1 Integrated Automated/Robotic On-site Factories

In this volume all worldwide conducted approaches following an on-site factory approach were analysed. Thirty different systems were identified, resulting in an application of automated/robotic on-site factory technology about 60 times. The analysis was for each system split into a more technical part and a part that focuses on indicators related to productivity, efficiency, and economic performance. All systems were analysed systematically and based on the same framework. On the basis of the analysis, a categorization system was developed and 13 categories were set up (10 categories for construction and 3 for deconstruction).

As discussed in **Volume 3**, one of the main ideas for setting up automated on-site factories was to integrate stand-alone or single-task construction robot (STCR) technology in structured on-site environments into networked machine systems and thus to improve through interlinked machine activities the organization, integration, and material flow on the construction site (apart from the possibility to off-site manufacture components discussed in **Volume 2**). The analysis clarifies for which building typologies automated/robotic on-site factories are an applicable approach and how and to which extent each of those systems is technologically flexible to be able to manufacture a variety of different buildings (products) on the basis of industrialized, automated, and flow-line–like stable factory processes on the construction site. Furthermore, it should be clarified whether, in contrast to the STCR approach (see **Volume 3**), the approach of setting up automated/robotic on-site factories is capable of achieving a performance multiplication (e.g., by 10-fold as in tunneling or automotive industry; for further details see **Volume 1**), which usually accompanies the switch from arts and crafts–based manufacturing to machine-based manufacturing.

In this volume, first, frameworks for the technical analysis and the efficiency analysis classified into various fields, analysis subjects, and indicators are set up. Second, 30 systems are analysed according to the technical analysis framework and classified into two main categories (construction: 24, deconstruction: 6) and a total of 13 subcategories. Ten of those systems are also analysed with regard to analysis subjects and indicators that determine or influence productivity, efficiency, and overall economic performance. An *Analysis and Categorization Matrix* (see Figure 2.35) gives an overview over systems, categories, analysed analysis subjects and indicators, and available data. Finally, the findings are summarized (see Chapter 4). The analysis claims to include all approaches to automated/robotic on-site factories that were conducted so far.

1.1 Framework for Technical and Efficiency Analysis

In this volume, the technical aspects of integrated automated construction sites (including their composition and configuration), as well as their resulting efficiency, are analysed. Automated construction sites represent on-site manufacturing (ONM) environments (fixed type or moving type) that conduct a final assembly of low-, medium-, and high-level modular components rather than a conventional construction process. The installation of a factory on-site structures the work environment and allows the application of automation and robot technology. Furthermore, the processing of value-added components designed according to robot-oriented design (ROD) strategies reduces on-site complexity. The modularization of both building products and manufacturing systems allows for flexibility and customisation of the products (buildings) to a certain degree. The technical analysis follows the identification of concepts and strategies relevant to the fields of multilevel modularity (see **Volume 1, Section 4.2**), manufacturing technologies and strategies (see **Volume 1, Section 4.3**), and automation and robot technology (see **Volume 1, Section 4.4**). An overview of the framework developed for the technical and configuration analysis is presented in Table 1.1. The data used in this analysis were acquired from various sources such as project descriptions by the companies, publications by companies and their R&D staff, publications by researchers who had analysed systems, expert interviews with developers and company staff, and own site visits. Furthermore, as a basis for the analysis, documentary material in the form of plans, project descriptions, and an own picture archive documenting the application of nearly all systems were used.

As far as efficiency and productivity are concerned, the analysis framework is based on the assumption that technical and economic efficiencies are generated by both an efficient combination of input factors and the set-up of a high-value product with a low defect rate. Individual performance indicators, such as work productivity, material efficiency, physical strain, health and safety, construction quality (related to the defect rate), and integration along the value chain have been identified as the most influential construction performance indicators (see **Volume 1**). In addition, as outlined in **Volume 1,** the construction industry is highly labour intensive, with decreasing labour productivity, a high rate of construction defects, a high rate of fatal and nonfatal injuries, and a relatively high amount of material input compared to the output value. This correlates with the low investment and R&D spending rate and the low capital stock, indicating that the value and quality of the existing manufacturing equipment, process technologies, and skilled workforce are low. However, integrated automated construction sites would require, for example, as in the automotive industry, a high investment and R&D spending rate, a high level of capital stock, and in that context of course demand for considerable improvements in the aforementioned performance indicators. The efficiency analysis for each system attempts to analyse whether integrated automated site technology has the potential to deliver the demanded efficiency improvements. The technical configuration of the systems and their efficiency are closely related to each other. In most cases, positive

Table 1.1. *Framework for the analysis of technical aspects and system configuration*

Field of analysis	Analysis subjects and indicators
Evolution scheme	Location of sky factory and ground factory Working direction General workflow
Elevation	Detailed vertically organized workflow Parallel work on various levels Configuration of main and sub-factories Analysis of the component installation process
Ground plan (main and sub-factory)	Detailed horizontally organized workflow Configuration of main and sub-factories
Subsystems	SF (covered, working platforms, closed sky factory, open sky factory) Vertical logistics (in particular vertical delivery systems) Horizontal logistics (in particular horizontal delivery systems) Manipulators (in particular overhead manipulators) Climbing mechanisms (in particular climbing systems) Assembly simulation and progress control tools (real-time monitoring and management system and material handling, sorting, and processing yard)
End-effectors	Types of end-effectors Relation of end-effectors and components/materials Modularity Possibility of tool changes
System variations	Realized system variations Possible system variations Inbuilt flexibility Modular flexibility
Robot-oriented design (ROD)	ROD on a component level ROD on a building level ROD on an urban level

or negative efficiency performance can be directly correlated to the general set-up, configuration, use of subsystems/end-effectors, and the deployment of ROD.

The analysis framework for the systems' efficiency was synchronized with the currently available data sets. Analysis subjects that companies deploying the systems did not analyse or make available (e.g., detailed data on investment or defects/errors, or injuries related to the application of the new technology) were not considered in the framework. The *Analysis and Categorization Matrix* (see Figure 2.35) shows which data were made available for each system. Obviously, companies that deploy their systems more often than others (Obayashi, Shimizu) also generate or are interested in generating more data sets. Table 1.2 outlines the analysis framework and shows which analysis subjects and indicators were considered as relevant for the efficiency analysis.

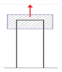
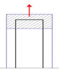
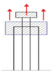
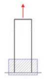
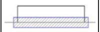
All of the data presented have to be considered from the perspective that all systems were still in an experimentation, prototype or test phase. With the development of such technologies, Japanese companies have aimed at long-term efficiency

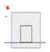
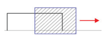
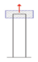
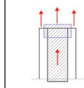
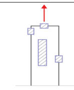
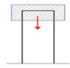
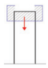
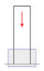
Table 1.2. *Efficiency analysis framework*

Thematic field	Analysis subjects	Indicators
Erection speed	Project schedule	Time necessary to set up a sky factory Operation period Time necessary for dismantling of a sky factory Floor production rate per month
	Floor erection cycle	Time and work steps necessary to complete a standard floor Parallel processing on several floors Equipment (e.g., overhead manipulator) operation sequence
Configuration	Technical data speed of equipment	Operational speed of horizontal delivery system Operational speed of climbing system Operational speed of vertical delivery system
	Experiment's degree of automation/system configuration/worker teams	Rate of automation – is installation operation remote controlled, partly automated, or fully automated? Could companies apply system in various configurations (flexibility) Influence of varying numbers of workers, e.g., on productivity
Productivity	Productivity workers/time (including comparisons with conventional construction or other systems)	Man-hours required for completion of floor Number of construction workers required for a specific task field Total number of workers Comparison with conventionally constructed buildings
	Learning effects	Reduction of time needed to install components with the novel site technology/equipment Reduction of time needed for welding Reduction of time required for factory internal logistics
Resource efficiency	Material and resource efficiency	Reduction of required input material Reduction of construction waste generated
Quality, health and safety	Product or process monitoring (real-time progress, decibel, etc., control room)	Real-time supervision of operations Real-time progress control, real-time monitoring and management system Simulation of optimized operation
	Safety	Influence of environment on safety
	Physical strain (heart rate, etc.)	Influence of environment on physical strain
	Weather influence	Influence of weather on: • Operation/task execution • Productivity • Quality
Usability studies	Evaluation of usability of on-site factory and equipment by workers/operators	Influence on work tasks Influence on motivation Influence on user acceptance and emotions

and at building up knowledge step by step, and thus made a number of compromises concerning short-term efficiency. Obayashi and Shimizu, for example, each of which deployed their systems in a multitude of construction projects (ABCS: applied six times; Big Canopy: applied six times; SMART: applied six times), introduced improvements in each new project and experimented with the configuration of the robotic crane systems or with the automation degree and the number of workers used (and thus the degree of work productivity). For example, during the first projects using the SMART, Shimizu had the intention of training its workforce on the general use of the new technology (according to Japanese philosophy, knowledge about new technologies and tools has to be spread fast among the workforce by special training procedures), and thus replaced half the workforce with new workers from project to project to train as many of their workforce in using the new technology as quickly as possible. Considering the fact that the learning effects within projects were enormous (see later in the efficiency analysis of the SMART system in Chapter 2), it can be assumed that this procedure influenced efficiency considerably, as it mitigated the impact of these learning effects across projects. Furthermore, most systems were still in a developmental phase, and did not fully utilize the capacity of their subsystems at any time during individual projects. Shimizu, for example, had up to 24 robotic trolleys (that can potentially be operated in parallel) available in a fully deployed SMART, but operated some projects with, for example, only 10 of them in an active mode.

Analysis and Categorization Matrix

			Construction by Automated/ Robotic On-site Factory														
			Sky Factory (moving upwards) supported by building								Sky Factory (moving upwards) on stilts (prolonging)		Sky Factory pulled up along core (main factory and core factory moving upwards)		Ground Factory (staying fixed place, vertically oriented building) and building push-up	Ground factory (staying fixed place, horizontally oriented building) and building push-up	
			Category 1								2		3		4	5	
																	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			Obayashi	Fujita	Goyo	Maeda	Takenaka	Toda	Shimizu	BAM	Obayashi	Shimizu	Taisei	Korean Cons.	Kajima	Skanska	Sekisui House
																	
			Automated Building Construction System (ABCS)	Akatuki 21	Future Automated Construction Efficient System (FACES)	Mast Climbing Construction System (MCCS)	Roof Push-up	Roof-Robo	Shimizu Manufacturing System by Advanced Robot Technology (SMART)	System Netherlands	Big Canopy	SMART Light	Totally Mechanised Construction System for High-rise Buildings (T-Up)	Robotic and Crane based Automatic Construction System (RCACS)	Automatic Up-Rising Construction by Advanced Technique (AMURAD)	System Skanska	J-UP
Technical Analysis	Factory Layout (Evolution Scheme, Elevation, Ground Plan)	Location of main factory	On top	On top	On top	On top	On top	On top	On top	On top	On top	On top	On top	On top	On ground	On ground	On ground
		Working direction	Vertically upwards	Vertically upwards	Vertically upwards	Vertically upwards	Vertically upwards	Vertically upwards	Vertically upwards	Vertically upwards	Vertical upwards	Vertical upwards	Vertical upwards	Vertical upwards	Push up vertical	Push up vertical	Push up vertical
		Building Material Main Structure	Seel	Seel	Seel	Seel	Seel	Seel	Seel	Concrete	Concrete	Concrete	Steel	Steel	Concrete	Concrete	Steel
	Sub-systems	Main Factory Cover Structure	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Vertical Delivery System		x			x	x			x	x		x	x		
		Horizontal Delivery System		x		x	x	x		x	x	x		x	x	x	
		Vertical/Horizontal Delivery System	x		x		x		x	x		x	x				
		Number of Overhead Manipulators	3	3	2	2	2	2	Up to 25	2	Up to 3	Min. 3	2	2	3	1	
		Climbing System (or push-up/sliding)	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
		Dedicated Facade Installation System	x														
		Sub-factory (storage, component preparation)		x				x	x			x	x		x	x	x
		Column Welding Subsystem	x		x	x			x								
		Beam Welding Subsystem	x														
		Logistics Robots for Interior Finishing	x						x				x		x		
		Other Robots for Interior Finishing					x	x	x				x		x		
		Material Management System	x	x	x	x			x		x		x	x	x	x	x
		Real Time Monitoring System	x	x	x	x	x	x	x		x		x	x	x		
		Component Alignment System	x		x	x		x					x				
		Construction Process Simulator	x		x				x		x			x			
		Number of Sub-systems	10	12	7	12	9	10	8	5	7	6	13	6	9	8	6
	End-effectors	Numer of End-effectors	6	4	7	1	1	1	1	2	2	1	4	>1	7	1	1
		In-built Flexibility (+, ++, +++)	+	+	+	+++	+++	+++	+++	+++	++	+++	++	+	++	+++	+++
		Modular Flexibility (+, ++, +++)	+++	+++	+++	+	+	+	+	+	++	+	++	+++	+++	+	+
	System Variations	Number of applied and planned Variations	4	2	2	2	1	1	6	1	3	2	6	1	3	1	2
	Robot Oriented Design (ROD)	ROD on component level	x	x	x	x	x	x	x	x	x		x	x	x	x	
		ROD on building level						x					x	x		x	
		ROD on urban level															
Efficiency Analysis	Erection Speed	Total on-site construction time necessitated	6-24 month		15 month						2 years		20 month		10 month		2-4 month
		Time necessitated for system set up	1 month	2 month	2-5 month	1-2 month	1-2 month	1-2 month	1-2 month	2-3 month	1 month		6 weeks		6 weeks		1 day
		Time necessitated for system dismantling	2-3 weeks	2 weeks	1 month	2-3 weeks	2-3 weeks	2-3 weeks	2-3 weeks	1-2 month	1 month		2 weeks		2 weeks		1 day
		Floor Erection Cycle	5/6 days	9 days	6 days	6-8 days	5,5 days	6-8 days	5/6 days	14 days	7 days	about 10 days	3 days		6 days		
		Number of Floors produced per month	4	2-3	2,5	2-3	2-3	2-3	about 3	1-2	2,7	2	2,4		2		1-2
		Start of operation form floor X	3	3	0	2	3	4	1		3	0	5-6	1	2	1	1
		Parallel work levels	>4	3	>4										6		
		Levels enclosed by Sky Factory	3	3	4										3		
	Configuration	Speed of eqipment	40 m/min	20-25 m/min	20 m/min	20-25 m/min	20-25 m/min	20-25 m/min	20-40 m/min		40 m/min	20-40 m/min			10 m/min	10-20 m/min	
		Automation ratio	Automatic/ remote	Automatic/ remote	Automatic/ remote (automatic mode was slower)	Automatic/ remote	Automatic/ remote	Automatic/ remote	Automatic/ remote	Remote controlled	Full automation and remor operation possible (remote 10% faster)	Remote	Automatic/ remote	Automatic/ remote	Automatic/ remote	Automatic/ remote	Remote
	Productivity	Task specific work productivity			Improvement of work productivity by the two to six fold				Manhours reduced by 50%, number of workers reduced by 30%								
		Total labor productivity							Time necessary to construct the building reducecd by about 15%,		Up to 70% less workers		Manhours 68% reduction, construction time: 20% reduction		Improvement of labor productivity of up to 50%, reduction of construction time up to 30%		
		Learning effects	Component installation 10%, welding 20%						20 % for column positioning		Up to 20%				40-50% for standard floor		
	Ressource Efficiency	Measurements to reduce consumption/ waste							70% waste reduction		50% waste reduction						
	Quality, Helath and Safety	Multible working platforms	x	x	x	x	x		x	x					x		
		Protection in terms of	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, rain	Sun, rain	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, rain
	Usability	Usability aspects	Positive influence of protected environment		Attract skilled workers by technology				Attract skilled workers by technology		Measurable decrease of heart-rate of workers						

												De-construction by Automated/ Robotic On-site Factory					
			Off- and on-site combined factory (both off and on-site factory fixed place)	Self-supported Ground Factory (horizontally moving)		Sky Factory (moving upwards) for simple tower manufacturing		Centralized Sky Factory (moving upwards) in combination with conventional construction		Decentralized Sky Factory (moving upwards) in combination with conventional construction		Closed Sky Factory supported by building (moving downwards)		Open Sky Factory supported by building (moving downwards)			Ground Factory (fixed place) and building lift-down
			6	7		8		9		10		11		12			13
																	
			16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
			NCC	Summerfield	Neufert	Taisei	Shimizu	Obayashi	Shimizu	Obayashi	Shimizu	Takenaka	Taisei	Nishimatsu	Shimizu	Obayashi	Kajima
																	
			NCC Komplett	Bauschiffverfahren	Hausbaumaschine	TS-Up	Tower SMART	Hybrid-ABCS	Hybrid-SMART	Loose Deployment of ABCS-Subsystems (e.g. Tokyo Skytree)	Loose Deployment of SMART-Subsystems (e.g. Mode Gakuen Cocoon Tower)	Hat Down	Taisei Ecological Reproduction System (TECOREP)	Move Hat	Reverse Construction Method (RCM)	Quakeproof, Quiet, Quick and Block-by-Block Building Disassembly (Cube Cut Method)	Cut and Take Down Method "Daruma Otoshi" (DARUMA)
Technical Analysis	Factory Layout (Evolution Scheme, Elevation, Ground Plan)	Location of main factory	Covers building	Covers building	Covers building	On top	On top	On top	On top	Distributed	Distributed	On top	On top	On top	On top	On top	On ground
		Working direction	Vertical/ Horizontal	Horizontal	Horizontal	Vertical	Vertical	Vertical + around	Vertical + around	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
		Building Material Main Structure	Concrete	Concrete	Concrete	Steel	Steel	Steel	Steel	Steel	Steel	Steel/ concrete	Steel/ concrete	Steel/ concrete	Steel/ concrete	Concrete	Concrete
	Sub-systems	Main Factory Cover Structure	x	x	x	x	x	x	x		x	x	x	x	x	x	x
		Vertical Delivery System		x	x		x			x	x						x
		Horizontal Delivery System		x	x		x					x	x				x
		Vertical/Horizontal Delivery System	x			x		x	x	x	x	x		x	x	x	
		Number of Overhead Manipulators	2	2	6-20	-	1	3	Up to 25	-	-	>3	>2	>2	-	-	-
		Climbing System (or push-up/sliding)		x	x	x	x	x	x		x	x	x	x	x	x	x
		Dedicated Facade Installation System						x			x			x			
		Sub-factory (storage, component preparation)	x						x		x	x	x	x			x
		Column Welding Subsystem						x	x	x		x	x				x
		Beam Welding Subsystem						x		x							
		Logistics Robots for Interior Finishing						x	x								x
		Other Robots for Interior Finishing							x							x	
		Material Management System	x					x	x	x	x	x	x				x
		Real Time Monitoring System						x	x			x	x				x
		Component Alignment System						x		x							
		Construction Process Simulator						x	x								
		Number of Sub-systems	6	4	5			10	9	7	6	6	6	5	5	5	7
	End-effectors	Numer of End-effectors	1	3	2	1	1	6	1	1	2	1	1	1	-	-	
		In-built Flexibility (+, ++, +++)	+++	+	+	+	+	+	+++	+++	++						
		Modular Flexibility (+, ++, +++)	+	+	+	+	+	+++	+	+	++						
	System Variations	Number of applied and planned Variations	2	3	1	1	1	3	2	>4	>4	1	2	2	2	2	2
	Robot Oriented Design (ROD)	ROD on component level	x		x	x	x	x	x		x						
		ROD on building level		x	x	x	x	x	x								
		ROD on urban level		x	x												
Efficiency Analysis	Erection Speed	Total on-site construction time necessitated	3-6 month					6-24 month				6 month	1 year	Same as conv. construction	Same as conv. Construction	Same as conv. construction	6 month
		Time necessitated for system set up	2 weeks					1 month	1-2 month								
		Time necessitated for system dismantling	1 week					2-3 weeks	2-3 weeks								
		Floor Erection Cycle						5/6 days	5/6 days			6-10 days	6-10 days	6-10 days	6-10 days	6-10 days	6-10 days
		Number of Floors produced per month	2-4					4	about 3								
		Start of operation form floor X	-1	0	0	2	2	3	1	0	0	1	1	0	0	0	-
		Parallel work levels						>4									
		Levels enclosed by Sky Factory						3									
	Configuration	Speed of eqipment	20-40 m/min				20-40 m/min	40 m/min	20-40 m/min	40m/min	20-40 m/min						
		Automation ratio	Remote	-	-	Remote	Remote	Automatic/ remote	Automatic/ remote	Automatic / remote	Automatic / remote	Remote	Remote	Remote	Remote	Remote	Remote
	Productivity	Task specific work productivity							Manhours reduced by 50%, number of workers reduced by 30%								
		Total labor productivity	NCC aims at enhanced productivity (e.g. 4-6 buildings per worker per year			Shortening of construction time by 20%	Shortening of construction time by 20%		Time necessary to construct the building reduced by about 15%,								
		Learning effects						Component Installation 10%, Welding 20%	20% for column positioning								
	Ressource Efficiency	Measurements to reduce consumption/ waste							70% waste reduction			> 90% recycling rate					96 recycling rate
	Quality, Helath and Safety	Multible working platforms			x	x		x			x	x	x	x	x		
		Protection in terms of	Sun, wind, temperature, rain, sound	Sun, rain	Sun, wind, temperature, rain, sound	Wind	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound	Sun, wind, temperature, rain, sound		Sun, wind, sound	Sun, wind, temperature, rain, sound, dust	Sun, wind, temperature, rain, sound, dust	Wind, sound, dust	Wind, sound, dust	Wind, sound, dust	Sun, wind, temperature, rain, sound, dust
	Usability	Usability aspects	Heated environment enhanced work speed and motivation					Positive influence of closed environment of conetration	attract skilled workers by technology			Safe deconstruction environment	Safe deconstruction environment				