bricks are subjected to forces in highly pressurized chambers, also called autoclaves. Calcium silicate bricks are created in this way (Bowley, 1994). Fly ash bricks are produced in a similar way, but ash obtained from coal combustion is added to the mixture (Cicek et al., 2007). One of the latest developments in ceramics is ceramic matrix composites (CMCs) or ceramic fiber reinforced ceramic (CFRC) (Chawla, 1998). These materials have excellent heat resistance and toughness, which allows them to be used as parts of brakes on aircraft and sports cars.

2.1.2 Keys and Figures

Brickwork construction has long been a tradition and is still one of the main building techniques used today. For residential buildings, the system is often the preferred first option, as opposed to other options such as concrete or steel. In the construction of residential buildings the use of brickwork is more popular than ever before in Germany thanks to the emergence of mechanized and partly automated assistance equipment (Figure 2.1).

2.1.3 Classification of Ceramic Construction Elements and Brickwork Products

The use of different moulds, dies, and turning tables enables the production of different shapes of ceramic elements. Both simple and customized elements can be assembled to create building components. Below, a classification of the morphology of brickwork and ceramic construction elements is presented.

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Figure 2.1. Assistance technology by Layher. (Photo: Layher Bautechnik GmbH)

- 1. *Simple elements*. All brick unit types are included in this classification. The bricks are available with/without holes, in all dimensional standards and quality for all types of brickwork.
- 2. *Customized elements*. Analysing another aspect at the volumetric level, customized elements are similar to single elements but with a higher complexity; they are more developed and designed for special functions in the building assembly system.
- 3. *Building components*. Bricks can be prearranged directly from factory production to build prefabricated building components such as walls and slabs. A particular aspect of the brickwork off-site production is that usually, in contrast with prefabricated concrete production, off-site component production brickwork is not associated directly with the brick production facilities. Usually, the brick production factories are separate and work as suppliers for assemblers.

2.1.4 Manufacturing Methods

We can differentiate between two main phases in the manufacturing process of brickwork/ceramic components. First, the basic element, that is, the brick or ceramic element, is produced from the raw materials. Then those basic elements are joined together to create a more complex (customized) element (which can then be referred to as a component). Ceramic basic elements can be produced in many ways and the production primarily consists of a few basic steps. First, the basic ingredients of the required material are mixed with water in order to create a mixture. Second, this mixture is transformed and brought into shape through a first mechanical manipulation process (e.g., moulded or extruded). All materials are able to take diverse sizes