

# Survey on automation of the building construction and building products industry

Pentti Vähä | Tapio Heikkilä | Pekka Kilpeläinen |  
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## **Survey on automation of the building construction and building products industry**

**Pentti Vähä, Tapio Heikkilä, Pekka Kilpeläinen, Markku Järviluoma & Rauno Heikkilä.**  
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### **Abstract**

A commonly held view is that the construction industry is labour-intensive, project-based, and slow to adopt emerging technologies compared to other “project shop” manufacturing industries [Product-Process Matrix]. A construction site can be regarded as a “project shop”, since tools and manufacturing equipment are brought on-site, whereas component prefabrication is a conventional shop, line or cell-structured. There have not been any dramatic changes in construction methods in the last 40 years, although some methods have been developing. The construction Industry is also considered to be a conservative innovator and late adopter of new technology. Therefore, construction is often considered a somewhat old-fashioned industry. However, in the design phase, methods such as Computer Aided Design (CAD) and Finite Element Method (FEM) are commonly adopted. Also Building Information Model (BIM) is increasingly applied in the design and engineering phase.

The construction life cycle includes 1) Requirements identification, 2) Project planning, 3) Design and engineering 4) Construction, 5) Operations and maintenance, and 6) Decommissioning. The operation and maintenance phase is the longest period during the life cycle of a building. Building Information Model (BIM), a digital representation of the physical and functional characteristics of a facility, covers e.g. geometry, spatial relationships, light analysis, geographic information, quantities and properties of building components with manufacturers' details. The model elements, representing the physical building parts, are digitally linked to information relevant to the model users, such as architects, engineers, contractors and owners. BIM can be used to demonstrate the entire building life cycle, including processes of construction and facility operations, and finally to take the advantage of its information in the demolition. From the life cycle point of view, BIM enables all stakeholders to share data throughout the entire life cycle of the building. Currently, BIM is widely applied in the design and engineering phase, but there have been very few efforts to explore the real-time integration of BIM to the site and task conditions, and the interaction of BIM with the field crew. For field workers, it is important to gain access to the most current model so as to be aware of possible changes made to the document [BIM, Beyond Clash Detection 2011] and [Wang et al. 2012].

Industrialization of building construction started in Japan around 1960, with the advent of prefabricated houses made of steel and wood. High-rise building construction has become common since 1968, and automation and industrialization of

building construction have been pursued since then [Shinko 2007]. Since 1988, major Japanese general contractors have investigated the potential complementation of integrated robotic and automated building construction systems [Bock et al. 2011]. Today, many construction operations have incorporated automated equipment, means, and methods into their regular practices. R&D activities are centring more on ICT technologies, including on-site sensory data acquisition and processing, the human operator's field safety and security and computer-based process control and monitoring as well as automated inventory and shop keeping, among many others. Although adaption of automation in the building construction sector has been slow, the civil engineering sector has developed and adopted several automated systems for industrial use. For example, Infra Information Modelling is currently under active research and development, especially in Northern Countries.

Automation has had a notable impact in a wide range of industries in addition to manufacturing. The principles of industrial automation are applicable to the construction sector, both to building construction, civil engineering (roadways, dams, bridges, etc.), and to the prefabrication of construction components. It is the application of electronic, mechanical and computer based systems so as to operate and control construction production.

**Keywords** construction automation, automated data acquisition, construction robotics, construction logistics, prefabrication

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## List of abbreviations

ABCS	Automated Building Construction System
AEC	Architecture, Engineering and Construction sector
AoA	Angle-of-arrival
BACS	Building Automation and Control System
BIM	Building Information Model
CAD-CAM	Computer-Aided Design – Computer Aided Manufacturing
CAM	Computer-Aided Manufacturing
CCC	Construction Consolidation Centre
CCD	Charge coupled device
CCI	Construction Cost Index
CII	Construction Industry Institute
CIM	Computer-Integrated Manufacturing
CNC	Computer numerical control
EBC	Ergonomic boom control
EDM	Electronic distance meter
ERP	Enterprise Resource Planning
FEM	Finite Element Method
GIS	Geographic information systems
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HVAC	Heating, Ventilation, and Air-Conditioning



ICT	Information and communication technology
IFC	Industry Foundation Classes
LADAR	Laser detection and ranging
LC	Lean construction
LIDAR	Light detection and ranging
MEMS	Micro Electro Mechanical System
NPL	Networking Platform for Logistics
OOP	Object Oriented Programming
PDA	Personal Digital Assistant
PLM	Product Lifecycle Management
PPMOF	Prefabrication, preassembly, modularization and off-site fabrication
RAC	Robotics and automation in construction
RF	Radio frequency
RFID	Radio frequency identification
RSSI	Received signal strength indication
RTK	Real time kinematic system
SFM	Structure from Motion
TDoA	The time-difference-of-arrival
UWB	Ultra Wide Band
WLAN	Wireless local area network

# 1. Motivations for building construction automation

A big motivation for automating building construction comes from the success achieved in the civil engineering sector, where typical robot applications are the automation of road, tunnel and bridge construction and earthworks. Several projects have been performed over the last decade mainly focusing on the development of the new generation of semi-autonomous road pavers and asphalt compactors [Heikkilä et al. 2003, Heikkilä et al. 2010, Kilpeläinen 2011, Viljamaa et al. 2009]. Road construction mechatronic applications are exploiting 3-D geometry road model in controlling robotic end effector movements. They are acquiring their set point values, e.g. road structure layer coordinates, directly from the road model. Performance of the control system has increased 100%, while the best-achieved geometric accuracy of road structure layers has been  $\pm 1$  cm [Heikkilä et al. 2003]. There is a strong indication that machines used in civil construction will be increasingly controlled by automated systems. Reference [Heikkilä et al. 2010] gives an insight into how automation in road construction has developed in Finland.

A commonly held view is, however, that the construction industry is a poor innovator and late adopter of new technology rather than a source of innovation [Abbot et al. 2001]. Many references can be found to support this standpoint. The industry has traditionally involved craftsman-oriented manual work with many small participating companies. There is a need to improve safety, productivity, constructability, scheduling and control while providing stakeholders with a tool for prompt and accurate decision-making. According to [Castro-Lacouture 2009], the strongest reasons given by industry respondents from 24 countries for robotic construction automations were 1) productivity improvement, 2) quality and reliability, 3) safety, 4) enhancement of working conditions, 5) savings in labour costs, 6) standardization of components, 7) life cycle cost savings, and 8) simplification of the workforce.

The construction life cycle includes 1) Requirements identification, 2) Project planning, 3) Design and engineering, 4) Construction, 5) Operations and maintenance, and 6) Decommissioning. The operation and maintenance phase is the longest period in the life cycle of a building. Building Information Model (BIM), a digital representation of physical and functional characteristics of a facility, covers e.g. geometry, spatial relationships, light analysis, geographic information, quanti-

ties and properties of building components with manufacturers' details. The model elements, representing the physical building parts, are digitally linked to information relevant to the model users, like architects, engineers, contractors and owners. BIM can be used to demonstrate the entire building life cycle, including processes of construction and facility operations and finally take the advantage of its information in the demolition. From the life cycle point of view, BIM enables all stakeholders to share data throughout the life cycle of the building. Currently, BIM is widely applied in the design and engineering phase. There have been very few efforts at exploring the real-time integration of BIM to the site and task conditions and the interaction of BIM with the field crew. For field workers it is important to have access to the most current model so as to be aware of possible changes made to the document [BIM, Beyond Clash Detection 2011] and [Wang et al. 2009].

## **1.1 Attitudes, resistance to change and willingness to adopt**

The construction Industry is considered to be technologically behind other industries, such as manufacturing where a product is designed for mass production, whereas construction products (or objects) are usually one-off and unique. Other reasons often adduced for the construction industry's technological lag are the industry's fragmentation and aversion to the risks associated with the introduction of new technologies. Field workers, who may not be familiar with the construction practices adopted by the firm on a particular project, make it difficult for managers to engage them in technologically advanced processes from the beginning of the project. In order to be able to enter the construction market, new technologies should have easy-to-use and intuitive user interfaces and be developed from the user point of view. Furthermore, on the automated or robotised work should not be just a copy the human work but be rather enhanced by robot oriented planning, engineering, management and labour training. In the future, investments should contribute to value, safety, quality, productivity, and performance.

Resistance may also come from laws and building regulations which can slow down the use of new methods and materials. For example in Finland national building regulations and especially fire safety regulations prevented construction of wooden buildings more than two storeys high, despite the fact that wood is a very traditional building material. The regulations changed in the 1990s, but building multi-storey houses from wood is still not common [Karjalainen 2002].

The production activity normally occurs in a field setting and is undertaken in the open air, on natural terrain, and often with naturally occurring materials. Thus, construction sites are for the most part unstructured, cluttered, and congested, making them difficult environments for robots to operate in. Human workers are also present in large numbers on the construction site, making safety a paramount concern. Although the constructor would like to use new technology such as robots on a construction project, the actual work on site is in many cases conducted by subcontractors who are often reluctant or financially unable to use advanced technologies not entirely adopted by the industry. Furthermore, as the goal of the

constructor is to meet the owner's requirements by the most efficient and least risky methods possible, traditional construction methods that have stood the test of time are preferred [Saidi et al. 2008, Castro-Lacouture 2009].

Apart from commercial barriers there are also sociological and industrial barriers. There will be substantial industrial or worker resistance to the widespread introduction of on-site robotics. Reasons for worker resistance are the potential job losses through displacement of labour [Saidi et al. 2008], general resistance to change and a fear of using robotised equipment on the site among other workers. For example, the Computer Integrated Manufacturing (CIM) concept permits not only a reduction in the cost of manufacturing, but also changes the corporate culture [Kangarii 1996].

In general, the construction industry continues to be very conservative compared to manufacturing industry. In many cases when the new automatic products are not complementary to the old ones, they are scarcely implemented, and their use is kept to minimum. Moreover, if these products introduce inconveniences to the whole construction cycle, they are openly rejected. On the contrary, in the manufacturing industry the people and the environment respond very positively to technological innovation. Researchers and end users speak the same "language" and share the same objective, which allows introducing these new technologies very quickly [Balaguer & Abderrahim 2008].

## **1.2 Market acceptance**

Customers like custom features and unique appearance. Automation works best, when production is standardized. Houses or apartments that are too standardized are neither preferred nor even accepted by customers. Therefore automation should be flexible, and individual modifications should be easy and economical to implement from the point of view of the manufacturer and thus be attractive to the customer. This may be possibly achieved by "digital products which can be manufactured on-demand". A digital product is a computer model, and if the customer chooses to use it, it can be made automatically without extra costs. Thus, market acceptance can be gained if automation and robotics enable giving the customers the feeling that they can implement individual housing needs without extra costs or at reasonable costs and without delays.

## 2. Background and outline of the study

Automation means the use of control systems and information technologies so as to reduce the need for or change the type of human work in the production of goods and services. It plays an increasingly important role in the world economy and in daily experience [CII 2001–2003]. One definition of construction automation states that it is “the technology concerned with the application of electronic, mechanical and computer based systems to operate and control construction production” [Castro-Locouture 2009].

Construction automation describes the field of research and development focused on automating construction processes, and the use of robots is only one aspect of that field. In short, construction automation deals with applying the principles of industrial automation to the construction sector, like in building construction, civil engineering (roadways, dams, bridges, etc.), or in the prefabrication of construction components [Saidi et al. 2008]. In any case, automation has had a notable impact in a wide range of industries beyond manufacturing, where it began.

There have been several attempts to increase the automation level in the construction industry. During the 1980s, a number of development projects with wide participation were initiated in Finland in order to create the necessary bases for the second wave of industrialization in construction [Koskela 1991, Vähä 1992]. One of these efforts was the national program “Industrialized Building Technology” initiated and coordinated by Tekes (The Finnish Funding Agency for Technology and Innovation). The aim of the national RATAS project was to define the basic structure of the computing environment of the construction industry, a necessary complement to the changes in the construction process and in the building system. Also the Federation of Finnish Building Industry of which practically all construction firms are members, established a co-operative research carried out by VTT, universities and consultants.

Research and development on mechanisation, automation and robotization in construction were carried out by research organisations and construction material industry. The research focus of VTT Technical Research Centre of Finland was on 3D measurements in construction [Lindholm et al. 1990, Pieskä et al. 1989, Vähä et al. 1993], on the automation of concrete component factory, mechanization of bricklaying technology on the building site [Koski 1991 and 1996], robotized tiling of outsides of the prefabricated concrete facades [Lehtinen et al. 1991] and on the

development of intelligence for manipulators to be able to handle materials in unstructured environments [Taipale et al.1991]. During this period of activity, automation-related research and development actions were taken. Step by step these activities diminished toward normal development actions. Civil engineering automation activities started in the late 1990s and have been continuing since then [Kilpeläinen & Nevala 1999, Kilpeläinen et al. 2004a, Kilpeläinen et al. 2004b, Viljamaa et al. 2009 and Kilpeläinen et al. 2011, Heikkilä et al. 2003 and Heikkilä et al. 2010, Viljamaa et al. 2009, Huovila et al. 2009]. Success feeds the motivation to continue the automation work in the civil engineering sector. The development work has been progressive especially in Scandinavia and the Northern Countries, i.e. Norway, Sweden and Finland. Today, automation is quite largely utilized in road construction, more and more in railway construction and also widely in water way construction.

Castro Lacouture [Castro-Lacouture 2009] describes in a table form, see Table 1, the historical development of construction automation, from the early stages of equipment inventions to the latest trends in automated project control and decision support systems. The developments indicated in the table are shown in the period when it had a dramatic impact on construction means, management, and methods, and not necessarily when it was invented. Construction has been mostly an adopter of innovation from other fields rather than a source of innovation. Robotics and computer-aided design (CAD) development started in the 1970s. In the 1980s the use of CAD systems (3-D and 4-D) expanded due to mass production of personal computers. The internet emerged on the scene in the 1990s. So come also global positioning systems (GPS), barcodes, radiofrequency identification systems (RFID), wireless communications, remote sensing, precision laser radars (LADARS – laser radar or laser detection and ranging), enterprise resource planning (ERP), object-oriented programming (OOP), concurrent engineering, industry foundation classes (IFC), building information models (BIM) and lean construction (LC). The 2000 century introduced web-based project management as well as tracking, positioning, vision and nanotechnologies to the sector.

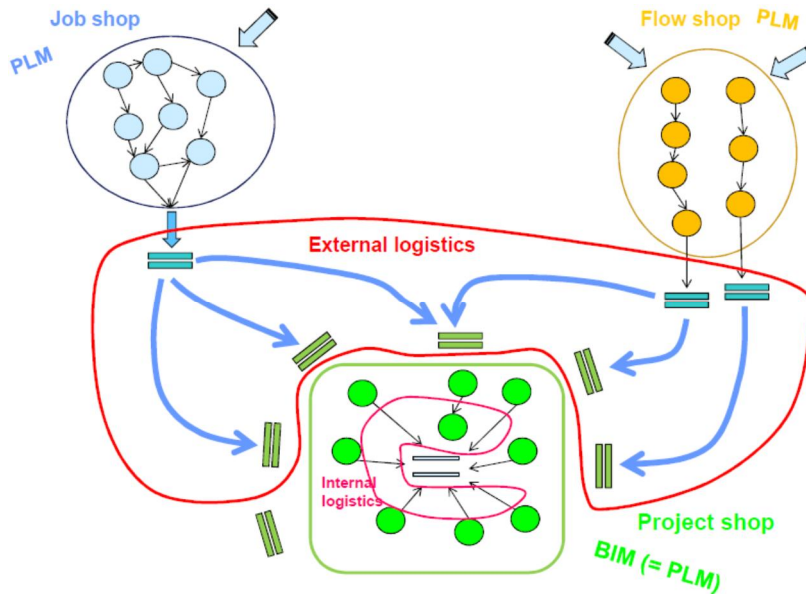
**Table 1.** Historical development of technologies related to construction automation [Castro-Lacouture 2009].

Period	Development
1100s	Pulleys, levers
1400s	Cranes
1500s	Pile driver
1800s	Elevators, steam shovels, internal combustion engine, power tools, reinforced concrete
1900s	Slip-form construction
1910s	Gantt charts, work breakdown structures (WBS)
1920s	Dozers, engineering vehicles
1930s	Prefabrication, hydraulic power, concrete pumps
1950s	Project evaluation and review technique (PERT), computers
1960s	Time-lapse studies, critical path method (CPM)
1970s	Robotics, computer-aided design (CAD), discrete-event simulation
1980s	3-D CAD, 4-D CAD, mass production of personal computers, spread sheets, relational databases, geographic information systems (GIS), large-scale manipulators
1990s	Internet, intranets, extranets, personal digital assistants (PDAs), global positioning systems (GPS), barcodes, radiofrequency identification systems (RFID), wireless communications, remote sensing, precision laser radars (LADARS), enterprise resource planning (ERP), object-oriented programming (OOP), concurrent engineering, industry foundation classes (IFC), building information models (BIM), lean construction (LC)
2000s	Web-based project management, e-Work, parametric modelling, Wi-Fi, ultra wide band (UWB) for tracking and positioning, machine vision, mixed augmented reality, nanotechnology

Today actual R&D activities are centring more on ICT technologies. This is not limited to software only but also includes computer hardware. It includes on-site sensory data acquisition and processing, human operator's field safety and security, computer based process control and monitoring, automated inventory control among many others.

## 2.1 Conditions for building construction automation

The project-based nature implies the periodic mobilization of construction equipment, materials, supplies, personnel, and temporary facilities at the start of every construction project. The historical development of construction automation has been marked by equipment inventions aimed at performing specific tasks originally carried out by workers, and by ground-breaking methodologies intended for improving the systematic behaviour of resources in a construction. Figure 1 describes the present building construction situation where prefabrication is made industrially, but actual construction work is project based.



**Figure 1.** Present situation of the building construction.

Although the construction industry has been mostly an adopter of innovation from other fields rather than a source of innovation, every development indicated in Table 1 has had a dramatic impact on construction means, management and practices. In the future investments in construction automation and robotics should contribute to value, safety, quality, productivity, and performance. Equipment should be easy-to-use and have intuitive user interfaces, be able to share work spaces with robots and workers as well as being able to encompass a high level of (proactive) safety.

Full potential of robotics will unfold as soon as robots do not just copy human work but be rather enhanced by robot-oriented planning, engineering, management and labour training. An important reason for a small number of robots being used compared to attempts made is that the robotised work phase is only a rather small part in the construction phase of the construction lifecycle [Shinko 2007]. Attempts have largely failed due to a lack of product and process flexibility and to market acceptance of the products. Robotic systems should be flexible enough to respond to the challenging unstructured and dynamical environment conditions on the building construction site. Despite the fact that many tasks in building construction are simple and repetitive (painting, grinding floors etc.), the automation of the building construction has proved to be demanding.

Automated data acquisition and monitoring as well as applications of ICT for supporting activities in management and social issues can provide automatic features for planning, procurement, control, and construction and maintenance as well as for the demolition phases. Thus automation can take place during the whole life cycle of the building.



## **2.2 Potential technologies for building construction automation**

Information and communication technology (ICT) will enable efficient, effective and flexible access to information and provide all possible channels of communication covering the use of ICT in Architecture, Design, Planning and Management of construction projects. This compose a rather wide application domain and can concern technologies such as Virtual Reality, Augmented Reality (AR), Integrated Data Models, 4D-CAD, Decision Support Systems, Web Technologies, Knowledge Management, Optimisation, Simulation, Mobile Computing and GIS. Currently Building Information Model (BIM) provides great potential for enterprises to have access to data repositories so as to store and share BIM model files on a subscription bases with the aid of ICT as a cloud service.

Open information structure and format is more and more important in the development of construction processes. Building Information Models (BIM) and in particular the Industry Foundation Classes (IFC) data format is a technology driver increasingly used for data sharing and communication purposes in the Architecture, Engineering and Construction (AEC) sector. Combined with mobile Augmented Reality (AR) and time schedules, 4D BIMs could facilitate on-the-spot comparisons of the actual situation at the construction site with the building's planned appearance and other properties at the given moment. Augmented Reality (AR) stands for superimposing virtual objects on the user's view of the real world, providing novel visualization technology for a wide range of applications in the Architecture, Engineering and Construction (AEC) sector. Numerous initiatives regarding AR on the construction site can be found on the web see e.g.: <http://graphics.cs.columbia.edu/projects/arc/arc.html>, <http://www.columbia.edu/cu/gsap/BT/RESEARCH/PAPERS/ar-asce.html> <https://www.icg.tugraz.at/~reitmayr/lgo/woodward-abstract-final.pdf> [http://www.constructech.com/news/articles/article.aspx?article\\_id=9231](http://www.constructech.com/news/articles/article.aspx?article_id=9231)].

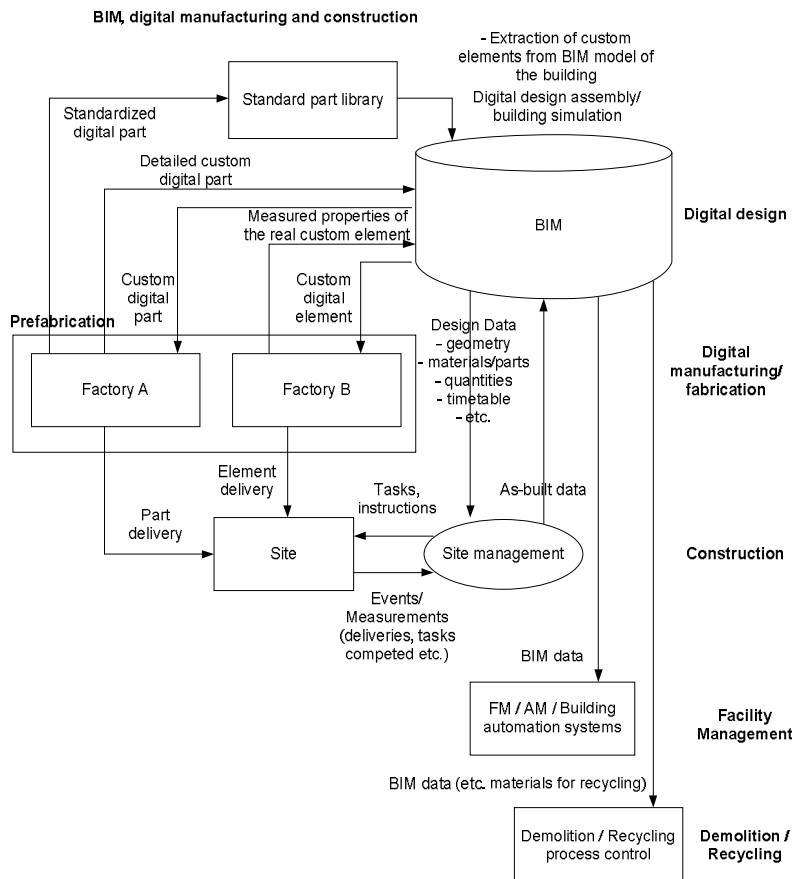
Recent advances in computer interface design, and the ever increasing power and shrinking size of computers, have recently enabled the use of “augmented reality” possible in demonstration test beds for building construction, maintenance and renovation. Use of AR could be beneficial in layout, excavation, positioning, inspection, coordination, supervision, commenting and strategizing. Additionally, related application areas would be communication and marketing prior to construction work, as well as building life cycle applications after the building is constructed [Woodward and Hakkarainen 2011].

## **2.3 Sensor and model data integration for building construction automation**

Automation is the use of control systems and information technologies so as to reduce the need for human work in the production of goods and services. It plays an increasingly important role in the world economy and in daily experience [CII 2001–2003]. Construction automation describes the field of research and

development focused on automating construction processes in building, civil engineering or in prefabrication of construction components [Saidi et al. 2008]. The use of robots is only one aspect of that process. Instead of equipment inventions aimed at performing specific tasks originally done by workers, future investments in construction automation and robotics should contribute to value, safety, quality, productivity, and performance. Equipment, like robots should be easy-to-use and have intuitive user interfaces, be able to share work spaces with workers as well as encompass a high level of (proactive) safety.

Automation of the building production requires exploitation of information models in each phase of the working process. This means the exploitation of BIM throughout the construction process. The application of ICT can support construction automation process by bringing BIM to the site for task operations both for workers and work machines. It can also automate data acquisition and monitoring and activities supporting planning, procurement, control, maintenance and demolition. Figure 2 illustrates possibilities to utilize BIM in the building construction phases.



**Figure 2.** Process chart for building manufacturing.

BIM is a data-rich, object-oriented, intelligent and parametric digital representation of the facility where objects are defined in terms of building elements and systems such as spaces, walls, beams and columns. For the automation of prefabrication, on-site operations and logistics BIM provides accurate geometrical representation of the parts of a building in an integrated data environment. In automated assembly, digital product data can be exploited in downstream processes and be used for manufacturing/assembling of structural systems [Azhar 2011]. It is also a modeling technology and associated set of processes to produce, communicate and analyze building models which are composed of components represented by digital objects that carry data and parametric rules. Documented advantages of 3D-BIM and 4D-BIM include: early multidisciplinary collaboration, accurate generation of 2D drawings from BIM, clash detection, reduced field coordination problems, increased productivity, fewer requests for information, and fewer change orders [Ocheoha and Moselhi].

In prefabrication BIM can be exploited in manufacturing and automated assembly of prefabricated components, in digital fabrication and also to improve component manufacturing methods. On the site BIM can be used to support coordination, construction monitoring, installation methods, constructability, automation and robot control systems, integration of subcontractor and supplier data as well as worker safety. All these actions require sensors and model data for successful operations. It can also be utilized to assist manual on-site assembly work. The guiding system will inform the crane driver by bringing element assembly related information (element identification number and its assembly place and planned assembly time) taken from the BIM model. After assembly, BIM is updated to correspond to the present assembly situation. After assembly, the guiding system will provide the driver with the information for the next lifting task. Also, the manual assembly work can be facilitated by planning joints to support automatic assembly, e.g. chamfers or other means in the manual assembly, too.

There is a variety of SW tools with the emphasis on different aspects on building construction. For the architecture, engineering and construction (AEC) industry there are planning tool software such as Tekla Structures that enable the creation and management of accurately detailed, highly constructable 3D structural models regardless of material or structural complexity [<http://www.tekla.com/UK/PRO-DUCTS/Pages/Default.aspx>]. These professional BIM tools support construction management, precast concrete detailing, steel detailing and cast in place for model-based project co-operation. Other example tools are Autodesk Revit, a tool that includes features for architectural design, mechanical, engineering and plumbing (MEP) and structural engineering, and construction [<http://www.autodesk.com/products/autodesk-revit-family/overview>] and ArchiCAD offering BIM-based documentation workflow and simplifying the modelling and documentation of buildings even when the model contains a high level of detail [<http://www.graphisoft.com/archicad/>]. For building services MagiCAD software is a tool for designing ventilation, heating, piping, electrical and sprinkler systems [<http://www.magicad.com/en>]. In principle, all these can serve as repositories for as-built BIM information.

### **3. Data acquisition technologies for construction operations**

In the construction phase, measurements are typically needed for object locations, asset management, and component installations during assembly, for capturing the existing condition of a construction project and for gathering as-built information essential for the maintenance and redesign of the facility. More accurate data acquisition comes along with the automation of the construction process. BIM provides reference values for dimensioning the prefabricated components, as well as accurate locations of components on the building site. The traditional measurement system used in manual assembly involving tape measures, transits, levels, and plummets that were used for decades cannot be used any more. In automated operations, data acquisition has to be digital, fast and accurate enough in order to provide the possibility to control the process according to the reference values given in BIM. Although there are plenty of suitable data acquisition technologies available that are used in other sectors, applications in the construction sector are not very common.

Basically there are four types of data acquisition needs; 1) positioning, 2) tracking, 3) progress monitoring, and 4) quality control. The first acquisition system to be automated is the most demanding in speed and accuracy. Table 2 gives a comparison of position and tracking measurement technologies with possible applications in construction.

**Table 2.** Comparison of position and tracking measurement technologies.

Technology	Range	Accuracy class	Cost	Applications in construction
GPS basic differential kinematic	Very large Large Large	10 m 1 m < 0.05 m	Low Moderate Moderate	Vehicle positioning, 3D machine control, Surveying
RF/ Fi-Wi, Bluetooth	Large	2–5 m	Moderate	Asset management, personnel tracking
RF/ wide band	Moderate	0.5–1 m	Moderate	Asset management, personnel tracking
Laser indoor GPS	Moderate	0.2 mm	Very High	3D machine control
Magnetometers	Large	> 1 m	Low	Asset management
Magnetic field 6D positioning	Small	< 1 mm to 5 cm	High	Personnel tracking, asset management
Laser tachymeters trackers	Large Large	1 mm 0.001 mm	Moderate Very high	Surveying, 3D machine control, quality control
Optical trackers	Small (< 10 m)	> 0.001 mm	High	3D machine control, quality control
MEMS based Inertial positioning	Moderate	so far poor values	Low	Asset management
Camera positioning	Variable	Variable	High	Personnel tracking Asset management Assembly

For identification, barcode technology has been introduced in the construction industry since the late 1980s, when the Construction Industry Institute (CII) funded a research project to explore the potential applications and the resulting cost-saving benefits of barcode use in construction. From then on, barcode technology has been applied in many areas in the construction industry. These areas include quantity take-off, field material control, warehouse inventory and maintenance, equipment/tool and consumable material issue, timekeeping and cost engineering, purchasing and accounting, scheduling, document control, office operations, and other information management in construction processes of projects [Bell & McCullouch 1988].

In radio-frequency identification (RFID) radiofrequency is used to capture and transmit data from a tag embedded or attached to construction entities. Manufacturers, transportation businesses, logistics firms, food and energy companies, and other enterprises across Europe are employing radio frequency identification (RFID) to cut costs, enhance visibility, improve asset-utilization rates, streamline business processes, improve inventory accuracy and achieve many other benefits.

With RFID it is possible to read a tag through the packaging or the product itself. RFID scanning is carried out by automatic readers and does not necessarily require a labour force. One of the most important differentiators between bar coding and RFID tagging is the ruggedness and environmental performance of the electronic tags. RFID tags can operate effectively in temperatures ranging from -40 to +200 degrees C and can perform under rugged conditions or even when dirty. Other main difference between bar-code and RFID is that RFID does not require line of sight as bar-coding does [Tulla et al. 2009]. Furthermore, barcode labels are easy to fall off or become unreadable due to dust, dirt, or other contaminants.

### **3.1 Positioning**

Positioning is needed both in prefabrication of components and in assembling them on-site, and in both cases exact planned positions and dimensions for components can be obtained from the BIM. The accuracy demanded for dimension and position measurements is typically one millimetre or less. In addition to accuracy data acquisition speed is important and should be completed typically in less than one second. In prefabrication positioning can be used for component dimension measurements with an accuracy of one millimetre or less. On-site positioning is used for acquiring the location of components in assembly as defined in the BIM. Positioning systems are used for providing 3-D position and possibly orientation coordinates of components. Total stations (digital theodolites or tachometer; a combination of a theodolite and an electronic distance measuring device), GNSS (Global Navigation Satellite System), and laser planes, levels, and plummets are representatives of more modern sensor systems already beginning to be used in construction sites. Based on Table 1 especially the accuracy favours to use laser or optical tachymeters or trackers in position data acquisitions.

#### Laser tachymeters and trackers

Laser tachymeters, also called total stations, are already widely used in building and construction sites. In a total station an electronic distance meter (EDM) is integrated to a theodolite to constitute a total station. They can be used for positioning tagged objects with millimetre accuracy over a large area. Tachymeters measure two direction angles and the distance to the tag using e.g. time of flight measurement. They can either be manually operated or can follow the tag (or prism) automatically when it is moved around. Laser trackers e.g. from Faro, Leica, and API are so far used in aerospace industry for very accurate positioning in large 3D spaces. The working principle is similar to that of tachymeters, but distance measurement is based on laser interferometer. These devices offer superior performance with micrometre accuracy, but are very expensive. Where the indoor GPS systems can track several measurement devices simultaneously, the laser tachymeters and trackers can track only one at a time.

### Optical trackers

Optical trackers such as NDI OPTOTRAK [<http://www.ndigital.com/>] use cameras and optical triangulation to measure 6D pose (position and orientation) of a special handheld or otherwise moveable probe. Accuracy is in the level of micrometres with measurement range of less than ten metres. System is easy to set up but obviously requires that the probe is within sight. These systems are used e.g. for reverse engineering, vibration analysis, robot calibration and control. Price is in the same range as with tachymeters but the operation range is much smaller.

### Laser indoor GPS

Laser based indoor GPS systems provide more accurate (< mm) large scale 3D positioning in industrial environments. These kinds of devices are currently used mainly in aerospace industry. Nikon iSpace or iGPS belong to such systems and provide  $\pm 200\mu\text{m} \pm 10\text{ppm}$  accuracy [[http://www.nikonmetrology.com/en\\_EU/](http://www.nikonmetrology.com/en_EU/)]. The working principle is like that of GPS, but it uses infrared rotating lasers in the satellites to create a measurement field covering the whole working space, Figure 3. Several measurement devices (sensors) can then be accurately positioned within the working space simultaneously. This system can also be applied to construction, although the price is high compared to tachymeters and optical trackers.



**Figure 3.** iSpace modular system for measuring, positioning and tracking [source: Nikon, [http://www.nikonmetrology.com/en\\_EU/Products/Large-Volume-Applications/](http://www.nikonmetrology.com/en_EU/Products/Large-Volume-Applications/)].

### GNSS: GPS

GNSS (Global Navigation Satellite System) is a satellite system that is used to pinpoint the geographic location of a user's receiver anywhere in the world. GPS (Global Positioning System) by US government, one of the GNSS systems in

operation, currently commonplace in construction, is and will continue to be a significant enabler for construction automation. The latest GNSS devices also support the Russian GLONASS satellites. Also, the European Union is currently building a Galileo satellite navigation system which will reach its operational capability at the end of this decade, so the availability of the satellite positioning services will improve in the next few years [[http://www.esa.int/Our\\_Activities/Navigation/The\\_future\\_-\\_Galileo/What\\_is\\_Galileo](http://www.esa.int/Our_Activities/Navigation/The_future_-_Galileo/What_is_Galileo)]. Traditional GPS relying on line of sight based on Earth-orbiting satellites can track moving objects with metre accuracy and require a ground station to reach centimetre accuracy. A standard GPS receiver for civil use offers accuracy down to a few metres; in practice 20 m accuracy can be expected. The GPS system can be used in two ways: differential GPS based on range measurements or phase measurement based kinematic GPS system [Castro-Lacouture 2009]. Differential GPS can measure position at a metric or sub-metric accuracy [<http://www.kowoma.de/en/gps/accuracy.htm>], whereas kinematic systems can achieve centimetre accuracy. In real time kinematic system (RTK) typically used in surveying and construction the kinematic computation is done in real time giving  $\pm 10$  mm  $\pm$  parts per million (ppm) horizontal and  $\pm 20$  mm  $\pm$  2 ppm vertical accuracy. Although units can calculate their relative position in millimetres, the real accuracy cannot be better than that of the base station. GPS positioning system is mainly used on the site for positioning of equipment.

Indoors the line of sight from satellites is not available, and GPS cannot be used directly. However, the GNSS receivers have become more and more sensitive so that signals can be registered also indoors and there are studies going on, which aim at modelling signal propagation channels inside buildings and use of these models for correcting the position estimates [Hein et al. 2008]. These studies may provide possibility to use GPS indoors in the future.

In the meantime there are systems which act like GNSS by positioning a receiver or tag with respect to several nodes in known locations ('pseudolites' or pseudo satellites). The term 'indoor GPS' is sometimes used in this context. These systems are based either on Wi-Fi (WLAN) or Bluetooth wireless techniques, specialized RF techniques or laser techniques.

## 3.2 Tracking

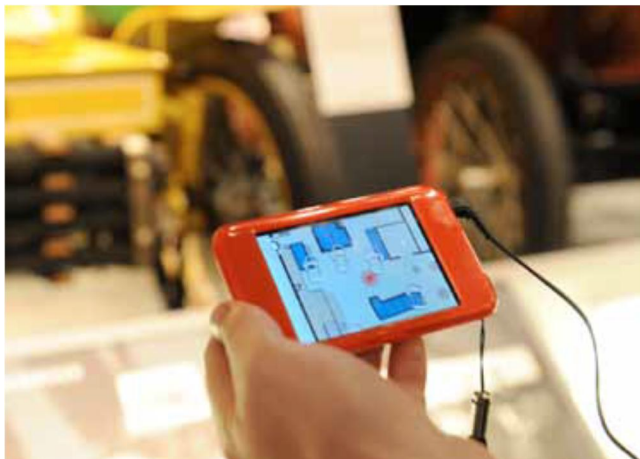
Possible applications for tracking in the construction sector are 1) tracking of components from prefabrication to the site (logistics), 2) tracking of equipment, component and assets on-site and in renovations, and 3) tracking of personnel on-site and in renovations. In all these cases speed and accuracy demands for data acquisition are not as critical as in positioning. In general, accuracy at the level of one metre is sufficient, and therefore there are plenty of technologies available. On-site, the BIM information can be used for visualising the position of the target being tracked. By knowing the position of object being tracked management of the construction project is made easier and the site safer.



## RF-based systems

Ultra Wide band (UWB) Radio Frequency (RF) location systems can be divided into model-based and map-based systems [Woodman & Harle 2009]. In model-based systems, e.g., [Ubisense 2009 ], nanoLoc [nanoLOC TRX 2009, Heikkilä et al. 2009] the location of the target is calculated from a radio propagation model and the known location of beacons. In map-based methods, a radio map is first constructed, with beacon signal strengths recorded in known locations, and subsequently this map is used to locate the target using measured beacon signal strengths and algorithms based on different methods, e.g. Bayesian modelling [Ladd et al. 2002 ], fusion maps [Aparicio et al. 2009], neural networks [Derr et al. 2008] or Kalman filtering [Paul & Wan 2009, Heikkilä et al. 2010].

In the simplest case, the Wi-Fi or Bluetooth positioning systems use the received signal strength indication (RSSI) for finding the node (e.g. WLAN or Bluetooth access point) nearest to a measuring device (tag). These systems are reasonably cheap and easy to set up. The more accurate systems involve use of complicated modelling and statistical methods and possibly also angle of arrival measurements. Usually, setting up such systems requires measurement of maps and fingerprints covering the whole area of interest. The simplest systems can locate a tag to a room (to the nearest node) and the more involved systems can achieve accuracy of up to a few metres [<http://www.iis.fraunhofer.de/en/bf/In/technologie/rssi.html>]. These systems can be used mainly for keeping account of the whereabouts of materials and personnel on the building site. These systems also provide access to data networks, which further facilitate asset management, Figure 4.



**Figure 4.** Awiloc® – Self-contained WLAN positioning in indoor and urban environments [source: Fraunhofer IIS, [http://www.iis.fraunhofer.de/content/dam/iis/en/dokumente/Positioning-and-Navigation/KOM\\_positioning%20in%20communication%20networks.pdf](http://www.iis.fraunhofer.de/content/dam/iis/en/dokumente/Positioning-and-Navigation/KOM_positioning%20in%20communication%20networks.pdf)].

Ubisense [Ubisense 2009] represents the model-based approach using a UWB real time locating system. It results in relatively high accuracy –  $\pm 0.5\text{--}1\text{m}$  – for target tracking, especially compared to other RF based methods suitable for distance in the range of 3 to 100 m. However, Ubisense has been noted to impose calibration challenges [Paul & Wan 2009], which may become a problem if frequent commissioning is necessary, as on construction sites. For this, Heikkilä et al. have contributed in [Heikkilä et al. 2010] by flexible calibration of the base stations. The UbiSense locating system has several fixed RF nodes, called base stations or sensors, where both the location and orientation needs to be known, as UbiSense system uses both the time-difference-of-arrival (TDoA) and angle-of-arrival (AoA) information. The flexible calibration of the base stations in [Heikkilä et al. 2010] utilizes the AoA measurements of the base station, while the target tag is located in known 3D positions in the environment.

Several pilot projects have been conducted in order to test the effectiveness of RFID for tracking the delivery of construction components to the construction site and maintaining an inventory of available parts and tools on site. A construction logistics system using a RFID technology for finely controlling several construction sites in order to improve the transportation and handling of construction materials is reported in [Tomoya et al. 2007]. In the past few years, numerous RFID applications and pilots have been demonstrated in the construction sector by researchers and industry professionals. Recently, BIM technology is emerging as the industry standard in the construction sector. Hence, the latest RFID applications are also combining BIM to monitor the movement of RFID tags in a BIM environment.

Sattineni [Sattineni & Azhar 2010] in his paper combines the two technologies so as to monitor the movement of RFID tags in a BIM environment. Real-time monitoring of RFID tags in a building information model is an improvement over other methods of tracking construction workers, equipment and materials on the jobsite. This method of monitoring can be used to improve the safety and productivity of construction workers, as well as for tracking equipment and construction materials on a construction site. The paper also explores strategies for combining the two technologies. Another example is given by Skanska USA, an international construction company, bringing together RFID and BIM for materials tracking, and estimates that this combined solution will accelerate the construction schedule by 10 days, which translates into \$1 million in savings [Skanska 2008].

### Inertial-based systems

Inertial positioning uses gyros and accelerometers for tracking the movement of the device. These are prone to drifting error due to signal integration. The advance of MEMS (Micro Electro Mechanical System) sensor technology in recent years has allowed the possibility of cheap and light weight inertial position systems, but because of signal drifting their accuracy is still too poor; it is not possible to achieve sub-metre accuracy with 60 minutes of operation [Woodman 2007]. Hence, a demand for millimetre accuracy leads to very expensive and heavy

equipment. These are used mainly in aviation, and usually combined with other systems using sensor fusion (GPS, magnetometers).

#### Camera-based systems

CCD cameras have been used for 3D positioning of objects for a long time [Bento & Correia 1998]. These systems tend to be case-specific where either selected features of the objects (edges, holes, etc.) or tags attached to object's selected surfaces are observed by more than one camera. The 3D pose of the object is computed using image processing and 3D vision algorithms. Good quality cameras are today available at reasonably low cost but, depending on the case, setting up the system may be laborious, involving arranging proper lighting conditions and developing the computing software and calibration.

#### Magnetometers

Positioning with magnetic field measurement is also studied for indoor applications [<http://www.indooratlas.com/>]. This system is based on mapping the magnetic field strength and direction within the region of interest and creating a map. Accuracy is expected to be on the same scale as with Fi-Wi and Bluetooth systems.

#### Magnetic field 6D positioning

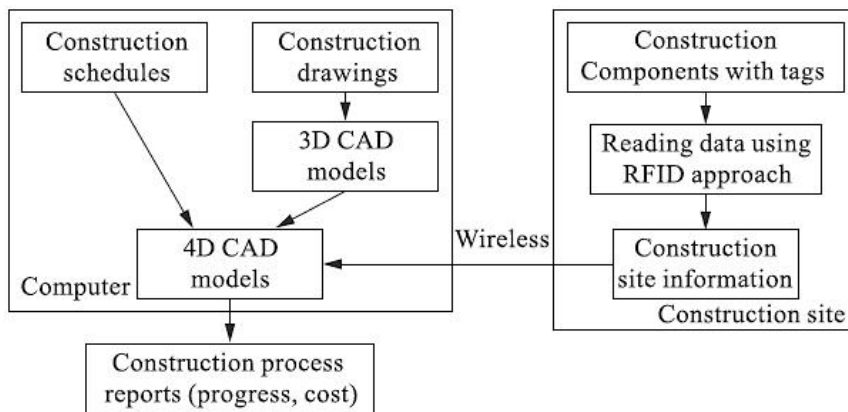
Magnetic field 6D positioning is possible using a magnetic field transmitters and magnetic field sensors. This technology is used in e.g. medical applications for tracking medical instruments, tracking human motions in virtual reality applications or capturing human motions in 3D animation productions. Magnetic field positioning is also used in military applications, etc., tracking the movement of a human head in simulator training applications. The benefit of the magnetic field positioning is that no line of sight is needed between the magnetic field transmitters and sensors. There can be several sensors positioned simultaneously with a high update rate, e.g. 120 Hz. The maximum range is about 4 m, and accuracy is from 1 mm to 5 cm, depending on the device and positioning distance. Usability can be limited if there are metal objects inside or near the measurement area. There are commercial devices, for example from Ascension Technology Corp or Polhemus.

### **3.3 Progress monitoring**

The objective of the progress monitoring is to automatically overlay as-built images with the as-planned model to determine and update the progress status of the construction project on the site. Colour coding (green and red) is typically used in schedule visualizations.

### RFID and CAD integration

RFID represents a practical technology to capture on-site data and integrate it into BIM. A progress management and 4D visualization Case Study is given in [Motamedi & Hammad 2009]. This case study is designed to facilitate the process of progress monitoring of construction projects and to provide a visualisation aid for component status tracking. The prototype system uses a database to store data extracted from the BIM, which will be updated by RFID reads and other updates (e.g., inspection data). Figure 5 below describes an example of how to use 4D CAD in order to visualize 3D components and construction schedules for construction project management.



**Figure 5.** An integrated model of RFID and 4D CAD [source: Hu Wenta 2008].

A system that is designed to investigate the use of RFID for automated schedule and inventory monitoring in real time is given in [Gajamani & Varghese 2007]. The technology with application software is integrated to identify the installed components and update the project schedule as well as present the as-built progress status. Finally the 3-D model of the building is updated and visualized in AutoCAD. A case for the utilization of RFID technology for tracking precast concrete components and their historical information from fabrication to post-construction is given in [Akinci et al. 2002].

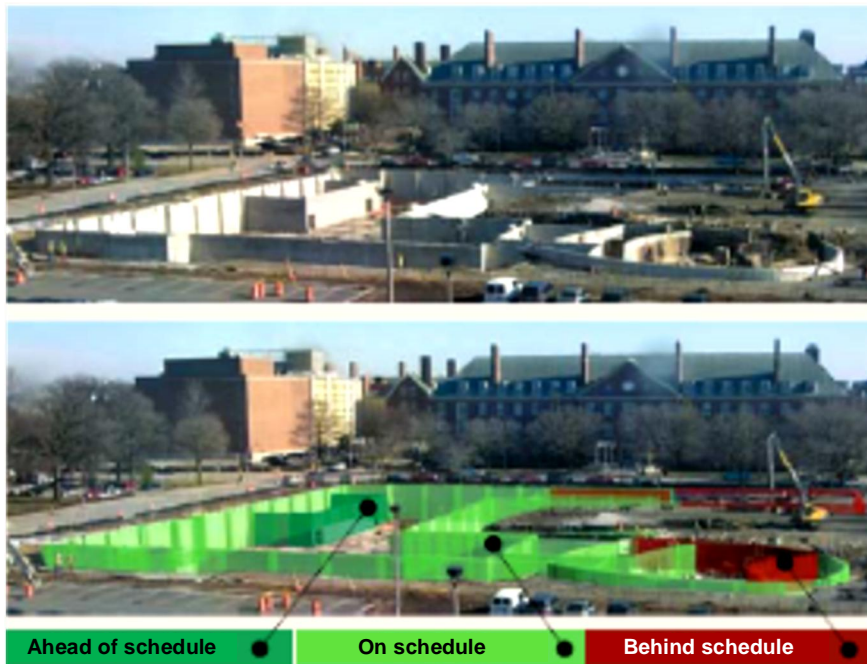
### Vision based monitoring

Vision-based applications have also been demonstrated for construction progress monitoring by ascertaining information on the placement of resources such as workers, parts, and heavy equipment. In visual tracking, computer vision has been used to perform a variety of measurement tasks. The advantage over the RFID method is that the camera is one of the sensors which are commercially available and can collect information economically. Furthermore, the technology is unobtru-

sive, meaning that there is no need for tagging or installing sensors to the monitored entities. The disadvantages of this method are associated with its limitations due to field of view, visibility and its inability to track indoor elements with the aid of peripheral cameras. An overview of a method for estimating the 3-D coordinated data for development of a project control system with stereo camera images is discussed in [Chae & Kano 2007]. It gives an example of an actual construction site application with location information in the 3-D space of time series from images.

A method for estimating the 3-D coordinated data for development of a project control system with stereo camera images is discussed in [Soungho & Naruo 2007]. It gives an example of an actual construction site application with location information in the 3-D space of time series from images. An SFM (Structure from Motion) method is used for the collection of camera motion and 3-D object data. The SFM method estimates camera motions and reconstruct objects simultaneously based on epipolar geometry [Shapiro & Stockman 2001]. The image taken of the 4D model is overlaid with the site photograph taken at the same time. Colour coding is very illustrative way to provide a visual representation.

Figure 6 below demonstrates the image taken of the 4D model overlaid with the site photograph taken at the same time. The 4D photograph displays the expected progress. Colour coding is a very illustrative way to provide a visual representation.



**Figure 6.** Site photograph, superimposed photograph, and colour coding [Castro-Lacouture 2009].

## Digital photos

Digital photos are an easy and commonly used method for documentation of the construction process. When the construction project is large, a systematic method for handling digital pictures is useful. There is commercial software to maintain picture archives and to link photos to other data, such as CAD drawings: [<http://www.constructionphotodocs.com/UnAuth/Pages/HowItWorks.aspx>].

A review of photographic and imaging applications in construction is given by Ibrahim and Kaka [Ibrahim et. al. 2008]. Digital photos are useful in tracking timetables and job site situations, sharing information between people and documenting different phases of construction. Picture data can be also used for documenting faults, training workers, investigating accidents etc. Image data has usually analysed visually (a manual approach), but advances in technology and computing power have made a more automated approach possible. Some examples of automatic image data processing in construction are: detecting cracks in the buildings, concrete bridges or tunnels, detecting rust on bridge coatings or damaged tiles in the floor. A sequence of digital pictures can also be compared to a 3D model of the building, for example detecting deviations or monitoring progress of the construction.

### **3.4 Quality control**

Quality control is a procedure or set of procedures intended to ensure that a manufactured product or delivered service adheres to a defined set of quality criteria, or meets the requirements of the client or customer. In this section, we concentrate on the collection of real world data, and exclude the procedures or criteria to meet quality control requirements. These measurements can be used to capture on-site as-built information for keeping the BIM updated.

#### Imaging systems, shape measurement and scanners

Imaging systems are used for capturing the existing condition of a construction project and for gathering as-built information. A laser-based imaging system creates an accurate 3-D image of the surface by giving a cloud of points (Z, Y, Z or angle, angle and range) associated with the surface. In addition, many systems can output the intensity of the return signal as well as colour information. Laser-based 3-D imaging systems are commonly referred to by some of the following names: laser scanners, laser radar or laser detection and ranging (LADAR) and light detection and ranging (LIDAR) systems. These systems can create highly accurate 3-D images of objects. Laser scanning is especially applicable in construction sites, due to its efficiency in capturing the existing condition of a construction project. Although data acquisition is fast, post-processing tasks can take much longer, depending on the level of detail of the 3-D model [Castro-Lacouture 2009]. Gathering as-built information is essential for the maintenance and redesign of the facility.

3D laser scanners (e.g. Leica) with millimetre accuracy on a large scale are very expensive. 2D laser range finders (e.g. SICK) are cheaper, but require additional mechanisms and angle measurements for 3D operation. A common practise for scanning buildings, bridges or similar structures in civil engineering is to install a laser scanner on a tripod. Then a 3D point cloud is measured with the scanner. When scanning, for example, buildings, the location of the scanner can be changed in order to measure the structure from each side. Several point clouds can be combined into one when post-processing the data. A high resolution digital camera is also commonly integrated to a scanner. This static scanning method can be impractical, if large area is to be scanned.

Mobile laser scanning, using either a vehicle-mounted laser scanner or an airborne laser scanner, is applicable for measuring large areas, such as cities, roadways, rail roads, power lines and similar. If laser scanning is carried out using a vehicle, plane or helicopter, the location and orientation of the moving scanner must be measured very accurately. This is done by combining the GPS and inertial measuring unit (IMU). Commercial airborne laser scanning systems are very expensive (\$500 000 –\$1.3 million) [Petrie 2011], but large areas can be measured very quickly. Mobile laser scanning is commonly used for collecting data from existing structures or landscapes before construction. There are several manufacturers of mobile laser scanner systems, etc. Leica Geosystems, Optech, Riegl, IGI, iMAR, TopEye, AHAB, Fugro, Trimble and Topcon [Petrie 2010, Petrie 2011].

Photogrammetric shape measurement systems may also be usable in some cases. Structured light scanners [Rocchini et al. 2001] are based on projecting light patterns onto a measured surface and observing it with multiple cameras. From the acquired images it is possible to compute 3D surface points and build surface models. So far, these can be used for small-scale (1 metre) shape measurements with an accuracy level of 1 mm. The advantage of these systems is their low price when compared to laser scanners.

Surface and shape measurement with scanners require that the measurement device sees the whole surface. If the surface measurements have to be obtained in some coordinate frame other than the measurement system's own frame, this might become problematical in varying environments like construction sites. In this case, the scanner can be combined with e.g. optical tracking system [<http://www.ndigital.com/industrial/products-3D-laser-scanners.php>].

Consumer-grade range cameras such as the Kinect sensor introduce a very high quality-to-price ratio. Even though they are designed for computer game applications, these have great potential also for indoor industrial applications in such cases where accuracy requirements are less strict. The Kinect sensor is based on the triangulation principle and uses a multiple pseudo-random pattern light ray projection measured with an integrated camera [Heikkilä et al. 2012]. It provides depth and colour image measurements simultaneously at a frame rate of up to 30 fps, with depth and colour data – as a coloured point cloud – of about 300,000 points in every frame. For locating and even identifying objects for sparse quality observations and also automatic or semi-automatic object handling, this may be good enough.

## 4. Applications for building construction automation

Actual construction takes place mainly on the construction site. However, a significant part of the on-site work can also be performed off-site so as to reduce on-site work and consequently cost, and increase quality. This reduction containing pre-fabrication, pre-assembly, modularization, and off-site fabrication, collectively termed pre-work, have become more viable with recent advances in design and information technologies. In the future, BIM can be expected to play a crucial role in automating the construction process.

In past decades, the main research activities of robotics and automation in construction (RAC) can be divided into two large groups: civil infrastructure and house building applications [Balaguer & Abderrahim 2008]. Typical civil infrastructure robot applications are the automation of road, tunnel and bridge construction, earthworks, etc. In the group of house construction, main applications include building skeleton erection and assembly, concrete compaction, interior finishing, etc. During the 1990s, R&D activities were led by Japanese companies and universities, and were focused on the development of new (tele-operated) robotic systems and on the automation of existing machinery – called *hard robotics*. These robots were used in an attempt to automate several construction processes in the house building and the civil construction. Examples of those were interior building finishing, brick layer masonry, construction of modular industrialized buildings, sensor-based guidance for road pavers, excavator control, infrastructure inspection, tunnel and bridge construction. However, only a few construction robots have succeeded in making their way onto the market. Therefore, investments in research activities have declined sharply. The main difficulty of RAC is related to the nature of the work environment, which is highly unstructured in general. Working in this environment involves handling heavy objects, elements made with big tolerances, a low level of standardization, medium level of industrialization and pre-fabrication, in addition to the intervention of numerous non-coordinated actors (architects, builders, suppliers, etc.). Therefore, a major effort needs to be made in order to increase the level of automation of this important sector and to better coordinate the processes involved in order to improve its productivity.



Construction work can be divided into off-site and on-site work. The first three phases, 1) Requirements identification, 2) Project planning, 3) Design and engineering, can be viewed as off-site construction work, whereas on-site work takes place in the last three phases, namely 4) Construction, 5) Operations and maintenance, and 6) Decommissioning. Phase 4) construction can be divided into different phases by type of actual construction activity involved. From a purely physical-world and practical point of view, construction may be viewed as being comprised of a finite number of basic construction operations, comprising 1) Civil engineering, 2) Foundation construction, 3) Frame erection, 4) Indoor works, 5) Yard works, and 6) Finishing works. The following parts of this chapter will give a survey on the current situation of the building construction automation.

## **4.1 Prefabrication**

Prefabrication is the practice of manufacturing and assembling the components of a structure in a factory or other manufacturing site, and transporting complete assemblies or sub-assemblies to the construction site where the structure is to be located, Figure 7. The term is used to distinguish this process from the more conventional construction practice of transporting the basic materials to the construction site where all assembly is carried out.



**Figure 7.** Prefabricated concrete products [source of the right figure: FINLAND – The home of precast expertise. A booklet about design, manufacture and construction with precast concrete].

Prefabrication, preassembly, modularization and off-site fabrication (PPMOF), collectively termed pre-work, have become more viable with recent advances in design and information technologies. On industrial projects, significant use of pre-work has occurred in the areas of equipment, instrumentation, ironwork, mechanical, piping and structural assembly [Song et al. 2005]. The three main drivers found include 1) cost, 2) schedule, and 3) workforce issues. The study also found that prefabrication and preassembly may increase craft productivity, improve quality, and reduce labour rates. On the other hand, impediments to prefabrication and preassembly are additional project planning and project coordination, increased transportation, greater inflexibility and more advanced procurement requirements.

Also, in the construction sector owners demand high levels of value, safety, quality, productivity, and performance in their capital projects for their competitiveness and profitability. In addition, both owners and constructors face a current and projected shortage of skilled labour. Pre-work can respond to the requirements of business owners expecting effective and efficient project delivery with tight cost and schedule control by transferring work to alternate locations both on and off the

site [CII 2002]. Industrialization in construction means a transfer of work from sites to factories. Pre-work supports industrialization and provides substantial opportunities for project teams to achieve a wide range of benefits, including 1) reduction of overall project duration, 2) improvement in productivity, 3) reduction in field labour needs and costs, and 4) risk reduction through a more predictable work process and shop environment. It also highlights the risks and obstacles to implementation, consisting of 1) engineering, 2) transportation, 3) communication and 4) organization and other factors.

In Europe as well as in the United States, there have been projects dealing with prefabrication automation [Neelamkavil 2009]. The FutureHome project focused on the development of an integrated construction automation concept and associated technologies for all stages of house-building construction process, from the architect's desk to site robots. The objective of the ManuBuild project was that customers could purchase high quality manufactured buildings that have a high degree of design flexibility at relatively low cost. In the United States, FIATECH for example created a Capital Project Technology roadmap in order to integrate various functions and any required information into a unified construction project. The automation-related fields include 1) Automated design, 2) Integrated automated procurement and supply network, and 3) Intelligent and automated construction job site.

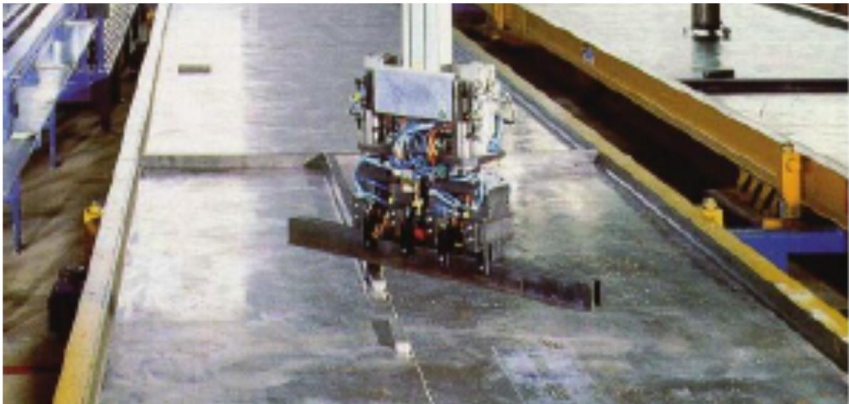
Automation pertaining to the prefab construction sector typically falls into one of three categories: 1) the prefab components making process, (parts, panels, pre-cast, formwork, etc.), which deals primarily with the construction of the building blocks; 2) the assembly process, in which the construction components (often from different suppliers) are installed to create buildings, houses, etc. by an array of sub-contractors, 3) the construction business processes that represents both the business and support processes (project management, supply chain management, document management, workflow management, change management, planning & scheduling, etc.).

Making of the concrete has been highly automated for several years in the pre-fabrication of large-scale pre-fabricated reinforced concrete parts. On the other hand, pre-fabrication of large-scale pre-fabricated reinforced concrete parts still involves a lot of manual work. Formwork, with all its shapes and openings for windows, doors etc., is largely done manually as is the placement of reinforcement bars and insulation layer. Distribution. The distribution of concrete to the formwork is performed by remotely controlling the gantry crane carrying the concrete distributor. Still the distribution of the concrete over formwork is controlled by manual workers.

#### Prefabricated components for modular housing

Robotic systems have found their way into the construction industry for component manufacture and the production of modular housing. Weckenmann for example has offered shuttering robots for form working since 1992 [<http://www.weckenmann.com/en>]. A new development surge has been under way for some years, which in individual cases has already led to Computer-Aided Manufacturing (CAM) and in some cases to

Computer-Integrated Manufacturing (CIM) of pre-fabricated concrete parts for ceilings, walls and roofs [Balaguer & Abderrahim 2008 and Neelamkavil 2009]. Bock [Bock 2007] elaborates a robotic precast concrete panel factory that uses a multipurpose unit, which allows flexible production of the concrete floor, wall and roof panels. Here, based on CAD data, a multi-functional gantry-type robotic unit with two vertical arms places magnetos on the steel production table, Figure 8. The unit also attaches shutters on top of the magnetos and then places horizontal, vertical and triangular reinforcement bars, as per design.



**Figure 8.** Multifunctional robot placing magneto moulds on 3 to 12 m dimensioned steel pallet for prefabricated concrete panel production [source: Bock 2008].

A CAD-CAM-controlled concrete distributor spreads the right amount of concrete while controlled by a CAD layout plan, which takes into account installation, window or door openings. Gantry type robots place the mould and reinforcement and distribute the concrete. The curing station works like a big automated warehouse. A production planning information system keeps the operator constantly informed via a graphics display of, for example, which pallet is located where on the plant, whether there is a malfunction, and when the element will be ready. For service purposes, both the master computer and the plant controls can be monitored from a distance via a modem. The various elements are produced on steel pallets which have dimensions of about 3 to 12 metres. The use of robotic technology in pre-cast concrete element production has also resulted in a constant quality of products and less waste in factories, because, due to computer-assisted planning and programming, only the necessary amount of concrete is being provided from the batcher plant.

#### Automation and robotics in masonry prefabrication

Mechanical-technical development has taken series of steps in the prefabrication of brick wall elements, which can now be manufactured in a wide variety of production plants with semi-automatic production systems or fully automatic brickwork

robots under industrial conditions [Bock 2008]. For stationary production of prefabricated brickwork parts, various machines exist. Thus, automated manufacture of individually planned prefabricated brick wall elements can be carried out in a wide variety of production plants, with semi-automatic production systems or fully automatic brickwork robots under industrial conditions, Figure 9. In addition to this automated and robotized facility there are semi-mechanized masonry wall prefabrication units, which are controlled by one or two workers [Bock 2008]. The high capital involvement is one difficulty which production outlets of brickwork elements have to face in view of economic fluctuations, and which is caused by establishing the expensive production systems.



**Figure 9.** Factory-based mobile semi-automated masonry wall production unit including automated mortar distribution, [Bock 2008].

Although robotic systems are used in prefabrication, BIM is not directly utilised in the way that the latest planning data is taken from the BIM. Instead, the component planning data may come even as a paper version to the factory, where it is input into the production planning (CAD-CAM) system. The factory manufactures the components more according to their production plan than according to the progress of the construction.

#### Prefabrication of wooden houses

Automation has come to the manufacturing of **log houses and timber frame houses**. The processing technology in wood construction is developing continuously from manual processing with small machines to full-scope processing on CNC machines which could automatically produce any wooden joint based on architectural floor plans, elevations, sections, structural plans [Bock 2008].

Recently, the focus has particularly been on the block construction systems (glued laminated wood, bulk wood and log wood construction). Automatic timber positioning systems and laser-assisted marking devices allow flexibility within

automated CAD-CAM timber element production. Automated production lines can manufacture wall, floor and roof components for wooden houses with complex timber frame designs. Furthermore, fully automated manufacturing processes machine laminated timber in accordance with the design drawings so as to produce dimensionally-accurate logs. Special log joints and advanced preparations facilitate and speed up work at the construction site. By means of 3D designing and CAD-CAM technology, the frame parts of the Timber Frame structure are factory-produced with precise dimensions:

<http://www.randek.com/products/wall-floor-and-roof-production-lines/complete-system-sf002/>,

<http://www.hirsilinna.com/category/log-houses/>,

<http://www.fbrantasalmi.com/manufacturing.html>.

## 4.2 Civil engineering

In this context, civil engineering means groundwork such as excavation, earth moving and piling occurs on the site before starting building construction.

### Earthmoving works

In building construction earthmoving is typically an open-pit mining (surface mining) excavation by using backhoe- type equipment. The work is a bulk wide area type of excavation, where the equipment works inside the pit against nearly vertical walls within a space that is shallow in depth and large in area. The site can be accessible from many directions. The excavated soil is hauled a short distance [Hemami 2008].

In the field of earthwork, the research is centred on the introduction of new control techniques for existing machinery such as excavators, bulldozers, draglines, etc. For earthmoving works, there are several examples of development projects, see Figure 10. The University of Sydney project developed an automated excavator that accounts for interaction forces in analysing the required bucket motion [Ha et al. 2000]. As the bucket comes into contact with its environment, the contact force is regulated such that it remains within a specific range by using specific control strategy. LUCIE – Lancaster University computerised intelligent mini-tracked excavator – has been automated so that it is capable of autonomously digging a good quality trench in highly variable ground [Seward 1996]. Application of the satellite global positioning system (GPS) for excavator positioning and navigation allows the vehicle to be positioned reliably with an accuracy of 25 mm. A key element in making construction robots acceptable to industry is their proper integration into the design/build process. This requires a seamless interface between the CAD drawings and the robotic operation.



**Figure 10.** Automated excavator from the University of Sidney [source: Balaguer & Abderrahim 2008] and LUCIE -Autonomous excavator [source: Saidi et al. 2008].

A robotic earthmoving system that completely automates the task of mass excavation and truck loading has been developed by Carnegie Mellon University [Cannon & Singh 1999 and Cannon 1999]. The excavator uses scanning laser rangefinders in order to recognize and localize trucks, measure the soil face and detect obstacles. The excavator's software decides where to dig in the soil and where to dump in the truck and how to quickly move between these points. This system was fully implemented and was shown to load trucks as quickly as human operators.

References [Sarata 2006, Arai 2011] describe an autonomous wheel loader "Yamazumi-4", successfully demonstrated to carry out unmanned autonomous earth moving operations on a construction site.

### Piling

In some cases, reinforcement of the foundation on the construction site has to be performed. To date, the pile work in the overall functional process makes very little use of information and automation technology opportunities. References [Heikkilä

2007 and Heikkilä et al. 2010] report on the development of automation for the foundation engineering of building and infra construction. The 3D functional process for foundation engineering utilizing automation needed in the sub-areas of pile driving, mass and column stabilization, and the sub-technologies and methods needed for these are reported to save piling time and reduce energy consumption and carbon dioxide emissions.

Pile driving and deep stabilisation are commonly used ground strengthening methods for reinforcing the foundation in Finland. The ground strengthening method is selected, based on requirements and soil properties that are measured beforehand. 3D design tools can be used for analysing captured soil property data and designing piling or column locations and the other properties, etc. required, the bearing capacity of the piles or the optimal amount of soil binding agent of the columns in deep stabilisation. As a result, BIM -based digital work instructions for the work machine (piling machine or deep stabilization machine) can be generated. This data can be used, for example, for installing piles or columns accurately based on RTK-GPS positioning. With wireless data connection to the work machine, the progress of the work can be monitored via the internet and e.g. several piling machines working on the same work site can synchronize piles that are already made.

Although the 3D functional process for foundation engineering utilizing automation is reported to save piling time, reduce energy consumption and carbon dioxide emissions it is, however, currently not economically feasible to fully automate the functions of the pile driving machine, but use automation and positioning operations to assist the operator.

### **4.3 Foundation construction**

Formwork is a die or a mould including all the supporting structures, used to shape and support the concrete until it attains sufficient strength to carry its own weight. It plays an important role in construction projects, retaining fresh concrete until it sets and acquires adequate resistance. Wood or a combination of wood and plywood is the most traditional formwork, although reusable wood or metal frames have become popular for concrete construction; see for example Purdue University presentations on several Stay-In-Place (SIP) forming systems (<http://rebar.ecn.purdue.edu/ect/Links/technologies/Civil/sip.aspx>). Irrespective of material of the mould and irrespective of technology to be used traditional manual construction methods when making dies or moulds are used in on-site formworks. Despite of the material of the formwork and of the technology used in the forming system still conventional manual construction methods when making dies or moulds are used in on site formworks.

For pumping and placing of concrete, truck-mounted manipulators with concrete pumps are used ([http://www.putzmeister.com/pm\\_holding/data/BP\\_4200\\_GB.pdf](http://www.putzmeister.com/pm_holding/data/BP_4200_GB.pdf)). These truck-mounted shotcrete manipulators have optimised pump control and in many cases also semi-automatic boom control systems helping the operator in



the concrete distribution. The ergonomic boom control (EBC) functions can be operated directly using radio remote control, Figure 11. When EBC operation is activated, it is possible to control the boom with only one joystick ([http://www.pmw.de/cps/rde/xchg/pm\\_online/hs.xsl/3624\\_ENU\\_HTML.htm](http://www.pmw.de/cps/rde/xchg/pm_online/hs.xsl/3624_ENU_HTML.htm)).



**Figure 11.** Programmable, articulated-boom machine for the pumped delivery of fresh concrete [source: Saidi et al. 2008].

Reference [Kim et al. 2011] presents a conceptual design for an automatic footing device for one-day housing together with a prefabricated method for building low-rise multi-family houses. This foundation technique refers to a technique of making a wall foundation by connecting prefabricated blocks for straight lines and corners by using a backhoe or a forklift to place precast concrete modules on site. This technique enables accurate construction and also has the advantage of radically reducing the construction period, from 7–8 days to 2–3 days. Since there is no need to make a mould, there is also a reduction in construction waste.

#### **4.4 Frame erection**

Typical building structures include a reinforced concrete structure, steel structure and steel framed reinforced concrete structure, and automation in the building construction has developed for each type of structure. Nowadays, the reinforced concrete structure is the mainstream of building structures due to its use of less expensive materials, such as rebar and concrete. Steel structures are generally more expensive than reinforced concrete structures and more commonly used for office towers, where large floor spaces without partitions are required. Reinforced concrete structures are also commonly used for high-rise apartment blocks.

From the mid-1980s to the early 1990s, building contractors, especially major general contractors in Japan, made aggressive investments in order to develop building automation, and to introduce a wide variety of robots and automatic systems into their construction fields. At the same time, steel fabricators started introducing welding robots [Shinko 2007]. Combined with the development of robots, automatic systems for entire building construction started to develop around 1990. These systems combine automation technology, such as building robots and automatic transferring system, industrialization technology, such as prefabrication and unitization, and computer technology for controlling the systems.

One of the steel structure construction systems is the SMART system developed by Shimizu. It was used for the construction of more than office buildings of more than 30 stories. It consists of all-wheatear, full-robotic factory on the top of the building. The lift-up mechanism automatically raises the construction plant and at the same time raises the on-site factory, called a field factory [Balaguer & Abderrahim 2008]. The system has three different areas of work. First, a computerized office, where designers working with CAD systems lay out a set of predefined structural elements. Second, a factory production, where designers at the office transmit information required for material and manufacture of elements. This factory has a fully computer-integrated manufacturing and transporting process. And third, the construction site transformed into a place of automated assembly, where a central construction management centre is in charge of coordinate design information, materials delivery by the factory and constructive methods [Morales et al. 1999].

Another system, the Automated Building Construction System (ABCS), integrates factory automation with construction project operations and allows work to continue independently of adverse weather conditions [Taylor et al. 2003]. A parallel material delivery system performs the vertical and horizontal transport of structural components from the site delivery area to the construction operation level, Figure 12. The factory framework supporting the cranes and material hoists consists of the structural steel roof for the finished structure. The climbing mechanism rests on alternate structural steel columns, and the upper-most section of each column is equipped with a locking hydraulic jack system. On completion of two structural floors and exterior cladding, the factory is automatically jacked up.

The BIG CANOPY system by Obayashi uses a combination of precast and in situ concrete with modular sub-assemblies, Figure 12. Precast components include columns, beams, slabs and interior wall elements. Additional pre-fabrication includes vertical and horizontal drainpipes, air-conditioning ducts, low superstructure erection work with alternative construction techniques. The working environment is also improved by reducing the surface temperature of operatives and their work environment [Taylor et al. 2003]. Reference [Shinko 2007] introduces major Japanese automatic construction systems where Smart System and ABCS are used for steel structures, and Shuttle Rise and BIG CANOPY are used for reinforced concrete structures. It also gives a summary of the companies related to construction automation.



**Figure 12.** BIC CANOPY and ABCS construction systems [source: Shinko 2007].

NCC has developed and tested the NCC Komplet project where prefabricated flat elements are produced at the factory, and the assembly is conducted under a large weather-protected tent. Automation and mechanization are ergonomically designed so as to reduce labour fatigue. Apartments are 90% prefabricated. The on-site assembly factory is all weather-proofed, enabling ergonomic working conditions all year around [Bock 2008]. The NCC Komplet concept was based on a sort of type house with limited architectural freedom. However, the NCC Komplet project has terminated, and the last industrially built modules left the factory in 2008. The concept was based on prefabricated elements with very low tolerances, resulting in assembly problems at the building site [Pourghazian 2008].

The Automated Building Construction System (ABCS) developed for the construction of high-rise structural-steel buildings, applies the ideas of factory automation to the construction site, and allows work to be done in a comfortable factory [Ikeda & Harada 2006]. It applies automation, robotics, and computer technology to building construction. ABCS integrates the Super Construction Factory, which provides all-weather warehouse facilities, automated conveyor equipment and a centralized computer control system. The same concept can also be seen in the Canopy, SMART and other automated construction systems.

The EU project ROCCO developed a large-range (10 m reach) and high payload (up to 500 kg) hydraulic 6 DOF robot for brick assembly [Balaguer & Abderahim 2008]. The robot is equipped with auto-tracking laser telemeter in the tip in order to perform precise (up to 5 cm) brick assembly. In this way, the control system avoids important arm flexion. The robot performs the assembly sequence obtained by the planning software and needs an initialization process in order to know the brick's pallet position, Figure 13.



**Figure 13.** ROCCO project brick assembly robot [Source: Balaguer & Abderrahim 2008].

Erection of wooden houses is manually performed although the manufacturing lines in the prefabrication of timber frame and log houses are (semi)automated and factory-produced components have precise dimensions. The prefabricated house is delivered as a kit with erection instructions and images of all structures including many ready-to-install wooden parts enabling rather quick and easy assembly.

#### Wall assembly

As buildings become larger and more complicated, automation in construction is becoming more important. Components to be assembled are typically large, heavy breakable objects like e.g. curtain walls, requiring precise installations. Assembly is very laborious and is neither safe nor labour-friendly, and thus is a good candidate for automated installation. Several automatic assembly systems have been developed and used on construction sites [Gassel et al. 2006].

A multi-jointed handling robot assists in the installation of heavy exterior and interior materials, Figure 14. This 'Mighty Hand' (KAJIMA Japan) lifts heavy panels used in construction, including concrete or glass curtain walls. The robot operates under human supervision.



**Figure 14.** Kajima's interior wall assembly robot [source: Balaguer & Abderrahim 2008].

Gassel [Gassel et al. 2006] presents several robotic technologies for assembling wall panels. A mechanised panel assembly system has been developed by Ballast Nedam with the aid of a flying scaffold suspended from a tilting arm. The tower crane uses tilting arm to pick up the flying scaffold. The tilting arm's grab is positioned above the floor where installation will take place. Using its own weight, the flying scaffold is tilted into place on the proper floor. The flying scaffold then attaches the facade element to the building. This is done using a hydraulic system. Once disconnected, the tilting arm can be used for the next flying scaffold.

A multi-jointed handling robot assists in the installation of heavy exterior and interior materials (FUJITA Japan). This handling robot is manually operated from the vicinity of the place of assembly .

The FUJITA Shuttle method facilitates the construction of extra-large exterior wall panels assembled on the ground. Panels covering the entire perimeter of the building are hoisted into place one panel at a time and positioned automatically, working from the top down.

A stepwise system was used in the Rembrandt tower for assembling wall panels. First the panels are transported to the floor where they are required and placed on the floor where the panels will be installed. The actual assembly starts by moving the wall panels outside with the aid of a mobile hydraulically operated forklift connected to the tower crane for assembly.

SAMSUNG's curtain wall installation robot was built on a commercial excavator and tested at a real construction site. Results were used to refine the new concept of curtain-wall installation automation [Yu 2007].

Refurbishment of old buildings both outside and inside is an emerging area for robot applications. The task of renewing old buildings is demanding and requires a systematic process to facilitate a rapid upgrading without neglecting the specific situation of each case. Reference [Iturralde & Bock 2013a] focuses on the rehabilitation of the external envelope of the building with special attention to the double skin façade. Virtual refurbishment approach is used to evaluate automation possibilities. Another case concentrates on refurbishments of industrial buildings [Itur-

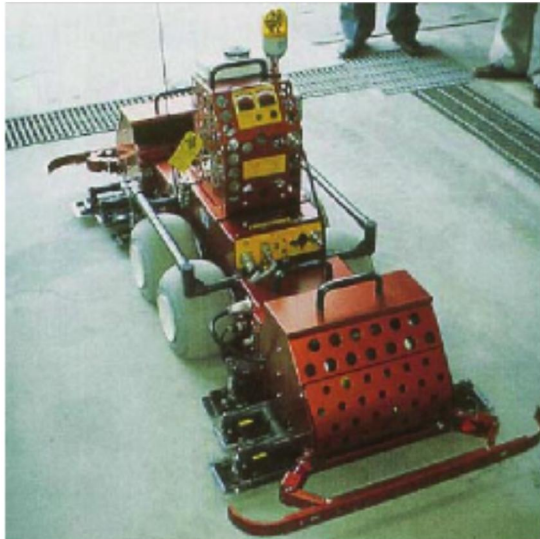
ralde & Bock 2013b]. The article reviews technologies such as 3D laser scanner to model the entire building, utilization of BIM in project management and in design each of the elements and finally using of robotics in the production of construction elements. For narrowing the field three major factors are defined; 1) minimization of the energy consumption bill of the building, 2) refurbishment or expansion should not try to interfere on the production process that takes place in the building, and 3) approach towards a robot integrated industrial or productive building.

## **4.5 Indoor works**

IndoorInterior works encompass finishing tasks on surface structures including partition walls, sauna benches and staircases.

### Concrete floor finishing

Concrete has to be finished within a limited time after it is poured onto the floor. The finishing work aims at giving a smooth level finish to the surface of the concrete slab. In the construction industry, concrete floor finishing is hard and laborious, and the number of skilled plasterers has dropped sharply. The smoothing of a concrete floor is a laborious task which has to be executed in a hunched position, synchronized with the setting of the concrete. Hitherto, several types of concrete floor finishing robots have been developed in Japan [Shinko 2007, Balaguer & Abderrahim 2008]. These modular mobile light weight concrete finishing (plastering) robots automatically compact the concrete floor by using two sets of rotary floats, Figure 15. The robot designed for finishing cast-in-place concrete slabs produced by Kajima Construction Company is mounted on a computer-controlled mobile platform and equipped with mechanical trowels that produce a smooth, flat surface [Arai et al. 1988, Saito et al. 1985]. However, only a few are currently in economic operation or are offered on the market for sale.



**Figure 15.** Modular mobile light weight concrete finishing robot, [source: Bock 2008].

### Painting and coating

The paint chemicals can cause hazards to human painters such as eye and respiratory system problems. Also the nature of painting procedure that requires repeated work and hand rising makes it boring, time and effort consuming.

### Interior wall painting

An interior finishing robot can execute several interior tasks such as building walls and partitions, plastering walls and ceilings, painting walls and ceilings, and tiling walls. A roller-based autonomous robot for painting the interior walls of buildings is introduced in reference [Sorour et al. 2011]. The robot consists of a painting arm with an end effector roller that scans the walls vertically, and a mobile platform to give horizontal feed to paint the whole area of the wall. An interior finishing prototype robot, called TAMIR, was used, in addition to painting, also for plastering, tiling and masonry works [Rosenfeld et al. 1991, Warszawski & Rosenfeld 1994]. The robot has 6 DOF (Degrees of Freedom) with an average reach of 1.7 m and end effector payload of 30 kg. It was mounted on a three-wheeled mobile platform giving another 3 DOF. The platform moves between workstations and at each one it deploys four stabilizing legs. Another one described in reference [Russell & Kim 2003] has six degrees of freedom with a nominal reach of 1.6 m and a lifting capacity of 145 kg. The robot is designed to perform interior finishing work in residential and commercial buildings with single or multiple floor levels and interior heights of 2.60 to 2.70 m. A three-wheel mobile carriage enables motion of the robot between static work stations.

### Fire-retardant spray coating

The Shimizu Company has developed two robot systems for spraying fireproofing material on structural steel [Shinko 2007, Russell 2003]. The first version, the SSR-1, built to use the same materials as in conventional fireproofing, performed given tasks sequentially and continuously with human help, travelled and positioned itself, and had sufficient safety functions for the protection of human workers and of building components. The second robot version, the SSR-2, was developed to improve some of the job site functions of SSR-1. The SSR-2 can spray faster than a human worker but requires time for transportation and setup, Figure 16. Reference [Russell & Kim 2003] gives several examples of Construction Robotic Prototypes in table form, describing the system, its application and the institute or company who developed the system.



**Figure 16.** Fire-retardant spray coating robot [source: Shinko 2007].

## **4.6 Yard works**

Yard works on the construction site include soil works, plantations, construction of walkways and fencing. Soil works include excavation, soil distribution and lawn seeding. Plantations consist of planting trees and bushes. Construction of walkways typically contains typesetting of stones or concrete slabs on the passageways. Fencing is used between sites to separate plots from each other.

Robotised earthmoving machinery such as excavators and bulldozers can also be used in the yard works, but are not usually applied due to the small amount of earth to be moved. Instead, there are several manually or tele-operated machines assisting workers to perform the given yard work like carrying soil, sand or gravel.



For construction of groundwork for walkways, there are machines for levelling and compacting of the gravel and sand, Figure 17. Typesetting of concrete slabs or stones can also be performed with the aid of a machine. Plantations and fencing are also carried out manually. Also, small excavators are used for digging and filling the pits. Small cranes can be used for positioning plants. The same system can be applied also to setting up fences, since fence posts and modules are in many cases prefabricated and assembled on-site.

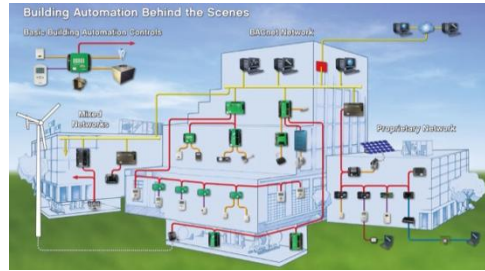


**Figure 17.** Slab installation machines (Courtesy by Hannu Koski).

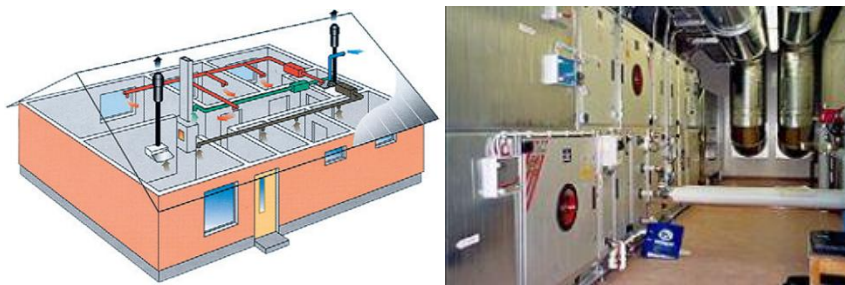
#### **4.7 Finishing works**

The finishing phase is a rather new addendum to the construction phase list. In large buildings Building Automation and Control Systems (BACS), also called Building Control System (BCS) or Building Management System (BMS), take care of the steering of different operations, such as the control of Heating, Ventilation, and Air-Conditioning (HVAC) and lighting systems as well as access controls. The purpose of the BACS system is to monitor and control the building and its environment. While managing various building systems, the automation system ensures the operational performance of the facility as well as the comfort and safety of building occupants. Typically, such control systems are installed in new buildings or as part of a renovation where they replace an outdated old control system. The aim of this phase is to put the BACS into service by checking measurements and devices and by adjusting all the related controls.

BACS follows general a hierarchical structure typical of automation systems, Figure 18. There are three main levels 1) management level containing local and remote control rooms, 2) automation level containing substations with I/O modules, and 3) field level containing devices such as sensors and actuators, as well as independent regulators, such as room controllers and integrated controls for air-handling units, heat exchangers, cooling machines, etc. [ST handbook 2012].



**Figure 18.** Generalized view of a BACS [source: KMC Controls, [http://www.kmccontrols.com/products/Understanding\\_Building\\_Automation\\_and\\_Control\\_Systems.aspx](http://www.kmccontrols.com/products/Understanding_Building_Automation_and_Control_Systems.aspx)].



**Figure 19.** HVAC systems [sources: PK-ilmastointi, <http://www.pk-ilmastointi.fi/> and Ilmastointi Salminen, <http://www.ilmastointisalminen.fi/fi/etusivu.html>].

The purpose of the HVAC system is to provide good indoor air quality, Figure 19. This is achieved by providing an adequate amount of ventilation and controlling the temperature and air quality of the building. A large number of international and national standards and codes exist to regulate or specify requirements for HVAC systems, such as for system sizing, duct insulation and energy efficiency. There are several CEN standards solely specifying performance criteria for HVAC systems. For example, the European standard EN 13779, *Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems*, provides general guidance on ventilation, air-conditioning and room-conditioning system in order to achieve a comfortable and healthy indoor environment (CEN 2007a) [Ihasalo 2012].

Lighting, office equipment and HVAC account for 90 per cent of expenditure on electricity [Leading Techniques for Energy Savings in Commercial Office Buildings 2006]. HVAC systems are among the largest energy consumers in buildings. Thus operation and running costs are very important the more installations the building contains. Also, they have a highly significant effect on the health, comfort and productivity of occupants. In many cases, sustainable energy sources such as solar systems and ground heating/cooling systems are more common in new buildings. Properly maintained heating and cooling equipment runs more efficiently, lasts longer and reduces energy costs. Not surprisingly, each building presented a

unique set of challenges, with different systems, energy performance, schedules, and goals.

#### Occupancy-based scheduling

Ideally, all building systems including HVAC and lighting should be scheduled to operate only when spaces are occupied. For buildings that have intermittent occupancy, such as schools and offices, this should be fairly straightforward with the building schedules following normal building occupancy hours. In most buildings, leaving these systems in occupied mode results in significant energy usage, as full ventilation and space conditioning is being provided [Ehrlich & Goldschmidt 2009]. Reducing the unnecessary use of ventilation and air conditioning reduces not only the utilization of electricity for the building services but also the use of the heating energy supplied in many cases as district heating. The best way from the energy savings and user comfort viewpoint is to use demand controlled-responsive ventilation and air conditioning instead of the ordinary time-based one. However, if a time-based system is used, it is important that the optimal time schedule for each air-handling unit is determined together with the users and operators of the building. Furthermore, the heat recovery efficiency of all air-handling units must achieve thermal efficiency that the equipment manufacturer promises for them in order to guarantee that they are performing as designed [Ihasalo 2012].

#### Decorations

Decorations in this context mean such installations as mounting ceiling lights, lamps, handles, mirrors, kitchen tables, sinks and cabinets, closets and skirting. Decorations are manual work and performed by professionals.

## **5. Experimental work for automation, robotics, digital design and manufacturing in architecture**

The obvious benefit of automation and robotics is the ability to repeat tasks without fatigue and with great accuracy. Despite the fact that many tasks in building construction are simple and repetitive (painting, grinding floors etc.), the automation of building construction has proved to be challenging. One reason is that robotic systems are not flexible enough for such an unconstructed and dynamical environment as a building construction site. In order to support the use of automation in building construction, structures of buildings have to be standardized and modularised. This reduces the unique nature of buildings.

Automation and robotization can be also viewed from the opposite perspective, as an enabler for erecting more unique buildings more economically. Unique architectural designs are more common in public and commercial buildings than, for example, in residential buildings. Residential buildings have to be very cost-effective and this limits the freedom of the designer. With automation, the extra cost of customising can be reduced to a more affordable level.

Using automation, it would be possible to manufacture more customized structures (etc. concrete elements), but the design of the structure should be done digitally and all modifications should be made by altering the digital model of the product. Then the manufacturing of the product can be carried out automatically according to the digital design. The goal is that complex products and product customisations, which can be very laborious and expensive to make with traditional methods, can be done at minimum extra cost. Several research groups are currently studying this kind of technology.

### 3D Concrete printing

In the last few years 3D printing has become a very common method for rapid prototyping in many industrial fields, for example manufacturing plastic parts. The evolution of this technology has also been an inspiration to test the same method on a bigger scale by using concrete as a material. At the University of Loughborough, a 3D concrete printing method has been developed for manufacturing cus-

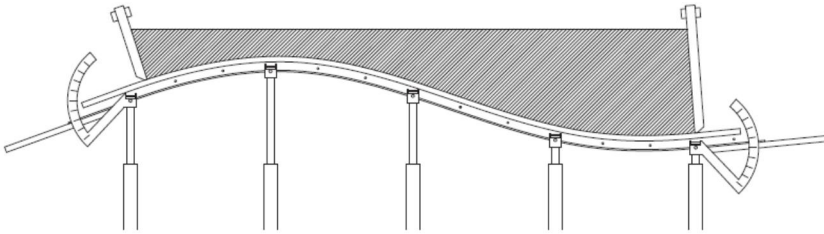
tomized concrete elements. The benefit of the method is the ability to produce complex 3D shapes easily. The shape of the concrete elements is designed using 3D CAD software. Then the element is manufactured automatically by using a portal type robot to deposit concrete very accurately layer by layer. With this method components in a build volume 2m x 2.5m x 5 m can be produced. This method is demonstrated by manufacturing a 1 tonne reinforced concrete architectural piece with complex 3D curvatures, Figure 20. [<http://www.buildfreeform.com/>]



**Figure 20.** Reinforced concrete element manufactured using 3D concrete printing. [<http://www.buildfreeform.com/>]

#### Flexible moulds in manufacturing freeform concrete elements

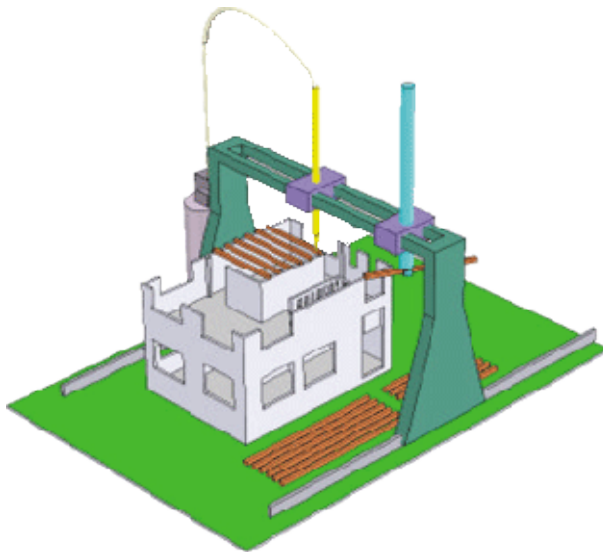
Digital concrete manufacturing has been studied in Denmark in the TailorCrete and Unique Concrete Structures (UnikaBeton) projects lead by the Danish Technological Institute. Manufacturing custom moulds for concrete elements is done using an industrial robot. In this approach, the mould is carved according to a 3D CAD model of the object. Custom-manufactured moulds can be made from foam materials that are cheap, fast and easy to mill [Raun et al. 2010]. Another approach is to use flexible moulds, Figures 20 and 21. In this method, the shape of the mould can be altered under computer control. The surface of the mould is made from a membrane, and under that membrane there are several actuators (pistons) that are used for changing the shape of the mould. With this method, curvatures and the level of details are limited, so flexible moulds are best suited for relatively large double curved surfaces like facades or walls [Raun et al. 2010].



**Figure 21.** Working principle of the flexible moulds. [Raun et al. 2010]

### Contour crafting

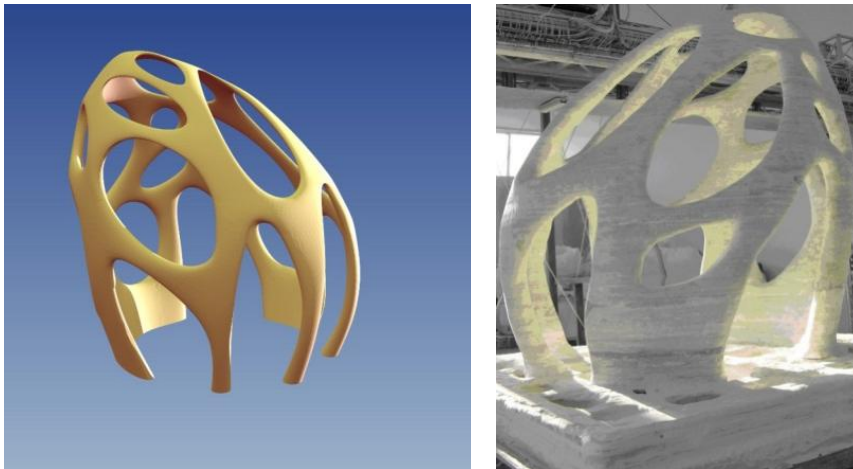
Contour crafting is a layered fabrication technology developed by Dr. Khoshnevis at the University of Southern California. In construction, this method is based on the distribution of concrete using a portal type robot with the aim of building the whole frame of a house automatically. This method has been under development for over 10 years. First, a miniature device capable of building small structures was developed for demonstrating the idea. Later, a bigger robot capable of building concrete walls was developed. According to the developers using contour crafting technology, a small house could be built in 24 hours. A potential application for this method is to build low cost houses e.g. for victims of natural disasters such as earthquakes. With contour crafting, curved surfaces could also be built, Figure 22. Contour crafting is an interesting building concept. It is still under development. [<http://www.contourcrafting.org>]



**Figure 22.** Robotised method for building low cost houses by using contour crafting [<http://www.contourcrafting.org>].

## D-shape

D-shape is a robotic building system based on the principle of 3D printing. The method was developed by Monolite UK Ltd. In this method, sand is used as a building material. A large-scale robot is used for moving the printing head. During the printing process a nozzle is used to deposit binder onto a layer of sand. The printing starts from the bottom of the structure and rises up in 5–10 mm sections. The solidification process takes 24 hours to complete. According to the developer, the appearance of the material is marble-like, and this artificial sandstone material has very good strength properties. The dimensional tolerances of the d-shape structures are 5–10 mm. Parts that fit inside a 6 x 6 x 6 m cube can be printed with this method based on the 3D design of the structure, Figures 22 and 23. In building construction, this method could be used for manufacturing elements such as stairs, arches, columns etc. An interesting feature of the d-shape method is that the complexity of the shape of the object does not increase the manufacturing costs of the object [<http://www.d-shape.com/>].

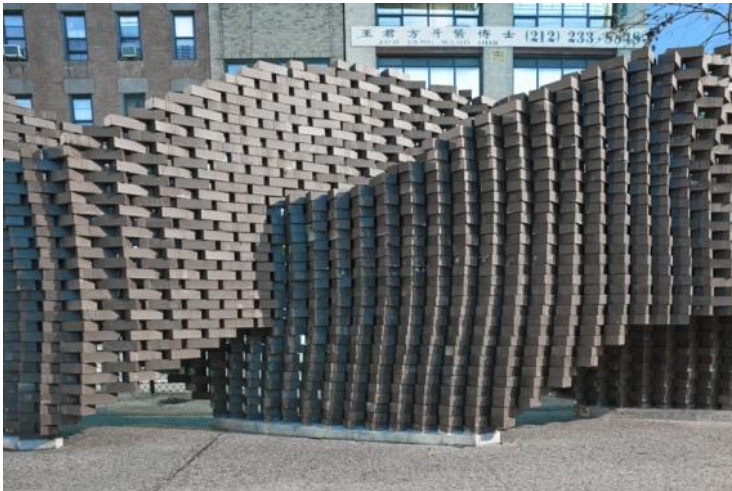


**Figure 23.** 3D model of the structure and the actual structure manufactured using the d-shape method. [<http://www.d-shape.com/>]

## Digital fabrication of architectural structures

ETH Zurich (Faculty of Architecture, Institute of Technology in Architecture, Architecture and Digital Fabrication, Prof. Framazio and Prof. Kohler) in Switzerland has studied robotics and digital manufacturing from the viewpoint of architecture. Several experimental applications are presented, where a digital model of the product is used as a basis for robotic manufacturing. For example, 3D forms are manufactured by assembling bricks or wood cubes very accurately by using an industrial robot. In one experiment, a 22 m long wall consisting of over 7,000

bricks was built in New York, using an industrial robot and digital 3D model of the structure. Robots have been used also for manufacturing moulds from the clay for manufacturing free form concrete parts. Also, wood carvings are manufactured using robots. In one experiment, small flying helicopter type robots were used for building a 6 m high 3D structure from 1,500 polyurethane bricks, Figure 24. These experiments show that robotics and automation can be an enabler for realisation of ambiguous architectural designs in the future: [<http://www.dfab.arch.ethz.ch/web/e/forschung/index.html>.]

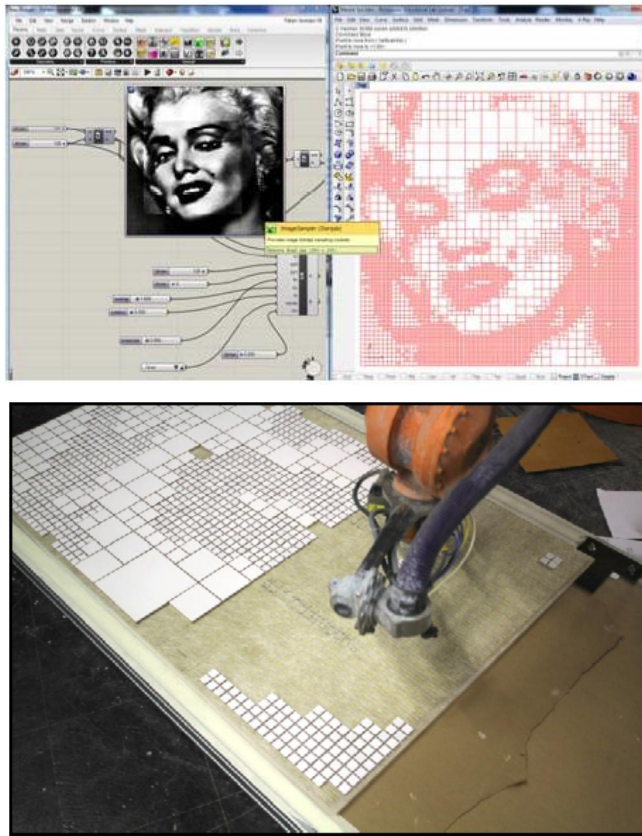


**Figure 24.** 22 m long brick wall assembled based on 3D model using an industrial robot. [<http://www.dfab.arch.ethz.ch/web/e/forschung/index.html>]

### Robotic tile placement

The Design Robotics Group (DRG, Harvard University, Graduate school of design) has studied the use of automation and robotics in manufacturing unique building structures economically. One example presented is a robotic tile placement on facade or floor elements of the building [King et al. 2012]. The research is focused on tile patterns that are very complex and extremely laborious and expensive to install manually. Examples of such patterns are computer generated random patterns consisting of different sized tiles or patterns based on digital images. An example of a digital workflow is that a digital image can be converted into a tile pattern, and movements for the robot are automatically generated according to the tile pattern, Figure 25. This digital workflow and robotic tile placement were tested. According to the tests, the expenses of the robotic tile placement are comparable to a manual tile placement, but the complexity of the tile pattern can be much higher in robotic tile placement. DRG has also studied manufacturing of customized ceramic tiles using robots [<http://research.gsd.harvard.edu/drg/home/>].





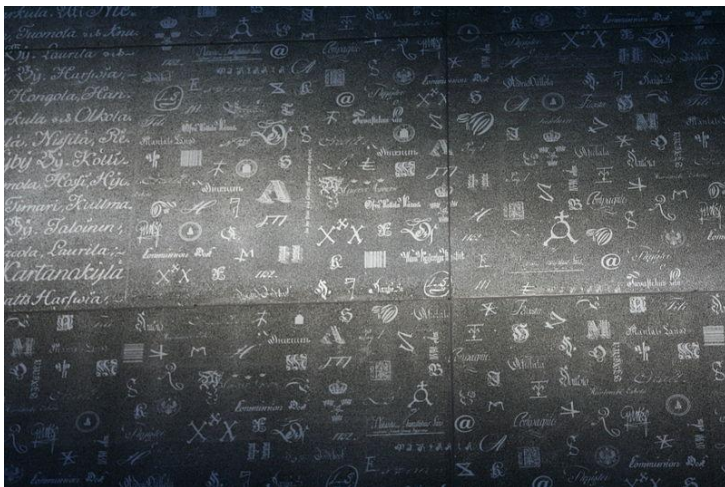
**Figure 25.** Robotic tile placement based on digital image [King 2012].

### Graphic concrete

For centuries, even thousands of years, buildings have been decorated using mosaics, carvings and frescoes applied to the walls and ceilings. These kinds of techniques are extremely laborious, and are currently used only in special cases. Digitalisation, robotics and automation can change this, and the decorative effects mentioned above might be applied in modern architecture. One example is graphic concrete developed by interior architecture Samuli Naamanka in 1997. The idea is to produce prefabricated patterned concrete elements. The digital image is printed on a special membrane. During the manufacturing, the printed membrane is added on the top of the concrete element, and a surface retarder is applied to the surface of the membrane. On the surface of the finished elements, the surface is rough in the spots where the retarder is applied. The contrast between rough and smooth surface makes make a picture visible, Figures 26 and 27. Also, coloured concrete can be used in the surface of concrete elements [<http://www.graphicconcrete.com/index.html>].



**Figure 26.** Examples of textured concrete surfaces [source: graphite concrete, <http://www.graphicconcrete.com/products.html>].



**Figure 27.** Wall of the Provincial Archives building in Hämeenlinna [source: [http://fi.wikipedia.org/wiki/Graafinen\\_betoni](http://fi.wikipedia.org/wiki/Graafinen_betoni)].

### Robotic mosaic manufacturing

Manufacturing mosaic is a very laborious work demanding great skill. Robotic mosaics manufacturing is one example of digital production. Mosaic4u is a company in Israel that has developed robotised solution for manufacturing mosaics based on digital image. Robot pastes 10 x 10 mm tiles on a 300 x 300 mm sheets with 0.1 mm accuracy. [<http://www.mosaic4u.biz>]

### Conclusions

Digital fabrication of customised structures of buildings or even the whole frame of the building and unique designs of shapes or surface decorations are one promising area of robotics in construction. All though most of the examples presented here are still under research, some applications are already quite near to commercialization, e.g. robotic tile placement. At first these kinds of products will be niche products, but they will become more common, if the extra price of customisation can be lowered.

## 6. Construction logistics

Logistics is considered to have a great effect on the competitiveness of the company. Large trading companies report that on average as much as 43% of the company's competitiveness originates from logistics. In addition, some 40–50% of company competitiveness can be affected by the company's own actions and decisions. Logistics costs of Finnish manufacturing and trading firms are on average 12.1% of sales (11.9% in 2009), including costs incurred in overseas subsidiaries. The share of transportation costs is 4.6% and has slightly increased [Solankivi et al. 2012]. For manufacturing companies, logistics costs vary between 15.2% of company turnover for micro-companies and 13.8% for small companies. In medium-sized companies they were an average of 14.5% of turnover, while the figure for large companies was 14.8%.

Construction has been slower than other industries in realising the benefits that good logistics can provide. On construction sites, time is often lost due to unavailable materials, inefficient handling systems and poor timekeeping by hauliers and suppliers, leading to congestion at access points. A widespread belief is that potential savings – from 10% up to 30% – can be achieved by improving construction logistics [Improved Logistics 2005]. The same reference provides plenty of non-quantified evidence to demonstrate the inadequacy of logistics in the construction process, whilst in other industry sectors there are increasing examples of how they are addressing logistics. Other industry sectors, especially manufacturing and retail, have made huge advances in improving logistics, whereas the construction industry does not seem to have been able to take advantage of these opportunities.

In the construction sector, there are different supply chains which operate in many respects like those in the industry and are not sector-dependent. There are, however, construction sector-dependent special features affecting the supply chain and information managements. Such features include 1) project production, 2) sub-contracting, 3) diversified procurement, 4) scattered construction sites, and 5) differences in product groups [Kiviniemi et al. 2008]. Operational practices used in construction are mainly caused by its project nature, since project organization concentrates on execution and not on the development of operational processes.

Big construction companies have taken to using company specific procurement systems with related ordering systems. However, the greater proportion of orders is done via phone calls, e-mails and even faxes. Correspondingly, nearly all the

remaining communication between the subscriber and supplier, such as e.g. change management and refinements in delivery time, are based on manual communications [Kiviniemi et al. 2008].

Supply chain management depends on the product supplier, delivery lot size, transport distance, site internal logistic solutions as well as on business cycles. Hence, supply planning should be specified according to the product and construction site. Verification measures, such as for example checking of the load (number and quality), filling of the consignment note and recording of shortcomings, storing of the consignment note, complaining of shortcomings and dismantling, transfers and protection according to the manufacturer's instructions, are similar to all products. Verification results in acknowledgement or rejection of goods. The measures of the securing of the delivery and of plan changes are usually on the sites known, but there are shortcomings in their practical realization. Single companies have no well-established common practice, but site personnel operate according to their own habits. Findings described above on construction logistics are based on the follow-ups of material supplies at several Finnish construction sites [Ketju report 2009].

Although the operational procedures were planned and agreed in advance, it appears that quite often there were deviations from plans and agreements. Consequences were mainly poor from the construction site viewpoint. Major causes of negative differences were the planning and content of the supply. The majority of the differences occurred during unloading or protection of the delivery, or during the assembly phase.

According to the Strategic Forum for Construction [Improved Logistics 2005], poor logistics will result in 1) unnecessary costs in the system, 2) poor image of the construction industry, 3) poor quality construction, 4) increased project time, and 5) added risks to health and safety. One of the reasons why logistics is so important in construction is the fragmented nature of the industry and the wide range of products and systems that need to be put together, invariably in an unpredictable outside environment.

One of the reasons why logistics is so important in construction is the fragmented nature of the industry and the wide range of products and systems that need to be put together, invariably in an unpredictable outdoor environment.

#### Development of supply chain management

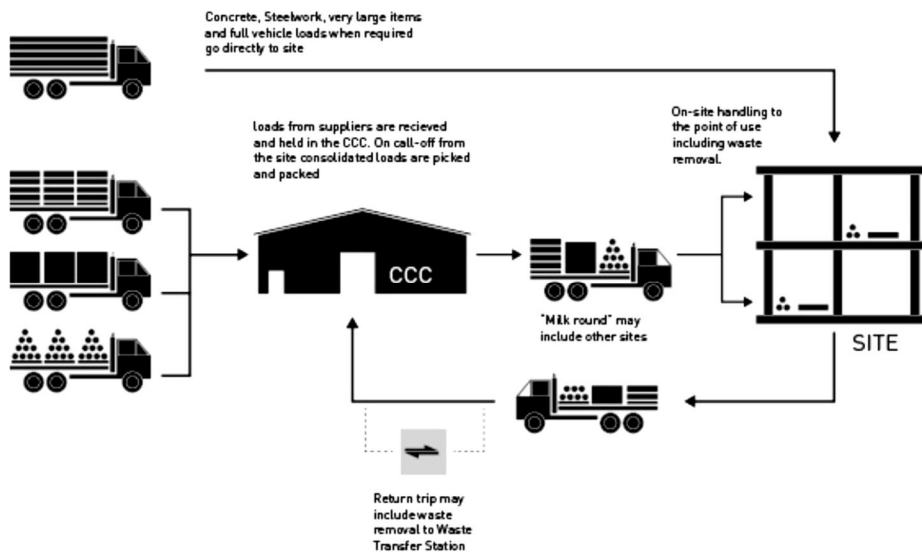
An efficient logistics plan can have a substantial effect on minimizing waste before it arises, and creates a number of cost-saving opportunities, including reduced material procurement and wastage, and reduced transport to and from site. The cost of wastage not only relates to the material cost but also to productivity losses associated with multiple handling of materials and inefficient practices that arise from poor logistics.

The Strategic Forum for Construction [Improved Logistics 2005] believed that the industry was not using information technology for communications as effectively as other industries were in order to help in improving logistics throughout the

supply chain. In particular, the industry was not utilizing bar coding for product ordering, or E-tagging for tracing products throughout the process, to the extent that seemed appropriate.

Reference [Ketju report 2009] gives a nine point recommendation for the development of construction logistics. The main points are that there must be a responsible person having the time to draw up the operational plans, which are verified and communicated to all stakeholders. There are also a need to train personnel and develop operational systems for supply chain management. Information must be communicated to all stakeholders if changes in delivery times occur. Furthermore, reference [Ketju report 2009] emphasises taking advantage of ICT in supply chain management. It is important that construction companies bring into use digital procurement systems so that all orders are registered in that system. When orders with related information are in the system, information management can be widened to include delivery information. As a part of the supply chain management, the reception of deliveries on the site must be also systematized in order to provide information for invoice verification, stock accounts and deliveries measurement. Then it is appropriate to apply RFID or bar codes in controlling and tracking operations.

A Construction Consolidation Centre (CCC) is suggested for use especially in big city areas, where there are normally space restrictions on site (limiting storage and/or access via gates) or restrictions limiting vehicle access such as narrow time windows [CCC 2010]. CCC is a distribution facility through which material deliveries are channelled to construction sites. The material is handled with the appropriate equipment and stored in dry, secure locations. On being contacted from the site, the CCC operator makes up consolidated loads and delivers them on a Just-In-Time basis. This process is often combined with on-site logistics specialists delivering materials to the point of use and provides an excellent opportunity to improve the overall resource efficiency of a construction project, Figure 28. Consolidation<sup>26</sup>. The consolidation centre concept has been used in other sectors such as distribution centres for many years. Within construction, it is a relatively new concept. In 2001, the Heathrow Consolidation Centre was set up to serve the on-going construction work at Heathrow's terminals 1–4. At the same time a well-publicised CCC was in operation in Stockholm to support a large residential project called Hammarby Sjöstad [CCC 2010]. CCCs can serve as reuse and recycling centres, too.



**Figure 28.** The principles of a Construction Consolidation Centre [source CCC 2010].

An approach based on logistics software, the 3D BIM model, ERP systems and timely executed predefined procedures from each party is introduced in [Jussila et al. 2012]. This case study of a new information-sharing method in the precast concrete element supply chain is performed in a typical housing building project. The aim is to save time, reduce errors and provide more accurate real-time information to all parties. Hence, a unique code is assigned to each precast concrete element so as to enable better tracking, and the delivery lots are planned well in advance. Even this rather small sample offered a good learning experience, and several advantages and disadvantages of the new operating model were identified. The information transfer using a 3D BIM model and status information transfer were successfully tested. The element manufacturer can take into account its own production schedule and limitations. The transportation company has the best knowledge of transportation capacity and would like to distribute the deliveries evenly throughout the working hours. Finally, the construction site has its own preferences for the content of the deliveries, and because of their dynamic nature, there will always be some changes in the installation dates that should be taken into account. As a result, advance planning of the deliveries combined with the well-timed advance notice of the need for a delivery by the construction site provides more predictability for the element manufacturer, improving warehouse management resulting in reduced delivery delays.

No one part of the construction industry can deliver improved logistics on its own. The benefits will come from the different parts of the industry interacting in a different way – planning together, sharing information, and exposing the real cost of activities in a way that is currently not typical.

## 7. Building construction cost

Eurostat, the statistical office of the European Union, provides **structural business statistics** covering industry, construction, trade and services at the European level. The construction cost index (CCI) (sometimes also referred to as “construction factor price index” or a “construction input price index”) is a European Union (EU) business cycle indicator showing the trend in the costs incurred by contractors in the construction of buildings. The CCI combines the indices for material costs and labour costs, which are the most important cost components for construction. In the aggregation of these two cost components, their relative weights are taken into account. The CCI measures developments from the points of views of the building contractors. It reflects the prices that they have to pay for the input factors in the construction process, see A in Figure 29. The CCI is made up of aggregated price indices for materials, labour costs and other types of costs [Eurostat 2012].

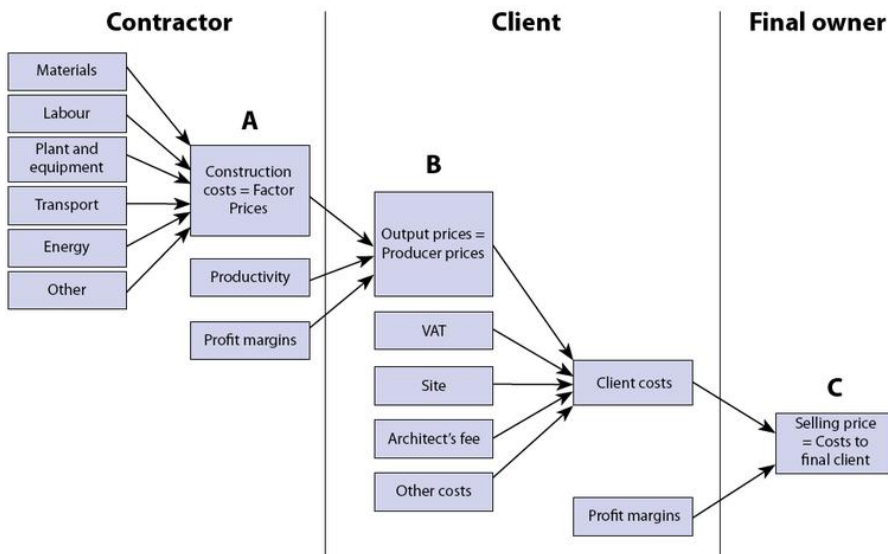


Figure 29. Formation of the construction cost index [Eurostat 2012].



Statistical indexes describe growth rates over a given time period, and it is not easy to get the percentage share of different costs. Regarding the CCI we should know at least the share of most important cost components, which are the costs of material and that of labour.

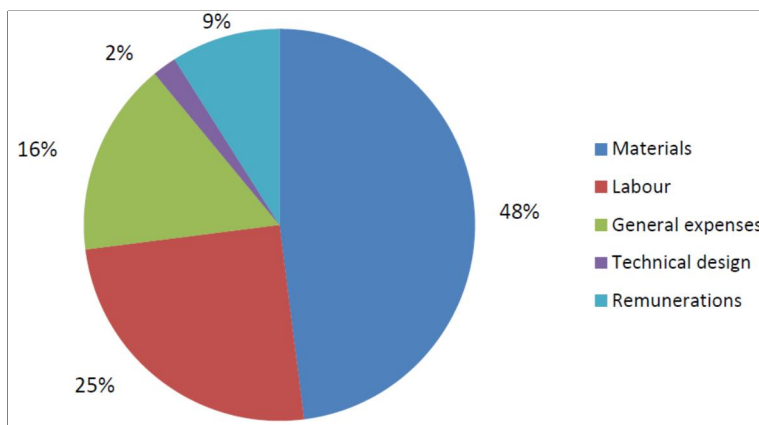
Construction costs are often presented as a price per square metre, where square metres are taken either as a gross exterior floor area or as the habitable area. In addition, these business ratios are dependent on the design and comfort requirements, and are thus unsuitable when development and optimization of the construction efficiency are targeted. Construction costs are also dependent on the construction method: in-situ, prefabricated or semi-prefabricated construction.

### The cost presentation

The total production cost includes the construction cost, which could be described as the cost of the actual construction of the building: including material, labour, sub-contractors, and the detailed design. Pourghazian [Pourghazian 2008] presents a way of viewing the costs in the building sector. He divides them into the following posts:

- Materials
- Labour
- Sub-contractors
- General expenses – rental of cranes, administration staff, establishment costs, scaffoldings, etc.
- Technical consultants
- Contractor remunerations – which is calculated as 10% of the total contract sum.

It is obvious that sub-contractor costs include material and working hour costs, and they must be distinguished from each other. By assuming a 40% shares for the labour costs of the contract sum while materials covering 60%, Figure 30 can be obtained.



**Figure 30.** Construction cost apportionment [Pourghazian 2008].

Here, the materials represent 48% of the production costs, and the labour costs have risen to a quarter (25%) of the total cost. This cost apportionment is obtained on the basis of detailed cost estimations of three building projects undertaken in the suburbs of Stockholm, Sweden. The buildings were erected by using in-situ casted load-bearing structure and outer-wall elements.

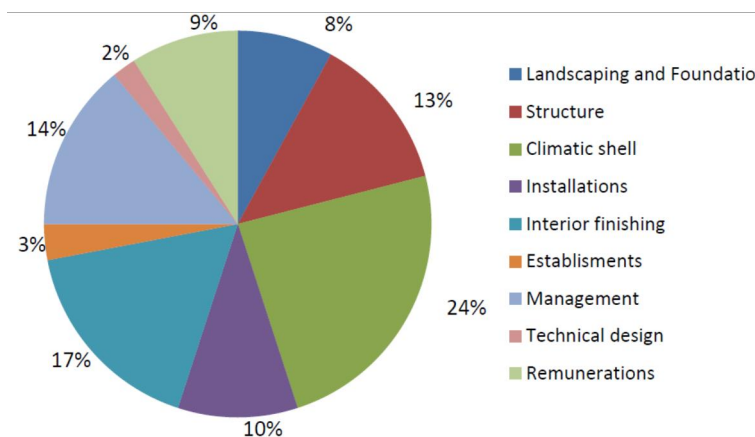
The Finnish cost structure of the index is based on 15 example sites selected on the basis of sector literature and building construction statistics. The official Building Code Index refers to the general index of professional new constructions. It is based on the breakdown of costs concerning blocks of flats, row houses, offices, commercial buildings and industrial production and storage facilities, as well as construction volumes [Vainio et al. 2003]. The kernel of the building cost index emphasises professional new construction, but it also includes professional renovations as well as self-construction of new buildings and that of renovations [Vainio et al. 2003]. Based on these calculations, the labour costs in Finland were 31.8% and those of materials 52.2% in 2005. Site and other costs were 16%. Over the years, material costs have risen to 57% in 2011 and corresponding labour costs stayed the same, at 32% ,and that of site and other costs fell to 11% [Building cost index 2011]. These 2005 figures are comparable to the figures given by Pourghazian [Pourghazian 2008]. Higher material costs may result from the construction method and from the way the index has been calculated. In Finland, professional construction uses a large number of prefabricated concrete components (pillars, walls, hollow core slabs, etc.) which of course include labour, but are not distinguished from material costs. Only the assembly of these components on the site is included in labour.

These figures provide the basic information about how improved production methods can affect the total production cost. Reduction of the total working hours will be visible in the labour post, while improved purchasing and reduced material waste can be accounted for in the materials post. In addition, reduction of the

labour costs in the prefabrication of building components will result in reduced component prices. All these will reduce the total building construction costs.

Pourghazian [Pourghazian 2008] analyses the production costs by distinguishing the costs of different building parts from each other, Figure 31. In this way, the proportional cost of each building part is more apparent in relation to other parts and to the total construction cost, as follows:

- **Landscaping and Foundation** – This includes everything that is related to the construction of the foundation and the landscaping, 8%.
- **Structure** – This pertains to the material and working hours that are related to the construction of the load-bearing structure, 13%
- **The Climatic Shell** – This includes the construction of the roof, the outer walls, and the work connected to the finishing of the exterior façade – such as rendering, plating, and placing of the gutters, 24%
- **Installations** – This includes the plumbing, electrical cabling, and the installation of HVAC systems, 10%
- **Interior finishing** – This includes the construction of bathrooms, kitchen, partition walls, painting, etc., 17%
- **Establishment** – These are one-time establishment costs – such as a security fence around the site or establishment of temporary roads, 3%
- **Management** – These are the running costs during the construction period – such as renting of scaffoldings or cranes, cost of site managers, renting of office, and changing-room containers, etc., 14%
- **Technical Design** – This is not including the architectural design, 2%
- **Remunerations** – These amount to 10% of the contract cost.



**Figure 31.** Division of the construction cost into the defined posts [Pourghazian 2008].

It may be noted that the largest costs during the production of a building are related to the completion of the climatic shell. Thereafter follows the interior finishing, which is logical due to more expensive surface-materials and electrical household equipment. The third largest post is, in fact, the management cost. It is noticeable that only a small fraction of the general expenses are made up of the establishment cost, since the majority of that post consists of the management costs that are linked to the construction time. Management costs can be reduced by speeding up the production, which can be done by exploiting prefabrication and industrial construction. Furthermore, by reducing labour costs in prefabrication and by improving logistic planning, just-in-time deliveries of material and components, total construction costs can be reduced accordingly. Hence, there is room for improvement, and even small changes in this field will yield large cost savings.

### Economic benefits of automation

Some of the economic difficulties associated with the application of robotics and automation in construction stem from the characteristics of the industry. Because it is primarily concerned with the production of large-scale custom-made capital goods that are specifically designed to fit a site, the construction industry is characterized by unique products, low production volumes and in situ development processes in open-air environments. Using manufacturing industry terminology, construction may be categorized as a *jobbing-type* industry [Saidi et al. 2008].

Major factors contributing to the economic benefits of construction automation are productivity, quality, and savings in skilled labour. These benefits must be weighed against the costs of automation, including initial investment and operating costs. Reference [Russell & Kim 2003] reviews the information gathered on the benefits of construction automation systems. The main benefits are related to reductions in construction time, labour costs and amounts of waste. Also, improvements in working environments and safety are reported.

Use of Kajima's AMURAD system resulted in a 30% reduction in construction time, in 5a 0% reduction in manpower, in a 50% reduction in waste, and a more predictive schedule by using all-weather protective sheeting and also a more comfortable environment for the workers. Obayashi's Big Canopy resulted in a 60% reduction in labour for frame erection and a reduction in material costs. In the ABCS system, the work environment was improved by all-weather sheeting. Shimizu's SMART system includes improvements in productivity and working environment. The method including all-weather protection resulted in reduced construction time, even an anticipated 50%, a reduced amount of waste and damage to materials.

Automation of placing and finishing concrete slabs would require a minimum annual work volume of 144,321 m<sup>2</sup> of pavement in order to become more economical than a conventional manual process. Results from outdoor experiments using a tile-setting robot indicate a setting efficiency of 14 m<sup>2</sup>/day with an adhesive strength of 17.2 kg/cm, representing improved productivity and quality. A performance study of an interior-finishing robot indicated that net productivity of the robot can reach 10–19 m<sup>2</sup>/h in a one-layer coating and 8–8.5 m<sup>2</sup>/h in a dry (mortarless)

building. These figures are four to five times higher than for an average construction worker. However, after wages of \$25/h and a robot working 1,500 to 2,000 h/a, suitable site conditions and proper organisation of material packaging can result in savings of 20% to 50% on the cost of interior work.

Over the years there have been several attempts to introduce robotics and automation to construction. However, those attempts have largely failed due to a lack of product and process flexibility and to a lack of market acceptance of the products. The robots still to be used (as of 2007) include the following [Shinko 2007]:

- Automatic unhooking device for crane work (YOSHINAGA Mfg. Ltd.)
- Concrete floor finishing (plastering) robot (TAKENAKA Co.), which automatically compact the concrete floor by using two sets of rotary
- Material-handling robot (PAL, KAJIMA Co.) floats which lifts heavy elements in construction as concrete walls
- Fire-retardant spray coating robot (SHIMIZU).

#### Evaluation of automation needs in construction

A significant aspect of construction automation is the division of work to be designed for automation. Because of the complicated nature of construction work, it is important to define the type of task which an automated device will perform. Therefore, a breakdown was performed for all the construction activities to the task level. This work resulted in forty-two generic construction tasks [Guo & Tucker 1996]. Cost Impact and Automation Concern Index for the various tasks revealed the relative automation. Five factors used for motivating the development of automation were 1) safety, 2) productivity, 3) superhuman handling, 4) worker utilization, and 5) quality. The Cost-Concern matrix was used to reveal potential automation needs for a civil engineering construction, applied in viaduct construction on the Taipei Rapid Transit System. The results showed that Tie/Weld rebar, Arrange rebar and Position parapet segment were identified as the main automation needs. This Cost-Concern matrix principle can be used in the building construction sector by breaking down the construction activities into tasks.

Potentially, the emergence of robotics and flexible manufacturing methods will have a great impact on the construction industry, since product and process variety can be accommodated much more easily than with hard automation methods. Apart from technical and commercial success, many people are concerned that there will be substantial industrial or worker resistance to the widespread introduction of robotics and automation in construction, especially on-site robotics. The possible reason for worker resistance is potential job losses through the displacement of labour. The full potential of robotics will unfold as soon as robots do not just copy human work but rather this is enhanced by robot oriented planning, engineering, management and labour training. BIM providing building-related information in a digital form enables better exploitation of automation and robotics during the life-cycle of the facility.

## 8. Conclusions and challenges

Construction work is characterized by three 3D attributes: Dirty, Dangerous and Difficult (synonymous with the famous Japanese 3 Ks for Kitanai, Kitsui and Kiken). The industry has traditionally involved craftsman-oriented manual work, with many small participating companies and is considered to be technologically lagging behind other industries. Regardless of the common view, CAD and FEM are commonly adopted in the design phase. Currently, BIM is a widely used design tool, and it is gradually pervading prefabrication and site construction phases, too. In addition, modern measurement and data acquisition techniques are also utilised on site and in prefabrication. Attempts at construction automation and robotics started as early as in the 1970s. Great advancement has been possible in construction automation since then. The internet came on the scene in the 1990s, when GPS, barcodes, RFID, wireless communications and other modern techniques also appeared. The World Wide Web comes into the picture in the 2000s as also do machine vision and augmented reality. All these developments have had a dramatic impact on construction means, management and practices. However, it is quite evident that exploitations of the latest advances are lagging and not widely used in construction industry compared e.g. to manufacturing industry.

Automation of building construction is today about 45–50 years old. A lot of research and development work has been done during these decades. The economic influence of these efforts has, however, been rather small despite hundreds of different robots and automated systems developed, only a few of them have been adopted by the construction industry. Currently accurate 3D positioning systems provide emerging possibilities for accurate dynamic tracking and control of moving on-site work machines facilitating the arrival of the construction automation at the site.

The construction activity normally occurs on the site and is undertaken in the open air, on natural terrain, and often with naturally occurring materials. However, a significant part of the on-site work can also be performed off-site so as to reduce on-site work. This reduction involving prefabrication, preassembly, modularization, and off-site fabrication, collectively termed as pre-work, has become more viable with recent advances in design and information technologies. Pre-work can lay the basis for construction industrialization by introducing modular building systems and standardized dimensions, components and connections. Industrialized precast

concrete construction can continuously, e.g. by using building modelling, 3D-design, efficient ICT and automation.

The role of logistics, both external and internal, is emphasized. One of the reasons why logistics is so important in construction is the fragmented nature of the industry and the wide range of products and systems that need to be put together, invariably in an unpredictable outdoor environment. A well-implemented logistics can substantially reduce waste and create a number of cost-saving opportunities including reduced material procurement and wastage, and reduced transport to and from site. The cost of wastage not only relates to the material cost but also to productivity losses associated with multiple handling of materials and inefficient practices that arise from poor logistics.

The basis for industrialization is modular building systems and standardized dimensions, components and connections. The challenge is to achieve sufficient on-site assembly accuracy and efficiency. From the constructability (buildability) point of view, the tolerance requirements for components including those of pre-cast concrete elements have to be strict and kept inside limits. Industrialized pre-cast concrete construction can continuously be improved, e.g. by using building modelling, 3D-design, efficient ICT and automation.

The full potential of robotics will unfold as soon as robots do not just copy human work but this is rather enhanced by robot-oriented planning, engineering, management and labour training. The main reason for a small number of robots still to be used compared to attempts made might be that the robotised work phase is only a rather small part of the total construction phase. The basis for industrialization is modular building systems and standardized dimensions, components and connections. Industrialized precast concrete construction can continuously be improved e.g. by using building modelling, 3D-design, efficient ICT and automation.

A different aspect of standardization and modularization is to use robotics and automation to produce highly customized, unique free-form structural elements. The enablers for this kind of development are digital manufacturing methods. The emergence of 3D printing technology has inspired researchers and companies to develop methods for building large-scale building elements or even small houses by 'printing' based on 3D design data. This technology is still in a development phase, and a challenge is to develop methods that are applicable on an industrial scale.

The production activity normally occurs in a field setting and is undertaken in the open air, on natural terrain, and often with naturally occurring materials. Thus, construction sites are for the most part unstructured, cluttered, and congested, making them difficult environments for robots to operate in. In the future, investments in construction automation and robotics should contribute to value, safety, quality, productivity, and performance. Equipment should be easy-to-use and have intuitive user interfaces, be able to share work spaces with robots and workers, and encompass high level of (proactive) safety. In the sector there is a need to improve safety, productivity, constructability, scheduling and control while providing stakeholders with a tool for prompt and accurate decision making.

As a final conclusion it can be proclaimed that productivity during the whole life cycle of the building is crucial, and to increase productivity means closer BIM integration in the building construction phase, too. Currently BIM is heavily applied in the building design phase, but in the future it will find its way to construction operations on the site both for workers and work machines as well as to management of the real estate and finally to the decommissioning. BIM integration with applications of automation and sensor technology during the whole building life cycle especially integration of prefabrication and on-site operations can help to increase productivity.



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Title	<b>Survey on automation of the building construction and building products industry</b>
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Abstract	<p>A commonly held view is that the construction industry is labour-intensive, project-based, and slow to adopt emerging technologies compared to other “project shop” manufacturing industries [Product-Process Matrix]. A construction site can be regarded as a “project shop”, since tools and manufacturing equipment are brought on-site, whereas component prefabrication is a conventional shop, line or cell-structured. There have not been any dramatic changes in construction methods in the last 40 years, although some methods have been developing. The construction Industry is also considered to be a conservative innovator and late adopter of new technology. Therefore, construction is often considered a somewhat old-fashioned industry. However, in the design phase, methods such as Computer Aided Design (CAD) and Finite Element Method (FEM) are commonly adopted. Also Building Information Model (BIM) is increasingly applied in the design and engineering phase.</p> <p>The construction life cycle includes 1) Requirements identification, 2) Project planning, 3) Design and engineering 4) Construction, 5) Operations and maintenance, and 6) Decommissioning. The operation and maintenance phase is the longest period during the life cycle of a building. Building Information Model (BIM), a digital representation of the physical and functional characteristics of a facility, covers e.g. geometry, spatial relationships, light analysis, geographic information, quantities and properties of building components with manufacturers' details. The model elements, representing the physical building parts, are digitally linked to information relevant to the model users, such as architects, engineers, contractors and owners. BIM can be used to demonstrate the entire building life cycle, including processes of construction and facility operations, and finally to take the advantage of its information in the demolition. From the life cycle point of view, BIM enables all stakeholders to share data throughout the entire life cycle of the building. Currently, BIM is widely applied in the design and engineering phase, but there have been very few efforts to explore the real-time integration of BIM to the site and task conditions, and the interaction of BIM with the field crew. For field workers, it is important to gain access to the most current model so as to be aware of possible changes made to the document [BIM, Beyond Clash Detection 2011] and [Wang et al. 2012].</p> <p>Industrialization of building construction started in Japan around 1960, with the advent of prefabricated houses made of steel and wood. High-rise building construction has become common since 1968, and automation and industrialization of building construction have been pursued since then [Shinko 2007]. Since 1988, major Japanese general contractors have investigated the potential complementation of integrated robotic and automated building construction systems [Bock et al. 2011]. Today, many construction operations have incorporated automated equipment, means, and methods into their regular practices. R&amp;D activities are centring more on ICT technologies, including on-site sensory data acquisition and processing, the human operator's field safety and security and computer-based process control and monitoring as well as automated inventory and shop keeping, among many others. Although adaption of automation in the building construction sector has been slow, the civil engineering sector has developed and adopted several automated systems for industrial use. For example, Infra Information Modelling is currently under active research and development, especially in Northern Countries.</p> <p>Automation has had a notable impact in a wide range of industries in addition to manufacturing. The principles of industrial automation are applicable to the construction sector, both to building construction, civil engineering (roadways, dams, bridges, etc.), and to the prefabrication of construction components. It is the application of electronic, mechanical and computer based systems so as to operate and control construction production.</p>
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## Survey on automation of the building construction and building products industry

A commonly held view is that the construction industry is labour-intensive, project-based, and slow to adopt emerging technologies compared to other manufacturing industries. The project-based nature implies the periodic mobilization of construction equipment, materials, supplies, personnel, and temporary facilities at the start of every construction project. The historical development of construction automation has been marked by equipment inventions aimed at performing specific tasks originally carried out by workers. Although the construction industry has been mostly an adopter of innovation from other fields rather than a source of innovation, every development taken to use has had a dramatic impact on construction means, management and practices. In the future investments in construction automation and robotics should contribute to value, safety, quality, productivity, and performance. Equipment should be easy-to-use and have intuitive user interfaces, be able to share work spaces with robots and workers as well as being able to encompass a high level of (proactive) safety.

In spite of all, productivity during the whole life cycle of the building is crucial, and to increase productivity means also closer BIM integration in the building construction phase. Currently BIM is heavily applied in the building design phase, but in the future it will find its way to construction operations on the site both for workers and work machines. Automation of the building production requires exploitation of information models in each phase of the working process. This means also the exploitation of BIM throughout the construction process. BIM integration with applications of automation and sensor technology during the whole building life cycle can help to increase building productivity. Especially integration of prefabrication and on-site operations can help to increase construction productivity. Further, automated data acquisition and monitoring as well as applications of ICT for supporting activities in management and social issues can provide automatic features for planning, procurement, control, and construction and maintenance as well as for the demolition phase.

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