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# Construction Automation and Robotics

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## 1. Introduction

A competitive, market oriented and rationalized construction tomorrow requires developing of automated and robotized construction system today. This includes industrialized process originating in a mining, construction material production, prefabrication of construction components, on site construction, facility management, rehabilitation and recycling.

Today's construction projects are characterizing by short design and build period, increased demands of quality and low cost. These problems can be approached by a flexible automation using robots based on computer assisted planning, engineering and construction management. Especially in high labor cost countries, automated and robotized construction technologies can compensate increasing demand on construction projects. I consider construction robotics technology as a key to rationalization. By automation, increased productivity could reduce high labor cost share of 40 or more percent. Automated and robotized construction process lead to a continuous working time through the year. Introduction of robotic technology would result in better working and health conditions, and advanced mechatronics know how and skills. The reduction of construction time would improve cost benefit analysis of construction project due to faster availability and return on investment of real estate.

## 2. Automation and robotics in Masonry prefabrication

German brickwork construction is characterised by the high percentage of private builders and an extreme orientation to the craft trade. Machines and auxiliary devices are applied at a larger extent on widespread level, and hardly contribute to increasing productivity, but relieve the worker of physical load. Pre-fabricated brickwork elements are often not applied on smaller construction sites due to lacking crane capacity.

Brickwork construction in Germany reflects two development trends:

Brickwork without dislocating aids will no longer be acceptable in the near future and therefore reduced to exceptions in modernisation, renovation or reconstruction. The monolithic production of brickwork at the construction site with increasingly large-format bricks and further developed dislocating aids or robots will therefore be a continuing development.

On the other hand the pre-fabricated brickwork elements will gain increasing significance, as they represent the economic solution due to the improved working conditions and independence of weather conditions and because they are the more economic solution for many construction companies due to more reliable calculations. For stationary production of pre-fabricated brickwork parts various machines are known.

With stationary brickwork machines drastically raised production capacities can be achieved. Moreover, they lead to considerable relief in labour and manpower savings.

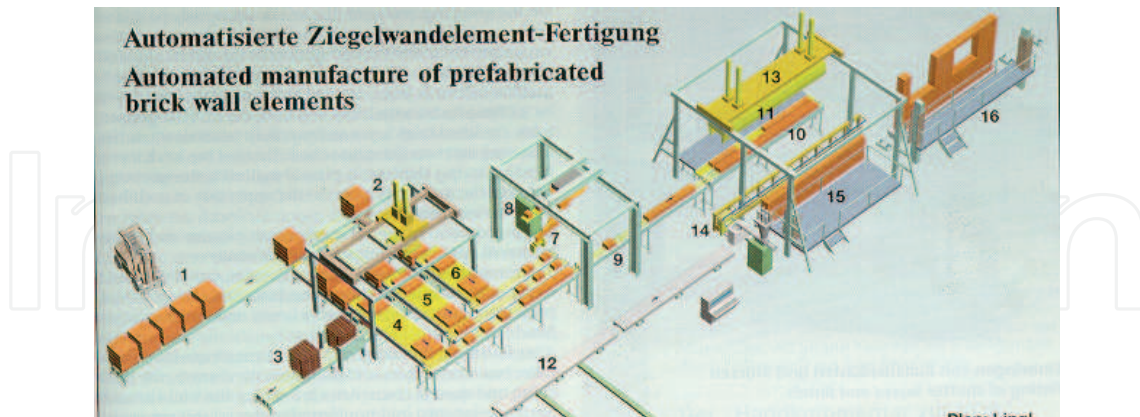


Fig. 1. Prebricated Masonry

The deliberations to manufacture pre-fabricated brickwork elements have taken a whole series of ideas in the mechanical-technical development into account so that individually planned brickwork elements can now be manufactured in a wide variety of production plants with semi-automatic production systems or fully automatic brickwork robots under industrial conditions.

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.

There is also a certain dependency on the supplied exactness of contractor products which have to observe certain tolerances not only in a geometric, but also in a physical respect to meet the exactness in robot dislocating.

An additional difficulty is the necessary standardisation of software and hardware used by the architects, engineers, building material manufacturers and constructing companies involved in the building process. Prerequisite for automated construction technologies is in other words the exact definition of all software and hardware standards as well as the respective interfaces.

In conventional on site masonry construction competitiveness is achieved by using large masonry elements of weight up to 40kg. Since further productivity can hardly be achieved by masonry wall elements produced in a similar way as a pre cast concrete elements which has been described above. All kinds of existing masonry such as bricks lime stone etc. can be horizontally positioned on a pallet. Reinforcement bars placed between the bricks in order to allow safe transportation and assembly. Concrete is placed between the bricks. All necessary wall openings such as windows, doors, water closet unit, plumbing, service pipes and wiring are also placed between the bricks on the pallet. Interior and exterior plaster is sprayed on the prefab masonry walls. Roof panels already contain roof windows, insulation and roof tiles. In addition there is vertical masonry production robot which place the bricks layer by layer in between distribute mortar and put vertical horizontal reinforcement bars.

Similar as their precast concrete panels, houses made of prefab masonry elements can be assembled in one day. It takes one to two weeks to finish a 120m<sup>2</sup> house.

Besides these automated and robotized facility are half mechanized masonry wall prefabrication units which are controlled by one or two workers.

In the case of these mechanized units the automation just includes distribution of mortar. The productivity of these facility ranges from 3.5 to 50 m<sup>2</sup> per hour.



Fig. 2. Factory based mobile semi automated masonry wall production unit including automated mortar distribution

### 3. Automation and robotics in the construction sector and precast concrete industry

In mining, tunneling, earthworks, road construction etc. we have reached a high degree of mechanization with partial automation. In the production of construction materials such as cement, steel, aluminum, glass and wood etc., the degree of automation is very high – almost up to 100%. Automation and robotics in constructions and building components prefabrication is high in pre cast concrete element production where we moved from a mass production to mass customization. This development was enabled by flexible production system using robotic cells which could execute various tasks such as setting molds, placing reinforcement bars or mats distributing concrete for various products such as floor, roof, wall, beam and column elements.

A high degree of automation has been prevailing for several years in stationary systems to mix building materials (concrete and tar) and in serial production of standardised concrete products. The automated pre-fabrication of large-scale pre-fabricated reinforced concrete parts has experienced a fluctuating development. After a gradual increase of the automation degree to the early seventies the beginning recession forced several pre-fabrication plants with higher degree of automation to discontinue manufacturing their products.

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 approaches to Computer-Integrated Manufacturing (CIM) of pre-fabricated concrete parts for ceilings, walls and roofs.

In the industry for pre-assembled units the term „Construction System“ is frequently viewed as a competitive instrument. Every manufacturer states that he has his own special systems to grant the contractor maximum advantages. This is often misleading and leads to reservations among planners who are not familiar with the construction of pre-fabricated

parts. The reality is, however, different: On the market there is a large number of systems for more or less complete solutions; these systems, however, almost all belong to a limited number of pre-fabricated systems with a more or less identical basis. In addition, these systems are as a rule limited to the carcass and the preliminary electrical installation. That means that the production systems are able to manufacture raw construction parts with the exactness of millimetres which are combined on conventional building sites with traditional building systems. Construction systems with a high, trans-trade pre-fabrication degree are generally non-customary.

The further developments from the generally offered raw construction product to the finished wall or ceiling/roof product pave the way to diverse possibilities with the product and product technology to manufacture pre-fabricated construction parts at low prices according to individual requirements for the housing construction industry.

For example, portal robots as they are already used as formwork robots could be further developed and transformed into installation robots for electrical cabling operations. In connection with that aspect the surfaces and assembly engineering should also be further developed. Finished roughcast and insulated wall surfaces could be manufactured in partially automated processes with systems already available on the market. With the increasing production depth, e.g. by installing windows, blinds, cabling etc. the added valuation at the production plant is enhanced. Suitable transport and assembly systems which supply and assemble just in time with optimised logistics are required for such products.

The use of robotic technology in pre cast concrete element production also resulted in constant quality of products and less waste in factories, because due to computer assisted planning and programming only the necessary amount concrete is being provided from the batcher plant. The computer assisted planning and engineering provides the necessary data for the production of all elements such as reinforcement bars or mats originating from the architectural design of floor plans, elevation sections, HVAC plans and structural calculation.

Compared to conventional prefabrication there are less mistakes in transferring data because of defined interfaces between planning, engineering and production.

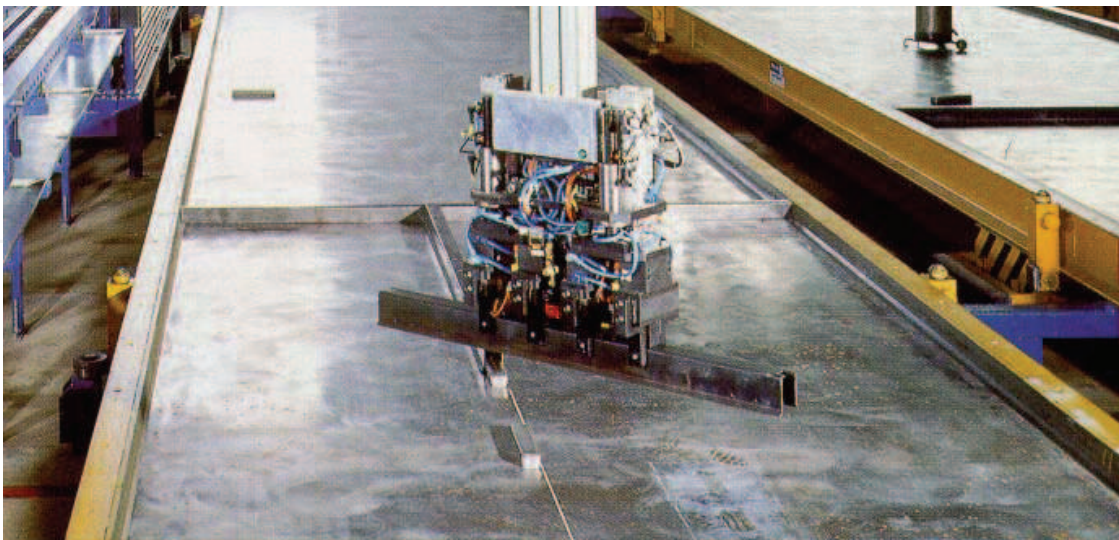


Fig. 3. Multifunctional robot placing magnet moulds on 3 to 12 m dimensioned steel pallet for PC panel production

The various elements are produced on steel pallets which have dimensions of about 3 to 12 meters. On these pallets the production management system optimizes layout and arrangement of the concrete elements to be produced depending on the priority of the factory manager. For example if there is an urgent customer order, all panels will be produced at one time. If there is a normal production run, then panels of different construction projects can be produced on one pallet in order to use pallet surface efficiently. The pallets run from station to station where various robots do the collection of previously used mold, cleaning of pallets, plotting of a panel production layout; gantry type robots place the mold, reinforcement and distribute concrete. The curing station works like a big automated warehouse.

You can find the highest degree of prefabrication in the production of concrete box units with a prefabrication ratio of 85% and 6 hours on site assembly time for a 120 m<sup>2</sup> house.



Fig. 4. Teleoperated concrete distribution

#### 4. Automation and robotics in timber construction

The prefabrication degree in wood construction can be characterised as favourable according to the current state-of-the-art prevailing in technology in Germany in comparison with other European countries. All conventional wood construction systems are applied. In the recent past focus has particularly been on the „novel block construction“ system (glued laminated wood, bulk wood and log wood construction). Perhaps also because this - in the form of massive constructions normally made of bonded two-dimensional wood - associates wood construction more intensively with massive construction („knock test“, wood/massive compound constructions).

The processing technology in wood construction is developing continuously from manual processing with small machines to full-scope processing on CNC machines.

The requirements with regard to flexibility in processing are noticeably rising.

The division between raw construction and interior design no longer exists. Wood constructions are transformed into pieces of furniture. The standards required with regard to precision in production exceed the general level of a carpenter by far.

In production there is an enormous difference whether raw wood constructions, construction parts for prefabricated houses, staircases or winter gardens or even all together have to be processed on one machine. In serial production the aim is to manufacture the largest possible quantity of identical or similar parts within the shortest possible space of time. For the wood construction worker the most important aspect is traditionally bonding construction wood. For these operations optimally functioning and reliable bonding systems have been on the market for many years. They are characterised by high performance and relatively low programming requirements.

The processing liberty is nevertheless limited: Only construction wood for roof construction, layers of beams or timber framework can be processed. Additional manual processing is in many cases essential; the dimension and form of the parts to be manufactured is also restricted to straight timbers in the majority of cases.

The technical evolution in the production sector indicates a development which will make the application of CNC systems with up to five axes the state-of-the-art in technology in a few years. Above all in the sector of CAD/CAM solutions there still seems to be a great deal of concealed development potential. In the field of prefabricated house manufacturing almost fully automatic plants in production belts are available in individual cases which leave only very few supplementary operations and finishing the surfaces to be performed by hand.

The intensified use of machines with several degrees of freedom has paved the way to new fields of operation for the wood processing companies, also beyond the construction wood sector, whereby new sales options and a higher diversity for the customer can also arise.

The further development of the software required will be a key field of tasks to exhaust the capacity of the machines and the diversity of the product. Direct machine monitoring on the basis of architecture plans without converting efforts by an additional engineer will be a cost factor of rising significance in the future. The advantage in comparison with competitors in this sector may result from the fact that due to the almost complete automation it is possible to manufacture in line with specific customer requirements and individual needs. In particular in the sector of prefabricated wooden house construction the aim of mass individualisation now seems to have come within reach.

Processing technologies gradually shift from handheld tools to precut CNC machines. Increasing flexibility and accuracy in timber processing is achieved by robotic and automated technologies. Functions of primary, secondary and tertiary building system merge by integrating structural components with fitting out functions of interior finishing and building service functions such as plumbing, wiring and HVAC. Carpenters who previously build just timber roofs are now offering complete buildings. They were enabled by multi functional CNC precut machines which could automatically produce any wooden joint based on architectural floor plans, elevations, sections, structural plans and HVAC CAD data. Modular home makers take advantage of these precut CMC machines by combining them with automated and robotic 5 axis assembly and transfer productions lines allowing an output of more than 1000 units and capital investment of about 10 million Euros or more depending on the value added within the prefabrication plant.



Fig. 5. Multifunctional robotic wooden wall production unit

Automatic timber positioning systems and laser assisted marking devices allow flexibility within automated CAD/CAM timber element production. The highest degree of prefabrication is achieved by the mobile home prefabrication with a prefabrication ratio of 95% and by box unit prefabrication where a prefabrication ratio of up to 85% can be achieved.

## 5. Automation and robotics in steel component production

From a technical point of view, in any case, it is hardly possible to explain the difference of the development between Germany and Japan in prefabrication automation in steel housing market. The current situation in steel construction and assembly can be characterised as follows: The building market mainly demands solutions from the steel construction companies which fulfil the clients' individual needs and therefore only conditionally allow rational standardisation with regard to production and assembly. This applies to all fields of steel construction, e.g. bridge construction, multi-storey building and hall construction, container construction, compound construction and steel machine and plant construction. As the percentage of steel in the housing sector is low, the steel frames applied in prefabrication for room cells are to a large extent welded or screwed manually.

If we wonder as to how the acceptance of steel in the housing industry can be enhanced in Germany, then Japan could be given as a good example. We see a possibility to learn from the experience made by Japan in the way the building material steel has been supported consistently and with perseverance by direct marketing with united forces.

Today the material steel offers a variety of new possibilities in comparison with the first steel enterprises. Material and production technology have gone through enormous



developments, whereby technological developments were in the majority of cases initiated by other branches (automobile industry). It can, however, be imagined that as a result of a new intensified use of steel in the housing industry innovation potential for the material will arise. By research, experiments and applications, steel can be improved in its capacities and characteristics so that any possible objections raised against steel in the housing sector will lose their validity.

CAD/CAM solutions are the state-of-the-art in steel construction companies to ensure the flexibility required from projecting via CNC production to delivery (logistics) to the construction site and, if applicable, to assembly organisation.

The aim is to produce constructions tuned to manufacturing and assembly requirements to a large extent without reworking at the construction site (e.g. adapting resp. cutting operations) enabling short assembly or construction operations. The construction parts are cut by laser, gas burner cutting, sawing, drilling, before undergoing straightening including metallic cleaning, interim and end coating and complete corrosive protection which are normally processes applied in pre-fabrication. These operations are performed with consistent high quality.

Here you can find a level of automation and robotics similar to the car industry. Factories churning out 5-10 thousands houses a year whether it is a panel based or box unit based system offer not only highest and constant production and product quality but also custom made houses where the client can choose from up to 2 million parts.



Fig. 6. Automated and robotic steel panel production facility

Production cycle time for box unit is down to 2,5 minutes and 120 m<sup>2</sup> houses can be assembled in 4 hours. Customers enjoy 10 or 20 years warranty. Suppliers provide the modular house factory in a 4 day cycle. One day for order output, two days for production

at the supplier and one day for delivery to final assembly factory. A house is produced within a week after order intake. If you want to exchange your old by a new house this can be done in two weeks. Within the first week the furniture is moved from the old house, stored and then the old house is disassembled and recycled. During the second week the new house is built and furnished. These customer friendly services made possible by extensive automation and robotics in production are very beneficial for the client since the purchased product is available within one or two weeks resulting in reduced financial burden.

## **6. International comparative developments: automation and robotics in Germany**

To compare the status of automation in housing construction in Japan with the situation in Germany and to derive further findings for possible development in automation, the Federal Ministry for Regional Planning, Construction and Town Planning have commissioned a survey within the scope of a research project<sup>1</sup>.

The focus of the current development covers primarily all fields of mechanical engineering and process engineering, e.g. manufacturing building materials, concrete products and prefabricated concrete products, brickwork machines and brickwork robots, controlling and monitoring mobile construction machines, as well as tunnel and microtunnel construction.

Automation and robotics have long found their way into the building industry in actual fact due to a variety of elements which can only be automatically manufactured and without which nowadays construction would not exist at all.

Building materials, construction boards, construction parts, installations, windows, fittings etc. would always have remained high-priced luxury articles, if it had not been possible to manufacture them in fully automated processes.

### **6.1 Development in Germany**

The majority of German building machine manufacturers and construction companies accompany these activities with an only moderate degree of interest.

As this is a part of the future building industry which is highly research- and development-intensive, there is the danger that this market with its long-term and probably existential technical and economic possibility will probably to a major extent be lost to foreign competitors without any resistance.

As a result of the violent technical development in the electronic age more and more focus is being devoted to the need to redefine the opinions regarding the building standards.

The increasing discrepancy between the performance of tools, machines and robots and small tools in general creates an increasingly unstable situation between the craft trade and industrial branches. This development is now intensified by the increasing application of low wages and the pending EU extension to the east, as a result of which it will become more and more difficult to survive in view of European competition. Due to subcontracting low wage workers companies are heading for the innovation and qualification trap. Instead of new technologies being developed and construction workers being further trained and educated they subcontract to low cost / low wage companies.

When examining the construction methods applied in Germany, the building methods and building systems used in concrete construction, brickwork construction, wood construction and in steel construction were investigated.

## 7. From factory to site automation and robotics

Since the 80s this procedure has led to the fact that the prefabricated house in comparison with the past enjoys a far better image than conventionally constructed buildings.

The annually recurring international symposiums on automation and robotics in the building sector underline the fact that considerable efforts have been undertaken world-wide in Japan and in the USA to utilise automation in all fields of the building sector.

In Japan automation and robotics have been operated consistently for many years on a widespread basis in cooperation with building enterprises, manufacturers, research institutes and national authorities.

In Japan robots of the third and fourth generation have also been presented. As argumentation for these activities the same conventional reasons are stated world-wide, e.g. lack of qualified workers, facilitation in working, quality enhancement, labour protection, environmental protection and productivity improvements.

A highly important reason for the Japanese enterprises is, however, the enhanced image in the building branch, which as low-tech industry enjoys hardly any prestige.

The developments of the last ten to fifteen years show that the Japanese building industry has achieved remarkable success with this strategy.

Impressive examples are 20 partly automatic superstructure systems with which the key building companies Obayashi, Shimizu, Taisei and Takenaka have been constructing buildings in Japan since 1992.

Lack of skilled workers is a coercive reason for forcing such measures which exists in no other industrial state other than Japan where restrictive immigration regulations largely prevent the employment of guest workers.

The reason why the Japanese have not yet offensively offered their construction robots on the world's major building markets is no proof for their assumed unsuitability. The fully automatic superstructure systems cannot be dismissed with the statement that their economic application presumes serial production either.

The automation of building processes has been the object of research and development by key Japanese building corporations since the end of the seventies. Japan started off with the development of individual robots and remote controlled manipulators for certain processes at the building site. These include robots for concreting, concrete treatment, applying fire protection measures to steel constructions, handling and positioning large-scale parts and facade robots for applying plaster and paint.

To date over 200 different prototypes of robotic solutions have been developed in the construction industry and tested on building sites. One common factor is that they have all been determined for specifically defined tasks under construction site conditions and moreover designed to prevent the building site workers' activities from being disturbed.

Experience has shown that under these premises only a few robots can be applied economically. The restrictions for workers, the necessary safety regulations paired with the unforeseeable and unplanned influences at the building site impose restrictions on the application of individual robots in parallel to normal construction site operation. Only a few

are currently in economic operation or are offered on the market for sale. These comprise, for example, the concrete smoothing robots manufactured by Kajima or Shimizu.

The outcome of this development is the finding that it is not possible to transfer production situations similar to those prevailing in the production hall to the construction site either without having to face difficulties or economic drawbacks. This may seem to be a trivial and foreseeable result, but it is necessary to realise that these developments were seen at the beginning of work only as a way into the automation of construction processes and that their economic use was not the foremost goal to be achieved. Two other results which play a key role in the future of Japan's building industry were moreover decisive. On the one hand these were the findings and capacities acquired in the field of automation and robotics resp. sensitisation of the employees for innovation in the building sector. On the other hand, preparation of the actual goal, this being the fully automatic production of a terrain on the building site under application of the regularities known from serial production.

About 200 different robotic devices had been developed, tested on site and improved. The highest degree of automation had been reached in tunneling from the prefabrication of tunnel sections, its transportation and assembly.

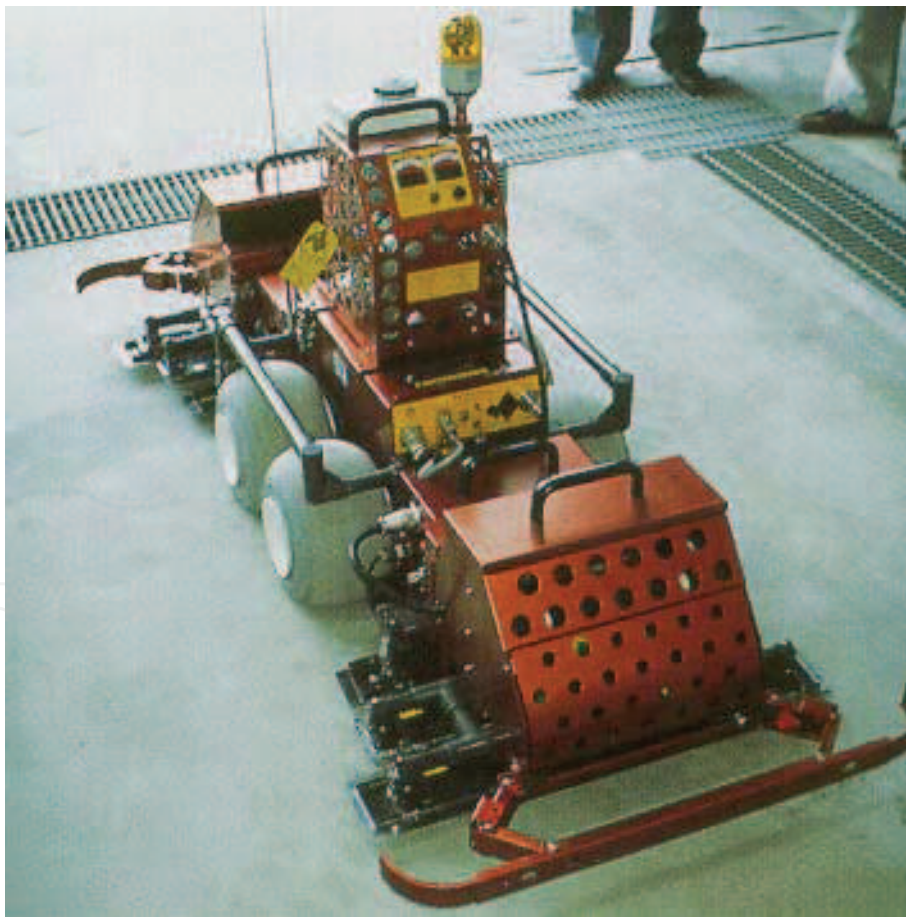


Fig. 7. Modular mobile light weight concrete finishing robot

Since sites and its conditions greatly vary at each project, the processes have to be well defined in order to be robotized. Furthermore the planning and design has to facilitate robotic construction by robot oriented design methodology.

The full potential of robotics will unfold as soon as robots do not just copy human work but rather be enhanced by robot oriented planning, engineering, management, labor training and qualification. Robots will probably not be used if total hourly labor cost is below 35, -euro. Another positive side effect of these high labor cost and high labor productivity would be wealth generation for construction workers as consumers.

Financing of expensive robotic equipment must be supported by financial institutions. Investors should appreciate the immediate availability of their real estate by forwarding their higher and earlier return of investment in the form of higher construction project costs. About 20 integrated automated and robotic building construction systems were running between early nineties till year 2008. Some companies developed systems that pushed the building up to ten floors, others had climbing systems with one to three gantry cranes or about 22 trolleys simultaneously transporting and assembling columns, beams, floor, interior wall and exterior wall panels and sanitary or installation units. The machine reutilization ratio was about 95%.

It took about a week for one floor and the finishing ratio reached 85% by using prefabricated and highly integrated components.

Working conditions on site became similar to factories and there were no accidents or quality problems.

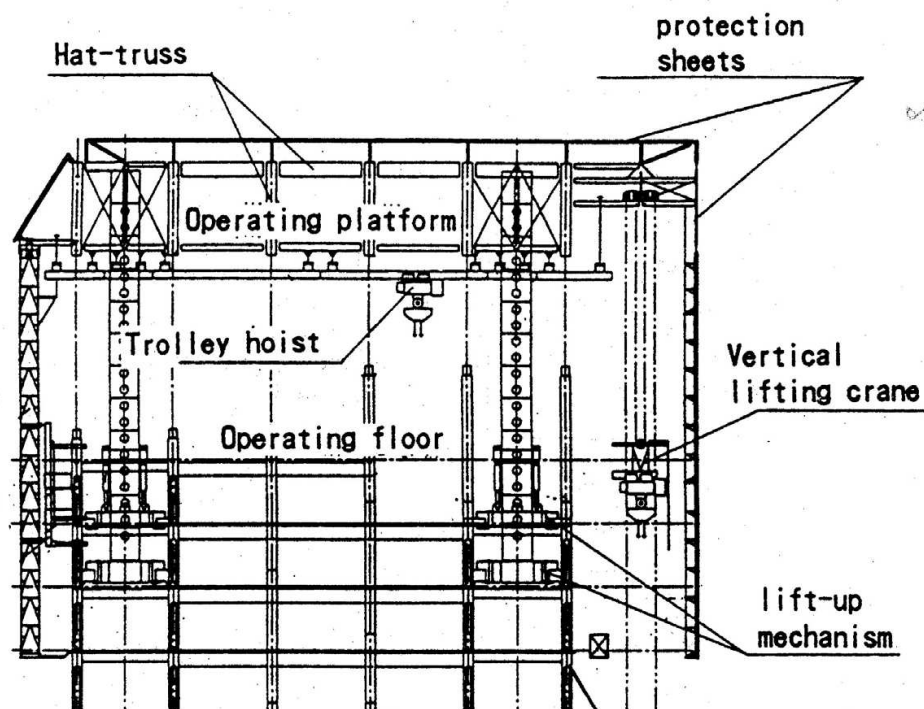


Fig. 8. Section of an integrated automated building construction unit with about 20 robotic trolley hoists for logistics and positioning

Similar as the JIT just in time of the Toyota production system the factories supplied building components in a ten minute cycle to the site. Since there were no storage areas for construction materials on site, construction materials were directly grasped by the robotic trolley hoists from the truck. Some systems could also adjust to non rectangular floor plan lay out proving that flexibility in design can be achieved by constantly improving robotic technologies.

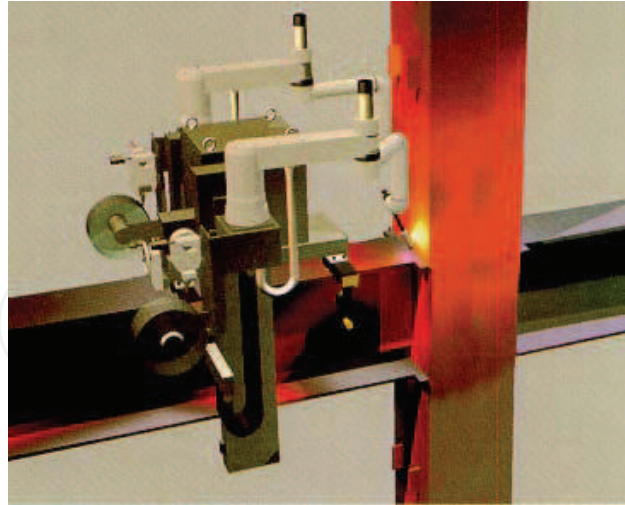


Fig. 9. Transportable welding robot in an integrated automated building construction site

The work force reduction initially was 30%, then 50 % and can reach up to 70%. It takes between 3 to 6 weeks to construct and disassemble an integrated automated and robotized building construction system. Investment cost for the on site integrated automated building construction units are about 5 to 10 mio Euro or more depending on its functionalities and performance. These additional costs have to be recovered from faster return of investment by earlier availability of rental space.

#### **Service robot systems and humanoid construction robots**

Building automation systems are state of art.

Energy costs had been successfully reduced due to efficient HVAC systems and energy saving facades. This leaves cleaning, building servicing and rehabilitation costs with a considerable impact on life cycle costs of real estate.

Since the real estate servicing costs during the building life cycle is several times -up to 6-30 times depending on the building type- of the initial investment or construction cost, it is obvious to rationalize this significant cost factor by automation and robotics.

There are many examples of façade cleaning robots, interior cleaning robots, security robots, transport robots, service robots for hospitals, elderly and physically disabled.

Since approximately six years humanoid construction robots were developed to drive fork lifts, excavators or carry building parts jointly with a construction worker. These humanoid robot technology transfer to construction is based on nearly two decades of humanoid robot subsystem technology development.

Humanoid construction robots vary from teleoperated devices through autonomous ones that can walk on 5 degrees inclined slopes, compensate 2cm high obstacles and are able to get up by itself once they fell down. Positioning is achieved by vision systems, force sensors in the feet recognize inclined slopes, balancing sensors detect the body's inclination versus the surface slope and an autopilot controls its attitude.

### **8. Guidelines for construction robot development**

Focus in robot development in Germany is to be mainly determined from the viewpoint of the workers. It is necessary to inquire in which sectors high or unacceptable burdens are registered and it is exactly there that analyses should take place to find out which technical

aids are required. An analysis of requirements based on the types of load is therefore urgently necessary.

Robots are primarily developed for the sectors in which poor labour conditions prevail and in which a reduction of the load is possible. The comparatively high frequency of accidents as well as the high statistics of labour-related sickness and premature retirement in the building industry are an indication for the special requirements. Robot systems should take over the task of handling heavy loads, of performing dirty or dangerous work or of working at hardly accessible locations and in unfavourable physical positions.

Above all robots should function as tools of the human being. They are to be developed as intelligent tools and must not force the human being to the limits of working activities. It must be possible to integrate the robot systems into labour procedures. These must not disturb the existing communications structures and cooperation, for example, within the scope of a gang. Robot development should therefore be implemented together with those persons who will operate these systems at the building site at a later point of time. Changes in the labour environment and labour organisation by the application of robot systems must be primarily oriented to the working people in the first step and then in the second to technology.

One important aspect is high system flexibility to adapt the robots to the prevailing structures. Fully automatic systems are therefore only suitable in exceptional cases, for examples in areas with high safety risk. Semi-automated machines, in contrast, can be flexibly monitored and applied. The focus of development must therefore lie on semi-automated systems. Other industrial sectors have in the mean time also withdrawn from the aim to achieve inappropriate full automation. Semi-automated systems are by far cheaper and more flexible than fully automatic systems. They can be applied by smaller-sized and medium-sized building companies to improve their competitiveness.

## **9. Development of integrated construction automation and robotics building processes**

The building processes and systems to be automated and furnished with robotic controls have to be redeveloped. The existing management methods require revising before qualifying the staff involved according to the application of new technologies. A successful implementation of robot technology is enabled with a robot-oriented construction industry which reflects certain characteristic features: flexible industrial pre-fabrication, flexible production of different building parts on the site and project management enabling the application of construction robots.

Automated building comprises industrial and flexible prefabrication of complicated standardised building parts and their automatic construction and maintenance using construction robots. Automated building production enterprises are able to achieve a high level of variations with a wide range of construction parts. With the help of freely programmable robots a flexible production of a wide variety of building parts is enabled and administered using the suitable software. The industry manufacturing prefabricated parts should benefit in particular from the advantage that it is possible to flexibly manufacture with a large degree of automation by aligning production technology in order to meet the requirements of mass individualisation in the housing construction sector.

As far as automation of the construction company is concerned, the development of an integrated system to plan and produce buildings should be envisaged. This system can be

used not only in drafting buildings, but in operational planning for robots and in logistics for building sites.

Due to the high wage costs in executing construction work the largest rationalisation effects are achieved by an intensified rationalisation of the construction work with the help of automation components. On-site construction work has to be aligned to subsequent robot operation in the planning and construction phases. That means that all construction planning phases have to be integrated into the computer systems before being processed. The conventional building processes have to be tuned to automation requirements. These new building processes will differ fundamentally from the known building processes. The normal sequential procedures of building production will also be replaced by parallel procedures. Partial systems from prefabrication will also be integrated into building operation and will therefore drastically reduce the construction period.

By contracting a project for an automated building construction, the whole activity has to be furnished with robotic controls, planning, construction and manufacturing of construction parts. These parts will have been largely prepared and completed so that after signing the contract the construction project only represents a geometric configuration problem, timely organisation problem and a physical implementation problem.

The corporate structure is transformed from the current assembly company to a future service company.

Contemporary buildings consist in comparison with pre-industrial buildings of many partial systems. Planning, production and the product are increasingly mechanised and will be additionally mechatronised. This fundamental development in the building sector requires an integrated and interdisciplinary problem-solving approach. In implementing building management this means the specification of conditions for operating robots on the site with a geometric, physical and timely definition of the elements for every constructional subsystem.

That requires an interlinking of the data and information flow from the draft to design, manufacture, assembly and facility management. The interlinking in the prefabrication of partial systems and their integration into the building processes plays a decisive role hereby.

## **10. Strategies for an automation and robot oriented construction process**

Systems able for automation in construction should satisfy the needs of all parties participating in the construction process. Suppliers have to increase the quality of the construction materials and products under the geometrical, physical and design aspects, to fulfill the conditions for automation oriented design methods. The present production sequences in the construction process have to be adapted to an automation concept. A construction system able for automation should contain, additionally to the conventional properties like stability or economic efficiency, also a flexible strategy, which includes all participating parties and allows a future reusability.

The goal of an automated construction will be achieved, if following parameters will be met simultaneously without excluding each other:

- Freedom in esthetic and design
- Determination of the production costs before the execution of work
- Determination of the production time before the execution of work
- Guaranty and transparency of the price
- Continuous production



- Definition of quality
- Control and transparency of the quality

### **10.1 Information integration during the construction process.**

The task is not only the automation of the component's pre-fabrication and assembly, but also the coordination and connection of all processes by means of computer integration and interface management. Prerequisite for an automated construction technology is the exact definition of all soft- and hardware standards, all interfaces and communication protocols used for the project.

One essential base for the computer integrated construction process is the design of the building based on a 3-dimensional geometry model representation in the necessarily used CAD system. The second column of a successful construction is the exact description of the properties of the different sub-systems. According to the definitions, the suppliers are chosen. This information can be provided separately to the geometric information only referring to the single positions in the design. Also the third column can be generated separately: a time scheduling of the different construction processes on the level of the sub-systems provided by the respective suppliers. Under another point of view, the scheduling can be regarded as a rated assembly precedence graph for the different assembly procedures on-site, which can be referred to the different geometrical descriptions in the design database.

Through an intelligent interface management each supplier is able to get the necessary information concerning the geometries, the material properties and the time scheduling. It is not necessary to hold all information in one system or on one database. It is even not necessary to have all information at all on the computer. The only purpose is to create an internal production plan, whereas many informations can be used as easy and as fast as possible. The geometrical and the material information can be used for the automated production of the components of the demanded subsystem. The time and sequence information can be used to optimize the production sequence concerning delays and delivery time security. Additional, all three informations can be used for refining: more detailed plans of the sub-system, more detailed material information of the parts of the sub-system and a more detailed assembly sequence of the parts can be generated. This can be delivered back to the coordinator, who can use the information for the logistics on-site and the assembly of the parts as far as the supplier does not assemble the parts by himself.

After integrating all the information through the coordinator of the construction site, the information is ready to be used for the assembly of the sub-systems or of the parts of the sub-systems. The goal must be to use the information out of the three areas refined by the suppliers to generate the control sequences for the automated construction tools available on the construction site respective to generate the assembly instructions for the manual part of work. For that it is necessary to have all information in the access of the coordinator, where the different necessary interfaces and information flows and directions should be well and flexible defined. It is also necessary to have the possibility to integrate information in the databases at each level manually or via a defined interface.

The integration of all participants into an information network guarantees an individual and simultaneous efficient construction of buildings, which is able to cope with short term changes without increasing the costs or decreasing the quality and design freedom.

The gained data should be used also for the optimized operation and the recycling of the building, since the costs of a building concern not only the erection but also in a considerable amount the operation and recycling.



Fig. 10. NCC Komplet wall assembly in on site assembly hall

In the NCC Komplet factory 60 operators work on job rotation time schedule. The yearly capacity is 1000 apartments and each worker is producing 17 apartments yearly. Automation and mechanization are ergonomically designed to reduce labour fatigue. Every 15 Minutes a truck leaves the factory. The apartments are 90% prefabricated. The investment was about 30 million euro. The on site assembly factory is all weather proofed enabling ergonomic working conditions all year around.



Fig. 11. On site factory of NCC Komplet

### **10.2 Transfer of construction processes to the pre-fabrication.**

The automation and industrialization of the construction process will have the first break through in areas, where already a high mechanization rate is already existing. This is the stationary pre-fabrication of construction parts in contrary to the processes on-site, particularly in the building construction.

Through an intelligent shift of process parts from the site to the pre-fabrication, it is possible to achieve a higher automation rate together with a higher integration rate of the construction parts in an earlier and more defined stage of the construction process. This increases the quality and decreases the transport costs.

### **10.3 Increase of efficiency and quality.**

Through the higher integration of the parts, the more sophisticated design and the information integration, different effects occur during the construction process: In the pre-fabrication it is possible to apply industrial production methods for a higher integration of the parts. This results in lower production and transport costs with a simultaneous increase quality. Also the design flexibility of the produced parts is increased through automated production technologies and the integration in an information network. Additionally the integration of the complete construction process enables the suppliers to participate in the complete design and construction process. With this approach also "Just-In-Time" and "Simultaneous Engineering" concepts can be realized.

The advantages of the individual design of a single-piece production and of the industrial mass production can be combined. So the construction time can be reduced through higher parallelization, the flexibility increased without higher costs for short term changes and the quality enhanced through better quality control and new construction processes.

A hybrid high-rise construction site is understood as the semi-automated storage, transport and assembly equipment and/or robots used to erect a building almost completely automatically. It is the attempt to improve the sequencing of construction processes and construction site management by using real-time computerized control systems. This includes an unbroken flow of information from planning and designing the building through programming the robots with this data to using computers to control and monitor building operations on site.

After the foundations have been laid, the production equipment, on which the steel construction has been installed with assembly and transport robots, is covered completely with a roof of plastic film. Depending on the system, this takes from three to six weeks. Then the robots go into action. Two steel and ten concrete plants supply parts in ten-minute cycles on a just-in-time basis. This approach to supplying is not necessarily part of the system, but is due more to the lack of space around building sites in large Japanese cities. The prefabricated parts are checked and then placed in specific depots at the foot of the building or in the building itself to be available to the robots.

Once a story has been finished, the whole support structure which rests on four columns is pushed upwards by 12 hydraulic presses to the next story. Three 132 ton presses in each pillar are required to achieve this in 1.5 hours. Fully extended, the support structure is 25 meters high; retracted it measures 4.5 meters. Once everything has been moved up, work starts on the next story. By fitting out the topmost story of the high-rise as the roof at the beginning of the building process, the site is closed off in all directions, considerably reducing the effect of the weather and any damage it might cause.



Fig. 12. Hybrid Construction System

This system reduces labor requirements by around 30%. Future projects are expected to achieve a labor saving of around 50%. The building consists of a remarkably high proportion of prefabricated parts. Once the foundations have been laid, the remaining construction procedure can be described as a matter of configuring transport and geometry. All the elements are prefabricated; only some of the fitting, joint insulation and other minor works need to be carried out by hand. Problems with the construction arise less from the timing of deliveries of materials or from the choice of processes and/or machines but more from the need for accurate planning, from programming the robots or from the just-in-time supply of parts.

## 10.4 Construction components for an robot oriented design & construction

### 10.4.1 Clear product structure.

The clearer the structure of the products, the simpler a realization of automated construction becomes. It is necessary to insert the product system elements into clear hierarchical levels. The product has to be divided into "sub"-products according to the construction process. In the development phase it is necessary to check all product features according to their ability to be used for an automated application. With the following procedure, existing

products can be redesigned according to the rules of automated construction. After the first analysis of the product function, sub-functions are defined within each effecting area and each effecting direction. During further analysis all sub-functions are eliminated which refer not directly to the sub-functions of assembling and connecting. Elements with similar effects can be summarized to defined classes of functional solutions. In the next step the effects of these elements concerning the assembly process are analyzed. After the analysis a simplification of the functions through further sub-dividing and the search for solutions should follow, which are then combined again to a global solution.

#### **10.4.2 Design focused on simplicity, handling and assembly.**

Construction elements should be designed clear and simple. If an element has a specific assembly alignment, the design should support the easy alignment of the element. So problems concerning the handling, orientation and identification are reduced. If the assembly direction stays the same during the whole construction process, the costs are less than if several alignments have to be made. If a part is asymmetric, the asymmetry has to be emphasized to find the assembly direction easier.

#### **10.4.3 Families of components.**

The sequence of construction elements should be rationalized through grouping technology. Grouping creates families of parts that can be assembled or processed with the same or similar tools. Unnecessary distinction of construction components should be avoided. Necessary distinctions should be reduced to the system specific principle.

#### **10.4.5 Component interfaces.**

To get defined construction systems, the components have to be standardized to a certain extent. To realize all possible combinations it is necessary to confine oneself to few basic parts. The connections should be compatible to enable the mutual assembly. They have to be defined geometrically and physically. Similar to the "open systems" standards, the construction components of different suppliers should be compatible.

Connection surfaces and points should be compatible. The construction parts need an exact defined connection zone. If the structure becomes static effective, the importance of the connection zones increases. The assembly of complex structures may need specific parts for the connection zones.

#### **10.4.6 Integral product structures.**

The number of element connections and in parallel the connection work should be reduced. To achieve a lower number of components and sub-assemblies the product structure should be summarized. This leads also to lower assembly times.

The pre-assembly of complex structures is possible thanks new flexible production technologies. The cost intensive handling of small parts during positioning, adjusting and fixing can be avoided, if pre-assembled units are brought to the construction site.

#### **10.4.7 The accuracy problem.**

During the design process, one has to pay attention to the tolerance system, too:

- To avoid geometrical faults between to elements, which have to be connected.
- To compensate accuracy deviations in the control system.

- To handle the production tolerances of the construction elements.

Everybody dealing with construction is aware of the accuracy problem. The most inaccuracies can be recognized and corrected. But for automated equipment the increased necessity of sensors increases the complexity, susceptibility and price and reduces considerably the working speed.

To position components precisely, the structure must be produced and assembled with minimum tolerances. The statistical average of the accuracy, on which the construction is usually based, cannot be applied to automated construction processes since not all cases of minimum and maximum accuracy can be considered equivalently. Therefore the accuracy and its problems have to be described in categories, which are easy to integrate into the construction process.

The tolerances of the different trades vary very much: The low accuracy of foundation work is insufficient for other trades and the high accuracy of installation work is not necessary for the foundation. The different categories of accuracy for different trades have to be defined exactly and considered during the development of sub-systems.

## 11. Summary

Due to the high complexity of the construction process and the stagnating technological development a long-term preparation is necessary to adapt it to advanced construction methods. Architects, engineers and all other participants of the construction process have to be integrated in this adaptation process.

The short- and long-term development of automation will take place step-by-step and will be oriented to the respective application and requirements. In the initial phase existing building machines will be automated step-by-step. In the medium term a mixed concept consisting on the one hand of manual operation with programmable partial processes and on the other hand of automatic operation with manual monitoring options including all controlling concepts lying in between will gain ground.

In the end phase the CIC concept (Computer Integrated Construction) will be implemented. The use of robots will be more effective, the more appropriately it is integrated into a CIC production chain.

Not only in stationary industry, but also on-site the computer-supported building production of the future could be monitored by the human being in a control room, whereby a qualified building worker can simultaneously control several building machines. All that is needed is an effective communications system between the control officer and autonomous building machines. Application planning and monitoring will be automatically controlled, whereby every individual building machine will constantly communicate with the central control room. In the event of irregularities which are not stated in the program, automatic operation can be manually monitored by the control officer.

The performance of robotic technology is increasing rapidly and we can support its advancement by designing, engineering, managing the construction processes and products in a robot oriented way. On the engineer level we need robotic and mechatronic construction engineers, managers and architects education. The workers need mechatronic and robotic training and qualifications. For real estate to be build by robots and integrated automated construction systems we need additional investment in order to cover the higher construction costs caused by greater capital investment in construction equipment. One way could be borrowing financing methods from the leasing sector, aircraft or car industry,

which often offer 0% interest loans to attract new customers. Towards the investor we have to communicate the advantages of constant construction quality and faster availability of rental space resulting in higher return on investment.

The realization of automation and integration of advanced technologies in the construction field can be supported, if the guidelines for automation oriented construction systems are followed and took into the thinking process. Together with a slightly modified design, the effective pre-fabrication and automated assembly on-site are processes, which can be linked together through a sophisticated computer integration and interface management.

## 12. References

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## **Robotics and Automation in Construction**

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This book addresses several issues related to the introduction of automaton and robotics in the construction industry in a collection of 23 chapters. The chapters are grouped in 3 main sections according to the theme or the type of technology they treat. Section I is dedicated to describe and analyse the main research challenges of Robotics and Automation in Construction (RAC). The second section consists of 12 chapters and is dedicated to the technologies and new developments employed to automate processes in the construction industry. Among these we have examples of ICT technologies used for purposes such as construction visualisation systems, added value management systems, construction materials and elements tracking using multiple IDs devices. This section also deals with Sensorial Systems and software used in the construction to improve the performances of machines such as cranes, and in improving Human-Machine Interfaces (MMI). Authors adopted Mixed and Augmented Reality in the MMI to ease the construction operations. Section III is dedicated to describe case studies of RAC and comprises 8 chapters. Among the eight chapters the section presents a robotic excavator and a semi-automated façade cleaning system. The section also presents work dedicated to enhancing the force of the workers in construction through the use of Robotic-powered exoskeletons and body joint-adapted assistive units, which allow the handling of greater loads.

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