1 Introduction

In this volume, concepts, technologies, and developments in the field of building component manufacturing (BCM, outlined in Chapter 2) based on concrete, brickwork, 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) 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

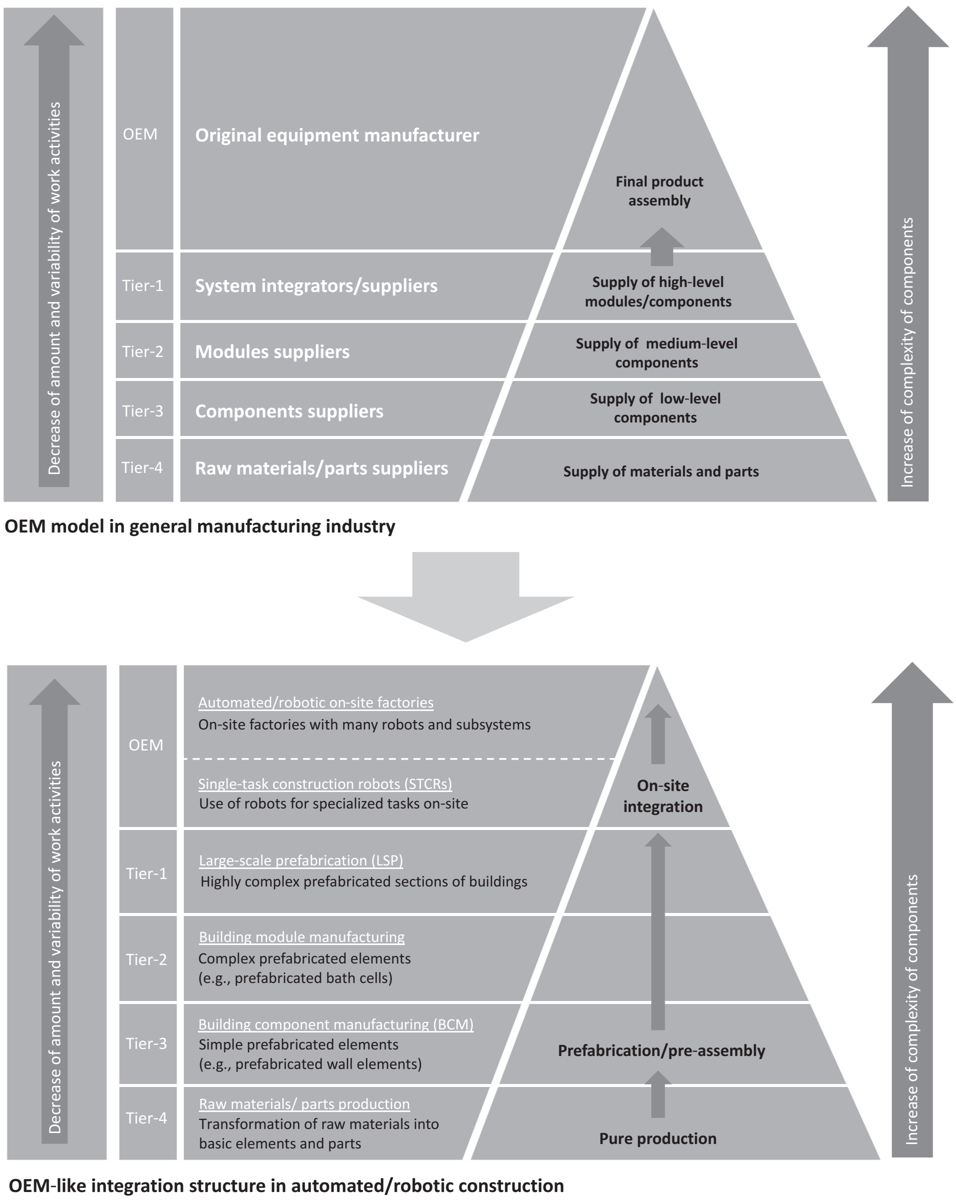

Figure 1.1. OEM model. OEMs rely on suppliers, called Tier-*n* suppliers, according to their rank in the supply chain. The model explains the general flow of material as well as the flow of information during manufacturing of the product and its subcomponents (Authors' interpretation based on Kurek, 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 considered (from raw material transformation to final assembly and operation/deconstruction of buildings), as each value added step holds the potential for prestructuring and simplification of processes (major success factors for efficient automation/use of robotic technology) for the next value added step.

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.

Table 1.1. *Analysis framework*

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

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