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978-1-107-07639-6 - Robotic Industrialization: Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication

Thomas Bock and Thomas Linner

Frontmatter

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## ROBOTIC INDUSTRIALIZATION

*Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication*

The Cambridge Handbooks on Construction Robotics series focuses on the implementation of automation and robot technology to renew the construction industry and to arrest its declining productivity. The series is intended to give professionals, researchers, lecturers, and students basic conceptual and technical skills and implementation strategies to manage, research, or teach the implementation of advanced automation and robot technology-based processes and technologies in construction. Currently, the implementation of modern developments in product structures (modularity and design for manufacturing), organizational strategies (just in time, just in sequence, and pulling production), and informational aspects (computer-aided design/manufacturing and computer-integrated manufacturing) are lagging because of the lack of modern integrated machine technology in construction. The Cambridge Handbooks on Construction Robotics books discuss progress in robot systems theory and demonstrate their integration using real systematic applications and projections for off-site as well as on-site building production.

In this volume, concepts, technologies, and developments in the field of building-component manufacturing – based on concrete, brick, wood, and steel as building materials and on large-scale prefabrication, which holds the potential to deliver complex, customized components and products – are introduced and discussed. Robotic industrialization refers to the transformation of parts and low-level components into higher-level components, modules, and finally building systems by highly mechanized, automated, or robot-supported industrial settings in structured off-site environments. Components and modules are (in modular building product structures) independent building blocks that are delivered by suppliers to original equipment manufacturers such as large-scale prefabrication companies or automated/robotic on-site factories. In particular, Japanese large-scale prefabrication companies have altered the building structures, manufacturing processes, and organizational structures significantly to be able to assemble in their factories high-level components and modules from Tier-1 suppliers into customized buildings by heavily utilizing robotic technology in combination with automated logistics and production lines.

**Thomas Bock** is a professor of building realization and robotics at Technische Universität München (TUM). His research has focussed for thirty-five years on automation and robotics in building construction, from the planning, prefabrication, on-site production, and utilization phases to the reorganization and deconstruction of a building. He is a member of several boards of directors of international associations and is a member of several international academies in Europe, the Americas, and Asia. He consulted for several international ministries and evaluates research projects for various international funding institutions. He holds honorary doctor and professorship degrees. Professor Bock serves on several editorial boards, heads various working commissions and groups of international research organizations, and authored or coauthored more than 400 articles.

**Thomas Linner** is a postdoctoral researcher in building realization and robotics and a research associate at TUM. He completed his dissertation (Dr.-Ing.) in 2013 in the field of automation and mass customization in construction with a particular focus on automated/robotic on-site factories. Dr. Linner is a specialist in the area of automated, robotic production of building “products” as well as in the conception and performance enhancement of those products through the embedding of advanced technology (service robots, microsystems technology). Today, more and more, issues related to innovation management are becoming key topics in his research. Dr. Linner is a frequently invited speaker at universities such as the University of Tokyo and Cambridge University.

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[More information](#)

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# Robotic Industrialization

## **AUTOMATION AND ROBOTIC TECHNOLOGIES FOR CUSTOMIZED COMPONENT, MODULE, AND BUILDING PREFABRICATION**

**Thomas Bock**

Technische Universität München

**Thomas Linner**

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Thomas Bock and Thomas Linner

Frontmatter

[More information](#)

## Contents

<i>Acknowledgements</i>	<i>page</i> ix
<i>Glossary</i>	xiii
<b>1 Introduction</b> . . . . .	<b>1</b>
1.1 OEM Model and Manufacturing Strategy	2
1.2 Analysis Framework	4
1.3 Organization of this Volume	5
<b>2 Automation and Robotics in Building Component Manufacturing</b> . . . . .	<b>7</b>
2.1 Brickwork- and Ceramics-Based Components	8
2.1.1 History and Techniques of Brick and Ceramic Parts Production	8
2.1.2 Keys and Figures	9
2.1.3 Classification of Ceramic Construction Elements and Brickwork Products	9
2.1.4 Manufacturing Methods	10
2.1.5 Possibilities for Industrial Customization	12
2.1.6 End-Effectors and Automated Processes	12
2.1.7 Factory Layouts	20
2.1.8 Emerging Techniques in the Field	22
2.1.9 End-of-Life Strategies	24
2.2 Concrete-Based Components	25
2.2.1 History and Techniques of Concrete Prefabrication	26
2.2.2 Keys and Figures	27
2.2.3 Classification of Precast Concrete Products	28
2.2.4 Manufacturing Methods for Precast Concrete	30
2.2.5 Possibilities for Industrial Customization	32
2.2.6 Equipment and End-Effectors for Automated Production	33

Cambridge University Press

978-1-107-07639-6 - Robotic Industrialization: Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication

Thomas Bock and Thomas Linner

Frontmatter

[More information](#)

vi

*Contents*

2.2.7	Factory Production Layouts	36
2.2.8	Emerging Techniques in the Field	36
2.2.9	End-of-Life Strategies	43
2.3	Wood-Based Components	43
2.3.1	History and Techniques of Wood/Timber Construction and Prefabrication	43
2.3.2	Keys and Figures	44
2.3.3	Classification of Products	44
2.3.4	Manufacturing Methods	46
2.3.5	Possibilities for Industrial Customization	47
2.3.6	End-Effectors and Automated Processes	49
2.3.7	Factory Production Layouts	52
2.3.8	Emerging Techniques in the Field of Timber Prefabrication	52
2.3.9	End-of-Life Strategies	54
2.4	Steel-Based Components	54
2.4.1	History and Techniques of Steel Production	54
2.4.2	Keys and Figures	55
2.4.3	Classification of Products	55
2.4.4	Manufacturing Methods: Steel Elements	57
2.4.5	Possibilities for Industrial Customization	60
2.4.6	End-Effectors and Automated Processes	61
2.4.7	Factory Production Layouts	62
2.4.8	Emerging Techniques in the Field	63
2.4.9	End-of-Life Strategies	63
3	<b>Building Module Manufacturing</b> . . . . .	66
4	<b>Comparison of Large-Scale Building Manufacturing in Different Countries</b> . . . . .	72
4.1	Germany	73
4.1.1	Wood-Based Housing Prefabrication in Germany	73
4.1.2	Steel-Based Building Prefabrication in Germany	76
4.2	United Kingdom	82
4.2.1	History	82
4.2.2	General Overview	83
4.2.3	Companies	84
4.2.4	Manufacturing Methods	87
4.2.5	Conclusion	87
4.3	Spain	88
4.3.1	History	88
4.3.2	General Overview	88
4.3.3	Companies	88
4.3.4	Manufacturing Methods	88
4.3.5	Conclusion	89
4.4	China	89
4.4.1	History	89

Cambridge University Press

978-1-107-07639-6 - Robotic Industrialization: Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication

Thomas Bock and Thomas Linner

Frontmatter

[More information](#)*Contents*

vii

4.4.2	General Overview	89
4.4.3	Companies	89
4.4.4	Manufacturing Method	91
4.4.5	Conclusion	92
<b>5</b>	<b>Large-Scale Building System Manufacturing in Japan . . . . .</b>	<b>93</b>
5.1	Background, Development, and Strategy of the Industry	94
5.1.1	Overview Companies (Turnover, Output, Employees, Prices, Factories)	94
5.1.2	Japan's Prefabrication Industry Today and Tomorrow	96
5.1.3	Karakuri Technology Diffusion in Japan	98
5.1.4	Influences of Local and Cultural Specifics and Disasters	99
5.1.5	Roots in Chemicals, Electronics, and the Automotive Industry	101
5.1.6	Drivers for Prefabrication in Japan	103
5.1.7	First Approaches to Mass Production: Premos Home	104
5.1.8	Sekisui Heim's M1	107
5.1.9	From Japan's Traditional Organizational Culture towards TPS and Toyota Home	109
5.1.10	Automated and Robotized Production as Sales Argument	110
5.1.11	Sekisui Heim – ERP Systems for the Control of Increasing Complexity	111
5.1.12	Timeline of Evolution of Prefabrication in Japan	112
5.2	Robot-Oriented Design and Management Strategies Used in the Japanese Prefabrication Industry	116
5.2.1	The Idea of Robot-Oriented Design and Management	116
5.2.2	Complementarity as a Key Element in the Success of Automated Prefabrication in Japan	116
5.2.3	Robotic Logistics-Oriented Design	117
5.2.4	Robotic Assembly-Oriented Design	118
5.2.5	Degree of Structuring/Automation of Off-Site and On-Site Environments	119
5.2.6	OEM-like Integration Structure	121
5.2.7	Modular Coordination	121
5.2.8	Control of Variation by Platform- and Same-Parts Strategies	121
5.2.9	Linking of Customer and Manufacturing System	122
5.2.10	Innovation and R&D Capability as Key Elements of the Business Strategy	125
5.2.11	Performance Multiplication Effect	126
5.3	The Manufacturing Process	128
5.3.1	Product Variety and Types of Prefabrication	129
5.3.2	Production Process Explained by Sekisui's and Toyota's Unit Method	129
5.3.3	Factory Layouts and Process Design Strategies	135

Cambridge University Press

978-1-107-07639-6 - Robotic Industrialization: Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication

Thomas Bock and Thomas Linner

Frontmatter

[More information](#)

5.4	Analysis of Selected Companies and Their Manufacturing Systems	148
5.4.1	Sekisui House (Fully Panelized Steel Kit)	149
5.4.2	Daiwa House (Steel Frame Combined with Panels)	159
5.4.3	Pana Home (Steel Panels Combined with Steel Components)	162
5.4.4	Sanyo Homes Corporation (Steel Frame Combined with Panels)	166
5.4.5	Asahi Kasei – Hebel House Homes (Steel Frame Combined with Aerated Concrete Panels)	168
5.4.6	Misawa Homes Sub- and Mini-Assembly Units (Wood Panels)	171
5.4.7	Mitsui Home (Wood Panels)	174
5.4.8	Tama Home (Wooden Frame Combined with Panels)	176
5.4.9	Muji House (Wooden Frame Combined with Panels)	181
5.4.10	Sekisui Heim (Steel Units)	185
5.4.11	Toyota Home (Steel Units)	198
5.4.12	Misawa Homes Hybrid (Steel Units)	201
5.4.13	Sekisui Heim Two-U Home (Wood Units)	206
5.5	Evolving Tendencies in the Evolution of the Japanese Prefabrication Industry	207
5.5.1	Advanced Product Service Systems	208
5.5.2	Prefabrication Industry as Part of a Large-Scale Disaster Management Strategy	211
5.5.3	Extending the Value Chain through the Development of Prefabricated, Sustainable High-Tech Settlements	216
5.5.4	Reverse Innovation: Mass-Customized Housing Production as a Prototype for Future Manufacturing Systems	222
	<i>References</i>	225
	<i>Index</i>	233



Cambridge University Press

978-1-107-07639-6 - Robotic Industrialization: Automation and Robotic Technologies for Customized Component, Module, and Building Prefabrication

Thomas Bock and Thomas Linner

Frontmatter

[More information](#)

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Thomas Bock and Thomas Linner

Frontmatter

[More information](#)

---

### *Acknowledgements*

xi

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Frontmatter

[More information](#)

---

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Frontmatter

[More information](#)

## Glossary

**Alignment and accuracy measurement system (AAMS):** An AAMS creates a feedback loop between a system that measures how accurately components are positioned and an alignment system (e.g., a motorized unit attached temporarily to the joint of a column component) that automatically moves or aligns the *component* into the desired final position.

**Assembly:** In this book, assembly refers to the production of higher-level components or final products out of *parts* and lower-level *components*. The process of assembly of an individual *part* or *component* to a larger system involves positioning, alignment, and fixation operations. *Upstream* processes dealing with the generation of elements for assembly are referred to as *production*.

**Automated guided vehicle (AGV):** Computer-controlled automatic or robotic mobile transport or logistics vehicle.

**Automated/robotic on-site factory:** *Structured environment* (factory or factory-like) setup at the place of *construction*, allowing *production* and *assembly* operations to be executed in a highly systemized manner by, or through, the use of machines, automation, and robot technology.

**Batch size:** The amount of identical or similar products produced without interruption before the manufacturing system is substantially changed to produce another product. Generally speaking, low batch sizes are related to high fixed costs and high batch sizes are related to low fixed costs.

**Building component manufacturing (BCM):** BCM refers to the transformation of *parts* and low-level *components* into higher-level *components* by highly mechanized, automated, or robot-supported industrial settings.

**Building integrated manufacturing technology:** Automation technology, microsystem technology, sensor systems, or robot technology can be directly integrated into buildings, units, or components as a permanent system. Technology used to manufacture the building can thus become a part of the building technology.

**Bundesministerium für Bildung und Forschung (BMBF):** Federal Ministry of Education and Research in Germany. The BMBF funds education, research, and technical development in a multitude of industrial fields.

- Capital intensity:** The capital intensity (also referred to as workplace cost) is calculated by dividing the capital stock (assets, devices, and equipment used to transform/manufacture the outcome) by the number of employees in the industry. The construction industry not only has one of the lowest capital stocks, but also capital intensity is by far the lowest compared to other industries in Germany.
- Chain-like organization:** In a chain-like organization, the *flow of material* between individual workstations is highly organized and fixed, and a material transport system linking the stations exists.
- Climbing system (CS):** Automated/robotic on-site factories require, especially in the manufacturing of vertically oriented buildings, a system that allows the *sky factory* (SF) to rise to the next floor, once a floor level has been completed. Most SFs, therefore, rest on stilts that transfer the loads of the SF to the building's bearing structure, or to the ground. Other CSs are able to climb along a central core, pushing up the building or, in the case of the manufacture of horizontally orientated buildings, for example, to enable the factory to move horizontally. In some cases, in addition to climbing, CSs are used to provide a fixture or template for the positioning of components by *manipulators*. Because of the enormous forces necessary to lift SFs, hydraulic systems and screw presses are common actuation systems.
- Closed loop resource circulation:** Systems for avoiding waste and reduction of resource consumption, by integrating concepts such as reverse logistics, remanufacturing, and recycling. Material or product that flows on a factory, utilization, and deconstruction level can be related back to the manufacturing system to close the loop.
- Closed sky factory (CSF):** *Sky factory* that completely covers and protects the workspace in *automated/robotic on-site factories*, thus allowing the installation of a fully *structured environment* that erases the influence of parameters that cannot be 100% specified (e.g., rain, wind).
- Component:** In this book, in a hierarchical modular structure, components can be divided into lower-level components and higher-level components. Components consist of subelements of *parts* and lower-level components. Higher-level components can be assembled into *modules* and *units*.
- Component carriers:** Component carriers and pallets (special types of component carriers) play an important role in logistics. In many cases, parts, components, or final products cannot be directly handled or manipulated by the logistics system. Component carriers and pallets act as mediators between the handled material and the actual logistics system.
- Computer-aided design/computer-aided manufacturing (CAD/CAM):** From the 1980s on, the novel and highly interdisciplinary research and application field CAD/CAM was formed, which aimed at integrating computerized tools and systems from the planning and engineering field with manufacturing and machine control systems to allow for a more-or-less direct use of the digital design data for automated and flexible manufacturing. The field evolved further toward *computer-integrated manufacturing*.
- Computer-aided quality management (CAQM):** Control of quality by software, made possible through the linking of manufacturing systems with computer systems.

**Computer-integrated manufacturing (CIM):** From the 1990s on, the combined *computer-aided design/computer-aided manufacturing* approach evolved into the CIM approach. The focus was then broader and the idea was that more and more fields and tools, and also business economic issues (e.g., computer-aided forecasting or demand planning), could be integrated by computerized systems to form continuous process and information chains in manufacturing that span all value-adding nodes in the value system.

**Connector system:** The development of connector systems that connect complex *components* in a robust way to each other is a key element in complex products such as cars, aircraft, and buildings in particular. To support efficient *assembly*, connector systems can, for example, be compliant or plug-and-play-like. Connector systems can also be designed to support efficient disassembly, remanufacturing, or recycling.

**Construction:** Activities necessary to build a building on-site. Construction, in this book, is interpreted as being a manufacturing process, and accordingly buildings are seen as “products.”

**Cycle Time:** Important on the workstation level: The cycle time refers to the time allowed for all value-adding activities performed by humans and machines at a workstation within a network of workstations.

**Degree of freedom (DOF):** In a serial kinematic system each joint gives the systems, in terms of motion, a DOF. At the same time, the type of joint restricts the motion to a *rotation* around a defined axis or a *translation* along a defined axis.

**Depth of added value:** The depth of added value (e.g., measured as a percentage of the total cost of the product) refers to the total amount of value-adding activities, and thus in general to the amount of value-adding steps, realized by the *original equipment manufacturer* (OEM) or final integrator. A high depth of added value means that a large number of value-adding activities are being realized by the OEM (e.g., Henry Ford). A low depth of added value means that a low number of value-adding activities is being realized by the OEM (e.g., Dell, Smart).

**Design for X (DfX):** DfX strategies aim at influencing design-relevant parameters to support production, assembly maintenance, disassembly, recycling, and many other aspects related to a product’s life cycle. In this book, DfX strategies are classified into four categories: DfX related to *production/assembly*, to product function, to product end-of-life issues, and to business models. In this book, *robot-oriented design* is seen as an augmentation or extension of conventional DfX strategies, consequently aiming more at the efficient use of automation and robotic technology in all four categories.

**Deutscher Kraftfahrzeug-Überwachungs-Verein (DEKRA):** Major German consultant and surveyor association that evaluates technical artefacts, such as cars and buildings, and defines quality and the causes of defects.

**Efficiency:** Efficiency can be defined as the relationship between an achieved result and the combination of factors of production. Whereas *productivity* expresses an input-to-output ratio, with a focus on a single factor of production, efficiency considers multiple factors and their combination and interrelation. Productivity can be an indication of efficiency, and efficiency itself for economic feasibility.

**End-effector:** The element of machines, automation systems, or robot technology that makes contact with the object to be manipulated in *manufacturing* is called the end-effector. In most cases end-effectors are modularly separable from the base system. End-effectors have a certain degree of *inbuilt flexibility*.

**Factory external logistics (FEL):** FEL refer to logistics systems that connect the supply network to the factory integrating and assembling the supplied *parts, components, modules, or units*. FEL influences the organization of the manufacturing system, *factory internal logistics*, and the factory layout.

**Factory internal logistics (FIL):** FIL refers to logistics systems that manipulate *parts, components, modules, units*, or the finished product within a manufacturing setup or factory, for example, for the transportation between various stations. Other examples include mobile and non-rail-guided transport systems, overhead crane-type material transportation systems, fixed conveyor systems allowing a component carrier or the product itself to travel in a horizontal direction in fixed lanes, and fixed conveyor systems allowing a component carrier or the product itself to travel in a vertical direction in fixed lanes. Novel cellular logistics robots combine capabilities of unrestricted mobility with horizontal and vertical transport capabilities and can travel freely and self-organize with other systems.

**Factory roof structure:** Structure that allows the workspace on the construction site to be covered (and therefore to be protected from outside influences such as wind, rain, or sun) and thus creates the basis for a *structured environment*. Often used as a platform for the attachment of other subsystems, such as a *climbing system, horizontal delivery system, and overhead manipulators*.

**Final integrator:** In this book, a final integrator refers to an entity in a value chain or value system that integrates major components into the final product. Within the OEM model, the final integrator is called *original equipment manufacturer*.

**Fixed-site manufacturing:** *Off-site manufacturing* or *on-site manufacturing* system that stays at a fixed place during final *assembly*.

**Floor erection cycle (FEC):** Time necessary to erect and finish (including technical installations and general interior finishing) a standard floor with an *automated/robotic on-site factory*.

**Flow-line organization:** In a flow-line organization, individual workstations do not have a fixed *flow of material*, but a general directional *flow of material* (e.g., within a factory segment or a factory).

**Flow of material:** Refers to material and product streams in relation to space and time that take place during the completion of a specific product in a manufacturing system and the supply network connected to it. The *efficiency* of the flow of material is determined by the arrangement of equipment, the factory layout, and the logistics processes.

**Frame and infill (F&I):** F&I strategies are used in a variety of industries, including the aircraft, automotive, and building industries. The idea of an F&I strategy is to use a bearing frame structure as a base element that is subsequently equipped with *parts, components, systems, modules*, and so forth during the manufacturing process. The frame thus functions as a *component carrier*. In the aircraft industry,



the fuselage is interpreted as such a frame; in the automotive industry it is the car body or chassis; and in the building industry it can be seen, for example, in the form of two-dimensional (e.g., Sekisui House) or three-dimensional steel frames (Sekisui Heim).

**Ground factory (GF):** *Structured environment* (factory or factory-like) setup on the construction site on the ground level of the building as part of an *automated/robotic on-site factory*.

**Group-like organization:** In a group-like organization, individual workstations are bound together in groups. Those groups can refer to workstations with similar means of production or to workstations with complementary *means of production*. The *flow of material* between those groups can be either fixed or flexible.

**Horizontal delivery system (HDS):** System that transports, positions, and/or assembles *parts/components* on the construction site on a floor level.

**Idle time:** The unproductive standstill of a machine from end of completion to the beginning of the processing of the next material. Bottleneck operations, for example, may – when workstations are directly connected without a buffer – lead to material having to wait for a certain time until the next material can be processed and to an unproductive standstill of other workstations that are faster in processing the material.

**Inbuilt flexibility:** The changes in a manufacturing system can be realized without major physical or modularization enabled changes (e.g., exchange of systems, workstations, robots, *end-effectors*), but by reprogramming the existing system instead. A standard robot with 6 *degrees of freedom* (6-DOF robot) with an end-effector for welding, for example, has a high degree of flexibility and can be reprogrammed for a huge variety of welding operations within a given workspace.

**Joint of a manipulator:** A *manipulator* consists of at least one kinematic pair consisting of two rigid bodies (links) interconnected with a joint. The following types of joints can be distinguished: revolute joint, prismatic joint, and spherical joint.

**Just in sequence (JIS):** Various *parts, components, and products* are delivered from *upstream* to *downstream* workstations in the sequence in which they are handled or processed when they reach the *downstream* work stations. JIS can be performed internally within a factory or in relation to a supplier of an *original equipment manufacturer* (OEM). JIS is in most cases closely connected to *just in time* (JIT).

**Just in time (JIT):** Stocks and buffers are eliminated, and *parts, components, and products* are delivered from *upstream* to *downstream* workstations at the right time and at the right quantity. JIT can be performed internally within a factory or in relation to a supplier of an *original equipment manufacturer*. JIT is in most cases closely connected to *just in sequence*.

**Kinematic base body:** The combination of links and joints forms kinematic bodies that allow basic manipulation operations within a geometrically definable work

space (e.g., Cartesian *manipulator*, gantry *manipulator*, cylindrical *manipulator*, spherical *manipulator*). Those kinematic base bodies consider mainly the first three axes, and thus refer mainly to *positioning* activity. For *orientation*, further *degrees of freedom* and kinematic combinations can be added on top of those base bodies.

**Kinematics:** Kinematics focuses on the study of geometry and motion of automated and robotic systems. It describes parameters such as position, velocity, and acceleration of joints, links, and *tool centre points* to generate mathematical models creating the basis for controlling the actuators and for finding optimized trajectories for the motions of the system. *Manipulators* are a kinematic system consisting of a multitude of kinematic subsystems, of which the kinematic pair is the most basic entity.

**Large-scale prefabrication (LSP):** *Off-site manufacturing* of high-level *components*, *modules*, or *units* in very large quantity by a production-line-based, automation and robotics-driven factory or factory network, interconnected in an *OEM-like integration structure*.

**Link of a manipulator:** A *manipulator* consists of at least one kinematic pair, consisting of two rigid bodies (links) interconnected with a *joint*.

**Logistics systems:** Logistics can be defined as the transport of material within manufacturing systems and supply networks. Logistics is a kind of manipulation of an object by humans, tools, machines, automation systems, and robots (or combinations of those), positioning and orientating objects to be transported or processed in a three-dimensional space. However, logistics operations do not change or transform the material directly. Logistics systems can be characterized according to various scales, such as assembly system scale, factory internal scale (*factory internal logistics*), factory external scale (*factory external logistics*).

**Manipulator:** In this book series, a manipulator refers to a system of multiple links and joints that performs a kinematic motion. Depending on the ratio of autonomy and intelligence, manipulators can be machines, automated systems, or robots.

**Manufacturing:** In this book, manufacturing refers to systems that produce products. Manufacturing integrates *production* (parts or low-level component production) and *assembly* processes.

**Manufacturing lead time:** Time necessary to complete a product within a given manufacturing system, factory, or factory network.

**Mass customization (MC):** MC strategies combine advantages of *workshop-like* and *production-line-like* manufacturing, and thus product differentiation-related competitive advantages, with mass-production-like efficiency. On the product side, MC demands that a product combines customized and standardized elements, for example, through *modularity*, *platform strategies*, and *frame and infill* strategies to be able to efficiently produce it in an industrialized manner. On the manufacturing side, MC demands highly flexible machines, automation systems, or robot technology that removes the need for human labour in the customization process.

**Material handling, sorting, and processing yard (MHSPY):** Subsystem of an *automated/robotic on-site factory*; often related to the *ground factory*. An MHSPY can be a covered environment and/or can be equipped with *overhead manipulators* and allows the simplification or automation of the picking up of *components* from delivering *factory external logistics* in a *just in time* and *just in sequence* manner. An MHSPY can also be used to transform *parts* and low-level *components* into higher-level components on-site. In *automated/robotic on-site factories* used to deconstruct buildings, MHSPYs can be used to transform higher-level *components* into lower-level *components* and *parts*.

**Means of production:** Means of production can be classified into human resources, equipment, and material to be transformed.

**Modular flexibility:** When the change of a product or the variation of a product is so intense that the *inbuilt flexibility* of a manufacturing system, a machine, or an *end-effector* cannot cope with it, a rearrangement or extension of the manufacturing system on the basis of *modularity* becomes necessary. *Modularity* can be generic (predefined process or system modules) or unforeseen (use/design of completely new modules, new configurations).

**Modularity:** Modularity refers to the decomposition of a structure or system into rather independent subentities. It can cover the functional realm as well as the physical realm. If structures or systems are nearly impossible to decompose, on both functional and physical levels, the artefacts are referred to as “integral.” If systems can clearly be decomposed, on both functional and physical levels, artefacts are referred to as “modular.” Clear modularity is, in construction practice, still a rare phenomenon, and conventional buildings show basic characteristics of integral product structures. *Automated/robotic on-site factories*, however, require strict modularity.

**Module:** In this book, in a hierarchical modular structure, modules represent elements on a hierarchical level above high-level *components*. *Parts*, *components*, and modules can be assembled into *units*, which are ranked higher than modules.

**$n$ th,  $n - 1$ ,  $n - 2$ ,  $n - X$  floors:** Inside the main factory (e.g., a *sky factory*) of *automated/robotic on-site factories*, work (component installation, welding, interior finishing, etc.) is done in parallel on several floors ( $n$ -floors). The  $n$ th floor represents the uppermost floor in which work takes place in parallel and the  $n - X$  floors represent the floors below this floor in which work takes place in parallel.

**OEM-like integration structure:** Value systems or *parts/components* integration structures that do not fully follow the *OEM model* but show characteristics of it.

**OEM model:** An *original equipment manufacturer* relies on suppliers, which, according to their rank in the supply chain, are called Tier- $n$  suppliers. The model explains the general *flow of material* as well as the flow of information during development of the product and its subcomponents.

**Off-site manufacturing (OFM):** *Components* or complete products are manufactured in a *structured environment* distant from the final location where they are finally used. *Components* or complete products can be packed and shipped or are mobile (e.g., car, aircraft).

**One-piece-flow (OPF):** OPF refers to a highly systemized and *production-line*-based manufacturing system in which each *component* or product assembled can be different.

**On-site manufacturing (ONM):** Products such as buildings, towers, and bridges have to be produced on site by ONM systems at the location at which they are to be finally used as they cannot be moved or shipped as an entity.

**Open sky factory (OSF):** *Sky factory* covering and protecting the workspace in *automated/robotic on-site factories*, and, in contrast to *closed sky factories* allows only the installation of a partly *structured environment* that at least (compared to conventional construction) minimizes the influence of parameters that cannot be 100% specified/foreseen (e.g., rain, wind).

**Original equipment manufacturer (OEM):** Integrates and assembles *components* and subsystems coming from sub-factories and suppliers to the final product within the *OEM model*. Companies or entities in the value chain that do not fully follow the *OEM model* but show characteristics of it are also referred to as *final integrators*.

**Overhead manipulators (OMs):** OMs operate within off- or on-site *structured environments* and in *automated/robotic on-site factories* are often the central elements of the *horizontal delivery system*. On the one hand, OMs (e.g., gantry-type OMs) allow the precise manipulation of components of extreme weights and at high speed, which cannot, for example, be accomplished by conventional industrial robots such as anthropomorphic manipulators. On the other hand, OMs require a simplification of the assembly process by *robot-oriented design*, as their workspace and their ability to conduct complex positioning and orientation tasks are limited.

**Part:** In this book, in a hierarchical modular structure, parts represent elements on a hierarchical level below *components*.

**Performance multiplication effect (PME):** Once significant productivity increases in an industry can be achieved (i.e., by switching from crafts-based to machine-based manufacturing), an upward spiral starts: high productivity can become a driver of the financing elements for innovations related to even better machines, processes, and products and thus even higher productivity. This phenomenon was/can be observed in many non-construction industries (e.g., textile industry, automotive industry, shipbuilding) and is in this book series referred to as the PME.

**Platform strategy:** A platform is a basic framework; a set of standards, procedures, or parts; or a basic structure that contains core functions of a product. A platform allows for the highly efficient production of customized products, as it allows for the platform to be mass-produced and to wear individual modules on top of it, which can be customized or personalized.

**Positioning and orientation:** For unrestricted positioning of an object within a defined space, or within  $x$ ,  $y$ , and  $z$  coordinates, at least 3 *degrees of freedom* are necessary (also referred to as forward/back, left/right, up/down). For unrestricted orientation of an object around a *tool centre point*, at least 3 *degrees of freedom* are necessary (also referred to as yaw, pitch, and roll).

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Frontmatter

[More information](#)

## Glossary

xxi

**Production:** In this book, production refers to the generation of basic *parts* or low-level *components*. It includes transformation of raw material into *parts*. *Downstream* processes dealing with the joining of elements generated within production are referred to as *assembly*. *Manufacturing* includes production and *assembly* processes.

**Production line–like organization:** In a production line–like organization, the flow of material between individual workstations is fixed; a material transport system links the stations and the *cycle times* of the individual workstations are synchronized.

**Productivity:**  $\text{Productivity} = \text{Output (quantity)}/\text{Input (quantity)}$ . Productivity quantitatively expresses an input-to-output ratio, with a focus on a single (input) means of production or a single (input) factor of production. Productivity indices concerning the type of factor are, for example, work, capital, material, resource, and machine productivity.

**Pulling production:** Refers to a production system in which products are manufactured only on the basis of actual demand or orders. *Parts*, *components*, and products required are pulled from *upstream*, according to the actual demand. It might refer to the whole manufacturing system, as well as to individual workstations or groups of workstations. Examples: *Toyota Production System*, Sekisui Heim, Toyota Home.

**Pushing production:** Refers to the continuous production of elements/products in a certain fixed amount based on predictions or assumptions. Without taking into consideration the actual demand in *downstream* process steps, *parts*, *components*, and products are pushed through individual stations. It might refer to the whole manufacturing system or to individual workstations or groups of workstations. Example: Henry Ford's mass production.

**Radio frequency identification tag (RFID):** RFID tags are inexpensive tags that can be attached to *components*, *modules*, *units*, or products. RFID readers can be integrated into floors or placed over gates and can then identify the object passing by. They can be distinguished between simple low-cost passive tags and more complex active tags. Advanced readers can read multiple tags at once.

**Real-time economy (RTE):** Macroeconomic view of the impact of the multitude of changes our economy, manufacturing technology, and the relation between customers and businesses undergo. It targets the fulfilment of customer demands and requests in near real time. Products and services are processed within a few hours and delivered within a few days.

**Real-time monitoring and management system (RTMMS):** Data from sensor systems, as well as from the servomotors/encoders of the *vertical delivery system* (VDS) and *horizontal delivery system* (HDS), along with information obtained from cameras monitoring all activities (including human activities) in *automated/robotic on-site factories* are used to create a real-time representation of equipment activity and of construction progress. Furthermore, barcode systems often allow the representation and optimization of the *flow of material*, allowing equipment (such as VDS, HDS, or OM) to identify the *component* being processed. In most cases, real-time monitoring and management is done

in a fully computerized on-site control centre. An RTMMS simplifies progress and quality control and reduces management complexity.

**Re-customization:** Remanufacturing strategy that allows a building to be disassembled and for major *components* or *units* to be refurbished and equipped with new *parts* or *modules* on the basis of mechanized or automated manufacturing systems to meet changed or new (individual) customer demands.

**Robot-oriented design (ROD):** ROD is concerned with the co-adaptation of construction products and automated or robotic technology, so that the use of such technology becomes applicable, simpler, or more efficient. The concept of ROD was first introduced in 1988 in Japan by T. Bock and served later as the basis for automated construction and other robot-based applications.

**Rotation:** A term used to describe a kinematic structure. A revolute joint allows an element of a machine or manipulator to rotate around an axis and in a serial kinematic system adds 1 *degree of freedom* to the system.

**Selective compliance articulated robot arm (SCARA):** Developed by Yamanashi University in Japan in the 1970s. It combines two revolute and one prismatic joint so that all motion axes are parallel. This configuration and the thus enabled allocation of the actuators are advantageous for the stiffness, repeatability, and speed with which the robot can work. Owing to its simplicity, the SCARA is also a relatively cheap robot system. It laid the foundation for the efficient and cheap production, and thus the success of, for example, Sony's Walkman.

**Single-task construction robot (STCR):** STCRs are systems that support workers in executing one specific construction process or task (such as digging, concrete levelling, concrete smoothing, and painting) or take over the physical activity of human workers that would be necessary to perform one process or task.

**Sky factory (SF):** Structured environment (factory or factory-like) setup on the construction site as part of *automated/robotic on-site factories*. SFs cover the area where building *parts* and *components* are joined to the final product and rise vertically with the upper floor of a building through a *climbing system*. SFs can enclose and protect the work environment completely (*closed sky factory*) or only partly (*open sky factory*).

**Slip forming technology:** Moving or self-moving form that allows casting concrete structures such as columns, walls, or towers on site in a systemized manner on the construction site.

**Stilts:** In this book, stilts refer to elements of automated/robotic on-site factories. The *sky factories* of *automated/robotic on-site factories* often use stilts (made of steel) integrated within the *climbing system* to be rested on the building that they are manufacturing. Stilts can be lifted and lowered via the *climbing system*, thus allowing the *sky factory* to move on top of the building's steel column structure.

**Structured environment (SE):** In factories or factory-like environments, work tasks, workspaces, assembly directions, and many other parameters (e.g., climate, light, temperature) can be standardized and precisely controlled. The structuring of an environment creates the basis for the efficient use of machines, automation, and robot technology. The structuring of an environment includes

the protection from uncontrollable factors such as wind, rain, sun, and non-standardized human work activity.

**Superstructure:** The concept of dividing a building into superstructure and substructure is an approach that introduces the concept of hierarchies to a building's structure and *components* and thus can serve as a basis for possible *modularity* in construction. Goldsmith introduced the idea of making the transmission of forces within high-rise buildings by the superstructure to a clearly visible architectural element in his thesis (1953). A superstructure can serve as a platform or frame that allows customization by further infill and is thus closely connected to *frame and infill* strategies.

**Supply chain:** The supply chain connects value-added steps and transformational processes across the border of individual factories or companies. Its aim is to interconnect all processes and workstations to complete a product informationally and physically, in order to create uninterrupted on-demand or in-stock *flow of material*.

**Sustainability in manufacturing:** Manufacturing systems can be designed to be efficient and to equally meet economic, environmental, and social demands. In this book, sustainability in manufacturing refers predominantly to the ability of a manufacturing system to reduce consumption of resources and the generation of waste.

**Technology diffusion:** Technology diffusion describes the step-by-step spread of a technology throughout industry or as, for example, computer technology throughout society. To simplify the adoption of novel technologies and increase their application scope over time, novel technologies have to be made less expensive and less complex and be split into individual modular elements. Technology diffusion therefore often is accompanied by a switch from centralized to rather decentralized applications of the novel technology.

**Tier-*n* supplier:** Suppliers are, according to their rank in the supply chain, called Tier-*n* suppliers. A Tier-1 supplier is a first-rank supplier that relies on *components* from a Tier-2 supplier; a Tier-2 supplier relies on *components* from Tier-3 suppliers; and so on.

**Tool centre point (TCP):** The *end-effector* is a tool that is carried by the kinematic system. For each end-effector, a tool TCP is defined as the reference point for kinematic calculations.

**Toyota Production System (TPS):** The TPS is a logical and consequent advancement of the concept of mass production to a more flexible and adaptive form of demand-oriented manufacturing, developed by Toyota between the 1960s and 1970s. From the 1980s, TPS principles gained worldwide recognition and today they form the conceptual basis for manufacturing systems around the world. Concepts such as *just in time*, *Kaizen*, *Kanban*, *pulling production*, failure-free production, and *one-piece flow* have their origins in the TPS.

**Transformational process:** Any organization and its manufacturing system transform inputs (information, material) into outputs (products, services). The transformation is performed by the organization's structural setting and its means of production, resulting in a specific combination and interaction of workers, machines, material, and information.

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[More information](#)

**Translation:** A term used to describe a kinematic structure. A prismatic joint allows an element of a machine or manipulator to move in a given trajectory along an axis and, in a serial kinematic system, adds 1 *degree of freedom* to the system.

**Tunnel boring machine (TBM):** TBMs mechanize and automate repetitive processes in tunnel construction. TBMs are self-moving underground factories that more or less automatically perform excavation, removal of excavated material, and supply and positioning of precast concrete segments. TBMs are equal in many ways to automated construction sites (and the production of a building's main structure by *automated/robotic on-site factories*).

**24/7-mode:** The operation of a factory, processes, or equipment without major interruption 24 hours a day, 7 days a week. Requires the work environment to be structured (*structured environments*) and protected from influencing factors such as weather and the day/night switchover.

**Unit:** In this book, units refer to high-level building blocks. *Parts, components, and modules* can be assembled into units, which are higher ranked than *modules*. Units are completely finished and large three-dimensional building sections, manufactured off site.

**Unit method:** Sekisui Heim, Toyota Home, and Misawa Homes (Hybrid) break down a building into three-dimensional *units*. Those *units* are realized on the basis of a three-dimensional steel space frame, which, on the one hand is the bearing (steel) structure of the building, and on the other hand can be placed on a production line where it can be almost fully equipped with technical installations, finishing, kitchens, bathrooms (plumbing *units*), and appliances.

**Upstream/downstream:** Refer in this book to processes or activities in a value chain or manufacturing chain that are conducted before (upstream) or after (downstream) a certain point.

**Urban mining:** Refers to strategies that allow the city and especially its building stock to be a “mine” for resources, *parts, and components*. Systemized deconstruction of buildings under controlled and structured conditions, as in *automated/robotic on-site factories*, are enablers of urban mining.

**Vertical delivery system (VDS):** System that transports *parts/components* on the construction site from the ground (e.g., material handling yard) to the floor level where the components are to be assembled. VDSs play an important role in most *automated/robotic on-site factories*.

**Workbench-like organization:** The product stays at a fixed station in the factory where it is produced or assembled manually or automatically through the use of various tools. The means of production are organized around this one station.

**Workshop-like organization:** In a workshop-like organization, the product and/or its components flow between workstations. The sequence is not fixed and the times products stay at a certain workstation vary with the product.

**“Zero” waste factory:** A factory that minimizes resource input and waste output and allows (almost) all generated waste to be recycled.