The Cambridge Handbooks in Construction Robotics

ROBOT-ORIENTED DESIGN

Design and Management Tools for the Deployment of Automation and Robotics in Construction

Thomas Bock
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The descriptions provided in this book are intended to provide an overview of various technologies, approaches, machine systems, and business strategies. Every effort has been made in preparing this book to provide accurate information in accord with accepted standards and practices at the time of publication. This book is not intended as a guide to implementing any specific technology, approach, machine system, or business strategy. The authors, editors, and publisher disclaim any and all liability for direct or consequential damages resulting from the use of the material contained in this book. Readers are strongly advised to pay careful attention to information provided by the manufacturers, accepted engineering design practices, local building codes, and all other relevant factors, including scientific, legal, security, economic, and environmental concerns. The authors and the publisher are not responsible for misinterpretation, nor any incorrect implementation of the information contained herein.

ROBOT-ORIENTED DESIGN

Design and Management Tools for the Deployment of Automation and Robotics in Construction

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 or computer-integrated manufacturing) are lagging because of the lack of modern integrated machine technology in construction. The Cambridge Handbooks on Construction Robotics 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.

Robot-Oriented Design introduces the design, innovation, and management methodologies that are key to the realization and implementation of the advanced concepts and technologies presented in the subsequent volumes in the series. This book describes the efficient deployment of advanced construction and building technology. It is concerned with the co-adaptation of construction products, processes, organization, management, and automated/robotic technology, so that the implementation of modern technology becomes easier and more efficient. It is also concerned with technology and innovation management methodologies and the generation of life-cycle–oriented views related to the use of advanced technologies in construction.

Thomas Bock is a professor of building realization and robotics at Technische Universität München (TUM). His research has focussed for the past 35 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 has consulted for several international ministries and evaluates research projects for various international funding institutions. He holds honorary doctoral and professorship degrees. Professor Bock serves on several editorial boards, heads various working commissions and groups of international research organizations, and has authored and co-authored 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. 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, micro systems technology). Today, issues related to innovation management are becoming key topics in his research. Linner is a frequently invited speaker at universities such as the University of Tokyo and Cambridge University.

Acknowledgements

Construction automation gained momentum in the 1970s and 1980s in Japan, where the foundations for real-world application of automation in off-site building manufacturing, single-task construction robots, and automated construction sites were laid. This book series carries on a research direction and technological development established within this "environment" in the 1980s under the name *Robot-Oriented Design*, which was a focal point of the doctoral thesis of Thomas Bock at the University of Tokyo in 1989. In the context of this doctoral thesis many personal and professional relationships with inventors, researchers, and developers in the scientific and professional fields related to the construction automation field were built up. The doctoral thesis that was written by Thomas Linner (*Automated and Robotic Construction: Integrated Automated Construction Sites*) in 2013 took those approaches further and expanded the documentation of concepts and projects. Both theses form the backbone of the knowledge presented in this book series.

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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* (SE, factory or factory-like) set up 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* (SF) that completely covers and protects the workspace in *automated/robotic on-site factories*, thus allowing the installation of a fully *structured environment* (SE) 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 *component*s 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 towards *computer-integrated manufacturing* (CIM).

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 onwards, the combined *computer-aided design/computer-aided manufacturing* (CAD/CAM) 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 the 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* (ROD) 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* (FIL), 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 as wind, rain or sun), and thus creates the basis for a *structured environment* (SE). Often used as a platform for the attachment of other subsystems, such as a *climbing system* (CS), *horizontal delivery system* (HDS), and *overhead manipulators* (OMs).

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* (OEM).

Fixed-site manufacturing: *Off-site manufacturing* (OFM) or *on-site manufacturing* (ONM) 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 a 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* (SE, factory or factory-like) set up 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*, etc.), 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 it 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* (OEM). JIT is in most cases closely connected to *just in sequence* (JIS).

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* (DOFs) 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* (TCPs) 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* (OFM) 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*, FIL), factory external scale (*factory external logistics*, FEL).

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*–based 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 & infill* (F&I) 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* (GF). An

MHSPY can be a covered environment and/or can be equipped with *overhead manipulators* (OMs) and allows the simplification or automation of the picking up of *components* from delivering *factory external logistics* (FES) in a *just in time* (JIT) and *just in sequence* (JIS) 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 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, both on a functional and a physical level, the artefacts are referred to as "integral". If systems can clearly be decomposed, both on a functional and a physical level, 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.

nth, $n-1$, $n-2$, $n-X$ floors: Inside the main factory (e.g., a *sky factory*, SF) of *automated/robotic on-site factories*, work (component installation, welding, interior finishing, etc.) is done in parallel on several floors (n-floors). The nth 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* (OEM) 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* (SE) distant from the final location where it is 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, bridges, etc. 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* (SF) covering and protecting the workspace in *automated/robotic on-site factories*, and, in contrast to *closed sky factories* (CSFs) allows only the installation of a partly *structured environment* (SE) 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* (SEs) and in *automated/robotic on-site factories* are often the central elements of the *horizontal delivery system* (HDS). 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 as for example anthropomorphic manipulators. On the other hand, OMs require a simplification of the assembly process by *robot-oriented design* (ROD), as their workspace and their ability to conduct complex positioning and orientation tasks is 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 upwards spiral starts: high productivity can then 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 *performance multiplication effect* (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, or z coordinates, at least 3 *degrees of freedom* (DOFs) are necessary (also referred to as forward/back, left/right, up/down). For unrestricted orientation of an object around a *tool centre point* (TCP), at least 3 *degrees of freedom* (DOFs) are necessary (also referred to as yaw, pitch, and roll).

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: Productivity = Output (quantity)/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* (TPS), 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 simpler and 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 & 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 the 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* (DOF) 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 comparably 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 smoothening, and painting) or take over the physical activity of human workers that would be necessary to perform this one process or task.

Sky factory (SF): Structured environment (SE, factory or factory-like) set up 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* (CS). SFs can enclose and protect the work environment completely (*closed sky factory*, CSF) or only partly (*open sky factory*, OSF).

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* (SFs) of *automated/robotic on-site factories* often use stilts (made of steel) integrated within the *climbing system* (CS) to be rested on the building that they are manufacturing. Stilts can be lifted and lowered via the *climbing system* (CS), thus allowing the *sky factory* (SF) 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, etc.) 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