Automation in the Prefab and Modular Construction Industry

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Abstract

The construction industry at-large is dominated by numerous small and specialized sub-contractors who typically are not technologically advanced enough to embrace automation. The sector that represents factory built housing (the modular, prefab, panelized, precast, etc.) is an exception. Since the products are built in factories, the principles of mass production and mass customization that are the norm in manufacturing, apply. It will also make it easy to adapt to automation, integration and optimization. In this scenario, the constructability aspects can be verified prior to being built, and an optimum construction plan can be derived. Newer materials can be applied, tight tolerances achieved, while the built products are not affected by outside climatic conditions, as is the case for site built housing. With a view to gauge the needs of automation within the prefab sector, we reviewed several automation technologies relevant to construction, and also have been consulting with the prefab industry to understand their state of practice. This paper summarizes the findings of this study, provides an overview of the type of automation that is prevalent in the industry, and outlines a technology outlook with various elements comprising the aspects of prefab automation. It will help the prefab industry personnel arrive at a broad view of the essence of construction automation, while the research community gets a sense of industry 'pull' in embracing automation.

Introduction

The uniqueness of the construction sector poses several challenges for the direct adaptation of technologies that are used in many other industries, for example, those that support mass production and/or mass customization. This provides opportunities for researchers engaged in construction-related research. It also involves extensive use of information and support technologies across the enterprise and its market. The automation pertaining to the prefab construction sector, typically falls into one of three categories:1) prefab components making process, (parts, panels, precast, formwork, etc.) which deal primarily with the construction of the building blocks; 2) assembly process in which the construction components (often from different suppliers) are installed to create buildings, houses, etc. by an array of sub-contractors, sometimes having conflicting workflows; 3) construction business processes that represent both the business and support processes (project management, supply chain management, document management, workflow management, change management, planning & scheduling, etc.).

The FutureHome Project

A milestone European prefab automation project -The FutureHome - started in 1998 and was completed in 2002.The main objective of the FutureHome project represents the development of an integrated construction automation concept and associated technologies for all stages of the house-building construction process, from the architect's desk to site robots. This includes: a) the modular design of buildings with planned robotic erection, b) automatic planning and real-time planning of offsite prefabrication, transportation, and onsite assembly and c) onsite automated transportation, manipulation, and assembly of the prefabricated parts. The FutureHome building system derives from a Kit-of-Parts approach, which is a specific implementation of prefabrication. As noted by Wing et al (2002), virtual reality is employed, providing a common virtual environment that can be shared by clients, architects, engineers, constructors, etc. The clients can be led through the virtual design of their house, created on-line using "prefabricated" components. The construction process can be simulated, allowing examination of cost, quality and time aspects. This is an environment within which the user creates a design from its constituent prefabricated components. A 3D window lists a library of available components, which can be assembled

automatically. The user selects a component and views it in 3D and chooses to add the component to the design, using collision detection and constraint-based modeling techniques to ease the interaction process. As noted in Dietz et al (2007), several assembly connectors had been developed for the assembly of the modules, the structural connection, and electrical and service pipes connections. These connectors ensure automatic performance of complete assembly between modules. A noteworthy feature that evolved as part of this project is the development of a tool called AUTMOD3 - an automatic modular construction software environment. This system integrates architectural design, planning and simulation tools in a commercial CAD program.

The ManuBuild Project

Another prefab automation project - The ManuBuild - started in 2005, is due to be completed in 2009. This European project, as referred in Bock (2006) and the Manubuild website (refer 31), has set its objective such that customers can purchase high quality manufactured buildings that have a high degree of design flexibility at relatively low cost. Enabling business processes, ICT systems, new materials and smart components are major features of this project. ManuBuild has set its vision: 'Customers will be actively engaged in the design of their buildings, using state of the art interactive tools; it incorporates mass customization, and offers customers increased choice and design flexibility; the efficient, flexible and scalable manufacturing concept enables production efficiencies of production scale; an open system for products and components gives diversity of supply at competitive costs'. The potential impact includes significant reductions in waste, costs, time to construct and the number of construction related accidents. Striving to achieve automation, ManuBuild aims to provide ICT support for distributed building manufacturing. To achieve this, several decision support tools have been developed, ranging from catalogues of products via information delivery, design, custom configuration, and assembly planning.

Other Major Projects:

There have been other major project undertakings also pertaining to construction automation, especially in the United States. For example, FIATECH (2004) has created a Capital Projects Technology roadmap (refer to Figure 1) to integrate various functions and any required information in a unified construction project/facility management environment, as briefed in Bowden et al. (2006). In our study, we limit the scope to the elements of automation that are a) Automated Design, b) Integrated Automated Procurement and Supply Network and c) Intelligent and Automated Construction Job Site.
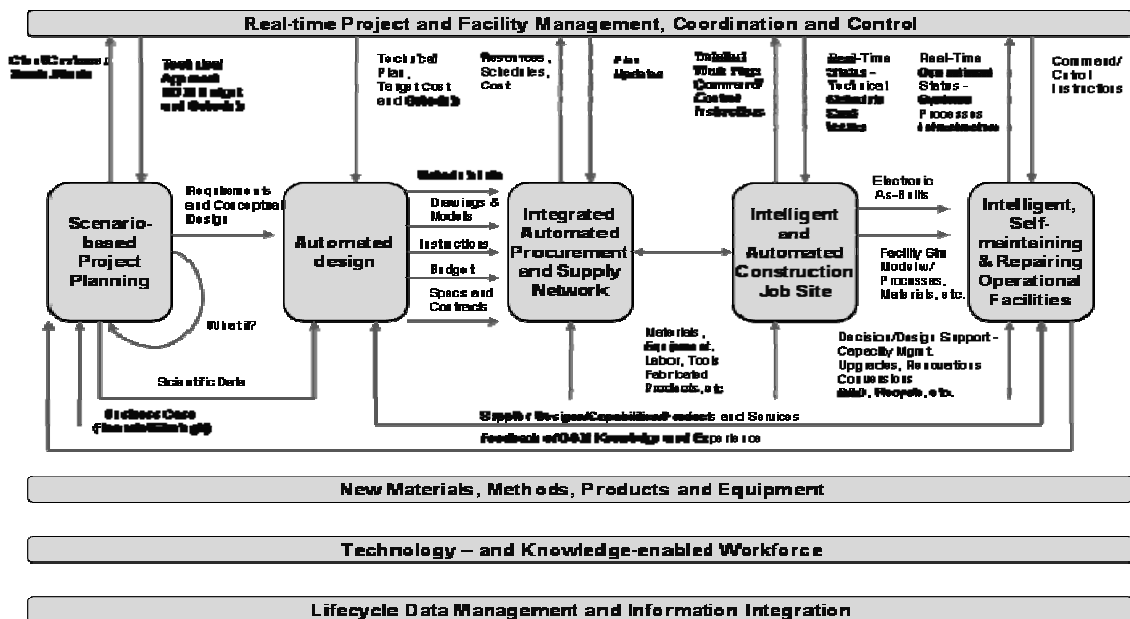

Figure 1: FIATECH Capital technology Roadmap (Adapted from: Bowden et al - 2006)

Automated Design

It may be argued that the construction starts at design phase of the built environment. The prime considerations of this phase is the advancement of automated design to improve cost-efficiency, enhance the lifecycle value of the project, and enable interoperability among a project's lifecycle entities, and all these can result in significant cost savings. Accordingly, technology integration, with capabilities in 3-D design, analytical modeling and simulation and distributed intelligence, offers a great opportunity to create a truly integrated and automated design environment. It will greatly reduce errors through automated design optimization and verification. Optimization could include a variety of options including installation cost, lifecycle cost, and plant output. It should process design options in an accurate, scenario-based visualization environment.

The present day 3D modeling tools embed pre-defined objects that facilitate the development, routing, and connection of building systems in 3D, and provide conflict detection to identify physical interferences between components. 4D modeling tools (3D CAD model with time as its 4th dimension) link a construction project's scope in 3D with its schedule to simulate the actual construction process. The benefits include the elimination of construction interferences, less reworks, fewer change orders, increased productivity and a decrease in delivery time, as detailed by Staub-French and Khanzod (2007). By reviewing project schedules in a 4D environment, and as referred in Yerrapathruni et al (2003), the construction professionals can readily identify design, constructability, sequencing and interdisciplinary interfacing issues.

BIM and Data Exchange Models

Automated data exchange and wide usage of Building Information Model (BIM) play major roles in achieving construction automation. Technology wise, as noted in the Autodesk website (refer 29), BIM is an approach to building design that is characterized by the creation and use of coordinated, internally consistent computable information about a construction project. And, according to National Building Information Model Standard published by The National Institute of Building Sciences (NIBS), BIM is defined as "a digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its lifecycle from inception onward." The foundation of BIM is parametric building modeling, which records, presents, and manages not only object data at the component level, but also the network of relationships among all of the objects of the building from various views. From a lifecycle point of view, BIM enables architects, engineers, contractors, owners, and facility managers to share data throughout the entire lifecycle of the building. The shared data includes the initial design data; geospatial information; financial and legal data; mechanical, electrical, and plumbing layouts; building product specifications, environmental and energy modeling results, and other information, as described in McGraw_Hill Construction 2007 (refer 33). With BIM in place, large amounts of data (typical in moderate and large projects) can be continuously exchanged among the key players. This enables facts, figures, designs and analyses that affect one or more information sources to be constantly updated to ensure that any decisions made are based on accurate information.

Automated Supply Network and Materials Management

As detailed in Ganeshan and Harrison (1995), a supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers. By properly managing the network, one ensures the supply of the right products in the right quantities at the right places at the right time and at a minimal cost. An important aspect of this setup is the 'coordination' of organizations. Xue et al. (2005) presented an agent-based framework for supply chain coordination, based on multi-attribute negotiation and utility theory. A notable feature here is the coordinated decision making process of multiple organizations through the integration of key business processes and key members involved in the construction supply chain, including client/owner, architect, general contractors, suppliers, etc. Complementary to the supply chain management is the materials management function. Navon and Berkovich (2005) have suggested a material management and control model that encompasses the purchase of materials, delivery to the construction site, and dispatching of materials for usage. Intelligent and automated data collection technology has been incorporated into this system for tracking materials, via enabling technologies like the use of barcodes, RFID, and/or personal digital assistants.

Robotics Automation in Prefab Industry

Robots found its way to construction first in components making and the production of modular housing. Later, mobile robots were developed for special on-site construction tasks. As reported by Bock (2004), robots played active roles at the production line of Sekisui Chemical Sekisui Heim in Japan, where more than 85 percent of the houses are prefabricated. 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, according to certain CAD data, a multi functional gantry type robotic unit with two vertical arms places magnetos on the steel production table. The unit also attaches shutters on top of the magnetos and then places horizontal, vertical and triangular reinforcement bars, as per design. 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.

Kye-Young Lee et al (2006) studied the human-robot cooperative (HRC) system to cope with the construction environment via real-time interaction with human and robot simultaneously. The power of a robot system helps a human to handle heavy materials with a scaled-down load. The human can feel and respond to the force reflected from the robot end-effecter acting with the working environment. The study also presents the experiments and evaluations to verify the HRC system for robotic applications giving the performance tests, like force assistance, force reflection, and position-tracking in a two axes manipulator. Engelbert Westkamper et al (2000) developed a robotic system for the automatic laying of tiles within certain tolerances on prefabricated modules. The pilot work consisted of a tile laying system that consists of tile positioning equipment, a centering and measuring system and laying unit; an adhesive application system, consisting of adhesive preparation and transport unit; a tile supply system consisting of a store and a measuring unit; systems for generating process parameters; and handling and positioning systems having industrial robot and process control. Peñin et al (1998) and Paster et al (2001) developed a robotized cell for making the pre-fabricated glass reinforced cement panels for a Spanish construction company. It is developed for the automatic programming and control of facade panel manufacturing, and a CAD based 3D-drawing of the building facade serves as the input.

Automated Construction Site

An automated construction site may use robotics for logistics and assembly, but can face many barriers that are technological or economical. The technological barriers are that a robot must cope with the complexity of the construction process involving a dynamic and evolving site, together with the need for performing multiple tasks with differing characteristics. As detailed by Zied (2007), robotics research in construction has moved to address technological barriers via: a) development of mobile platforms and manipulators, b) development of control systems and sensory systems integration, c) re-engineering of processes to suit robotic systems, d) software development related to support the above, and use of advanced IT systems to enhance the whole system performance. Economical barriers also influence the implementation of a robotic system in construction, such as: a) the cost vs. benefits, b) the changes required for implementing the new system, and c) the effect of the new system on the complete organization, which includes health and safety, and labor unions concerns.

Martinez et al (2008) have reported on the robotization and industrialization of the construction process, with objectives on: a) Modular design of buildings, with robotic erection in construction; b) automatic planning and real-time re-planning of the offsite prefabrication, transportation, and onsite assembly; c) onsite automated transportation and assembly of prefabricated components. They also have developed tools for the assembly of various building components and modules. SMART (Shimizu Manufacturing system by Advanced Robotics Technology) represents a systems approach (reference 34) to computer-integrated construction. The system set-up takes a few weeks, after which the building's top floor and roof are erected on top of four jacking towers. Jacking towers are used to push up the several-ton heavy top floor assembly - the main work platform - as well as lifting their own bases from floor to floor. The system is also composed of lifting mechanisms and automatic conveying equipment which are installed on the work platform. Overhead gantry cranes are connected to the underside of the roof structure. Trolley hoists are used to lift and position prefab components introduced at ground level, and floors emerge from under the top floor. The whole process is computer-controlled, though site workers oversee the operations.

Wakisaka et al (2000) have described a similar construction system for high-rise reinforced concrete buildings, which is often referred to as the 'Big Canopy'. Its set up consists of a parallel delivery system with three automated overhead cranes and one large construction lift under a synchronous, all-weather, climbing, temporary roof frame. A material management system is also part of it, with database linkage and communication with a CAD system, which draw resources based on prefabricated components. The Big Canopy construction system is divided into the following subsystems: a) a roof supported by four tower crane posts that are situated outside the building; b) a complex hoist system with three cranes mounted against the roof; c) a jib crane on the roof to mount and to dismantle the tower crane posts; d) a high-speed lift to all floors; e) use of prefabricated components with easy identification (RFID, etc.); and f) a material and delivery system to manage the flow of materials and components.

Virtual Reality and Simulation in Prefab Industry

Virtual reality (VR) enables real-time viewing of, and interaction with, spatial information. The visualization can simulate performing such tasks as production, transportation, handling and assembly of components. It can also evaluate which pieces of the building are to be assembled in what sequence, as well as reuse the model at different stages of construction. Team members can visualize their specific tasks and the relationships between the works of various other sub-contractors. Li et al (2008) described an integrated framework and process for general contractors to apply the virtual prototyping technology. In this framework, an expert (process modeler) accepts the BIM model from the designer, and decomposes it into formats required by contractors and consultants. At the same time, the process modeler integrates information provided by a team member into the BIM model to create a virtual prototyping of the construction processes. Through an iterative process, the process modeler enables the construction team to conduct 'what-if' analyses of different construction methods in the virtual prototyping environment until a satisfactory method is achieved.

Murray et al (2003) described a virtual environment that supports the design, and the assembly of a building from prefabricated components. The environment imports a library of 3-D models of prefabricated modules to interactively design a building. The construction schedule can be altered, and the information may be fed back to its simulation environment. The users can create their design through automatic constraint recognition and view the real-time construction process simulation. The site manager viewing the system gets a good project perception, as it provides the project's schedule management function integrated with an animated virtual reality display. Nasereddin et al (2007) described an automated approach to create a discrete event simulation model, developed using ProModel and Visual Basic. It is an approach for automating the model development for the prefab industry. A case study is presented to verify advantages that include a reduction in model development time and improved modeling consistency. Here, the animation data which was input manually includes the graphics library that they had created for the modular home industry. The library is used to show animation changes to the module as it is processed through the production line.

Planning for Prefab Automated Assembly

A building is comprised of components – the basic building blocks - assembled as per certain rules and constraints. And in some sense, the prefabricated building construction is analogous to the assembly of a manufactured product; if we consider assembly as the reverse of disassembly, the whole assembly process sequences may be inferred. But, the assembly of components is dependent not only on geometric properties, but also on the assembly relationship and spatial restriction information of the components. Hu (2005) has developed a method for the automatic determination of the construction sequence from a connection graph representing a pre-fabricated building via the extraction of components, and by a verification of disassembly. Components tightly connected geometrically and physically, but loosely connected to the rest of the assembly, are extracted as a preferred super-component. The process of extracting components not only makes it possible to reduce the problem space by early pruning of infeasible construction sequences, but also explicitly defines temporal and spatial parallelism in construction. Benjaoran and Dawood (2006) developed an innovative planning system called 'Artificial Intelligence Planner' (AIP) that helps automating the planning segment of 'bespoke' precast production. Its data integration features encourages automation in the planning process, and its decision support capability enables planners to improve the production plan

efficiency. These two complement each other to deliver optimum benefits to precast manufacturers. The AIP system adopts artificial intelligence technologies (neural network and genetic algorithm) to assist the process of production planning.

Scheduling Automation and Sensor-based Control

An efficient production schedule drives automation in the actual creation of prefab components. Several scheduling prototypes have been reported, which addresses this issue. For example, a decision support system for coordinated prefabrication scheduling has been described by Chan and Zeng (2003). It supports key elements of production (re)scheduling, namely, conflict detection, determination of the priority for conflict resolution, generation and evaluation of alternatives for conflict resolution, and ranking of outcomes for negotiation. It combines the use of an explicit constraints-based scheduling model, and genetic algorithms (GA) to determine scheduling parameters and conflict resolution priorities. A GA based searching technique is also adopted in a mixed precast flow-shop scheduling system proposed by Leu and Hwang (2002), providing near-optimal combination of production sequences, resource utilization, and minimum make-span while complying with resource constraints and mixed production. Take notice that prior to construction, the components delivered to the site need to be inspected, stored and then tracked, while the details related to installation require adequate documentation. Prefab components locations need to be known, and transported to the site with minimum time loss. Gajamani and Varghese (2007) have presented a RFID-based location tracking real time scheduling and monitoring system that make use of prefab/ precast components. Data is collected in real time and is converted using a software system, not only for the control but also for field material management and future use.

Conclusions & Future Directions

The ultimate objective of automation is to improve productivity, quality and safety, which will also contribute to cost reduction. The type of automation technologies detailed in this study revolves around actual construction projects as well as research activities that are related to building systems: that is, construction components, fabricated modules, panels, houses etc. As is somewhat obvious, the three prime areas of automation in the prefab and modular construction domain are: the design, the material handling (robots, etc.) and the business processes (including planning and scheduling). It is logical to conclude that some form of automation will be the norm in all factory-built housing of the future. Research directions in the form of a roadmap for the prefab industry is sketched out below, based on this study, and our interactions with the regional construction industry, as well as our own understanding of the type of automation that prevails in other sectors like manufacturing. This conclusion has been reinforced by the findings given in Mullens (2004), the technology roadmap by the manufactured housing research alliance (refer 32), and the summary based on a consultant's report (refer 30). The roadmap details primarily with the productivity issues of factory settings (where the components are built), and the quality and functionality of the built components and their subsequent assembly that constitute the buildings.

Prefab Factory Automation – A Productivity Issue

Embracing the technologies that revolutionized manufacturing industry, prefab builders may radically improve the efficiency with which it produces end products - buildings. The future builders will evaluate ways to improve productivity through the application of lean production, information and automation technologies. It will include efficient methods for warehousing, develop strategies to reduce construction waste, and adopt techniques for recycling. It will develop and deploy technologies for defect-free transportation of the prefab components. It will develop and test transportation system features that are high performance, low cost and more fully integrated into the building's structural system. Support processes will include optimization, simulation, visualization and project management tools to evaluate and control alternatives. Materials will arrive in the factory just in time to support production, and stored close to the point of use. Components will be identified and tracked in real time to monitor the exact location and status of all items. Material handling and manufacturing processes will be automated to eliminate injuries, minimize physical exertion, assure capacity and boost productivity. Production documentation will be accurate and timely, and can be accessed from remote locations. Employees will know the status of any order, recognize

the limitations of any resources, and will be able to react to meet schedule commitments. Product rework will be minimal and production flow will be smooth and synchronous with demand.

Prefab Construction Automation – A Quality and Functionality Issue

Technological advances to improve the quality of a product in terms of its function, is critical. Forward thinking on how the prefab product of the future will look and behave gives good insight. Prefab modules and buildings will adopt a systems integration approach to design, engineering and construction. The building envelope systems (roof, wall, floor, etc.) will maximize integrated performance. Builders will incorporate fully integrated structural systems that can resist the forces applied during component/module transport and site installation. It will develop new assemblies and sub-assemblies that improve performance that could be applied with ease in a factory setting. It will integrate plumbing and mechanical systems within the whole module, and will include new wiring and cabling systems that optimize whole-building performance. It will also incorporate functions that wired and wireless technologies and systems can offer. It will identify the reasons for material failures and/or systems linking to manufacturing and/or installation problems. It will develop new production, installation and joining (ie: fasteners, joints, etc.) techniques, and new designs to minimize failures. A virtual and simulation environment that supports the design of prefab components and their assembly, and simulating the construction to suit schedule will become the standard practice. The simulation environment likely will utilize a library of 3-D models of the prefab modules that can be used to interactively design the whole building. The design and operation of the building will promote and contribute to the health of its occupants. Buildings will have deployed methods for controlling sources of contamination, techniques for improving ventilation, and systems & procedures for controlling moisture. It will develop and deploy new and existing energy conservation and renewable energy technologies and strategies. The built environments will be the most energy efficient, and annual energy costs of these units will be low, or perhaps even lower than comparable site-built structures.

References

[1] Benjaoran, V.; Dawood, N (2006) "Intelligent approach to prod. planning system for bespoke precast concrete products", Automation in Construction 15, pp 737 – 745.

[2] Bock, T. (2004) "Construction robotics and automation: past-present-future", World Automation Congress, Proceedings June 28 2004-July 1, 2004.

[3] Bock, T (2006), Tech. University Munich, http://www.iaarc.org/external/isarc2006-cd/www/ISARC2006/00174_200606072132.pdf

[4] Bock, T (2007) "Construction robotics", Auton Robot (2007) 22:201–209

[5] Bowden, S., Dorr, A., Thorpe, T., and Anumba, C. (2006). "Mobile ICT support for construction process improvement." *Automation in Construction*, 15, 664–676.

[6] Chan, W.T.; Zeng, Z. (2003) "Coordinated Production Scheduling of Prefabricated Building Components", Construction Research, Winds of Change: Integration and Innovation of Construction.

[7] Diez, R, Padrón, V. M., Abderrahim, M, Balaguer, C (2007) "AUTMOD3: The Integration of Design and Planning Tools for Automatic Modular Construction", International Journal of Advanced Robotic Systems, Vol. 4, No. 4.

[8] Gajamani, G.K.; Varghese, K. (2007) "Automated Project Schedule and Inventory Monitoring using RFID", 24th International Symposium on Automation in Robotics in Construction – ISARC 2007.

[9] Ganeshan R., and Harrison T. P. (1995), Penn State University "An Introduction to Supply Chain Management".http://lcm.csa.iisc.ernet.in/scm/supply_chain_intro.html.

[10] Hu, W (2005) "Automatic Construction Process of Prefabricated Buildings on Geometric Reasoning", Proc: Construction Research Congress, San Diego USA.

[11] Lee, K.Y; Lee, S.Y; Choi, J.H; Lee, S.H; Han, C.S. (2006) "The application of the human-robot cooperative system for construction robot manipulating and installing heavy materials", SICE-ICASE International Joint Conference, Busan, Korea.

[12] Leu, S.S.; Hwang, S.T. (2002) "GA-based resource-constrained flow-shop model for mixed precast production", Automation in Construction 11, pp 439– 452

[13] Li, H.; Huang, T.; C.W. Kong, H.L. Guo; Baldwin, A.; Chan, N.; Wong, J. (2008); "Integrating design and construction through virtual prototyping", Automation in Construction 17, pp 915–922.

[14] Martinez, S; Jardon, A.; Navarro, J.M; Gonzalez, P. (2008) "Building industrialization: robotized assembly of modular products", Assembly Automation, Vol. 28, No. 2, pp 134–142.

[15] Mullens, M.A. (2004) "Production Flow and Shop Floor Control: Structuring the Modular Factory for Custom Homebuilding", www.pathnet.org/si.asp?id=1064

[16] Murray, N.; Fernando, T.; Aouad, G. (2003) "A Virtual Environment for the Design and Simulated Construction of Prefabricated Buildings", Virtual Reality 6:2 44–256, Springer-Verlag London Ltd.

[17] Nasereddin, M; Mullens, M.A.; Cope, D. (2007) "Automated simulator development: A strategy for modeling modular housing", Automation in Construction 16, 212–223

[18] Navon R., and Berkovich O. (2005) "Development and on-site evaluation of an auto. material management and control model", Journal of Const. Engg and Management.

[19] Pastor, J. M.; Balaguer, C; Rodriguez, F.J.; Diez, R. (2001), "Computer-Aided Architectural Design Oriented to Robotized Facade Panels Manufacturing", Computer-Aided Civil and Infrastructure Engineering, Vol 16, No. 3, pp. 216-227

[20] Peñin, L.F.; Balaguer, C.; Pastor, J.M. .; Rodríguez, F.J.; Barrientos, A.; Aracil, R. (1998) "robotized spraying cell of prefabricated panels in Construction industry", IEEE Robotics & Automation Magazine, Vol. 5. No. 3. pp.18-29.

[21] Staub-French, S., and Khanzod, A. (2007). "3D and 4D Modeling for Design and Construction Coordination: Issues and Lessons Learned", ITcon Vol. 12

[22] Wakisaka, T.; Furuya, N.; Inoue, Y.; Shiokawa, T. (2000) "Auto construction system for high-rise reinforced concrete buildings", Automation in Construction 9, 229–250.

[23] Westkamper E; Schraft, D.D; Laier, P. (2000) "Robot System for Automated Tiling on Prefabricated construction Elements", 31st Symposium on Robotics (ISR 2000).

[24] Whyte, J (2003) "industrial applications of virtual reality in architecture and construction", http://www.itcon.org/2003/4.

[25] Wing, R, Atkin, B. (2002) "FutureHome: A Prototype for Factory Housing", International Symposium on Automation and Robotics in Construction, 173-178 pp.

[26] Xue, X., Li, X., Shen, Q., and Wang, Y. (2005) "An agent-based framework for supply chain coordination construction", Automation in Construction 14, 413– 430.

[27] Yerrapathruni, S., Messner, J I., Baratta AJ., and Horman MJ. (2003) "Using 4D CAD and Immersive Virtual Environments to Improve Construction Planning" Construction and Virtual Reality conference CONVR 2003, USA.

[28] Zied, K. (2007) "An Augmented Framework for Practical Development of Construction Robots", International Journal of Advanced Robotic Systems, Vol. 4, No. 4, ISSN 1729‑8806, pp. 477‑500.

[29] http://images.autodesk.com/adsk/files/bim_parametric_building_modeling_jan07_1_.pdf - AutoDesk, Parametric building modeling: BIM's foundation, (2007)

[30] Consultant Report (restricted) - Altus Clayton (2008) "The Use of Prefabrication and Modularization in the Construction Industry".

[31] http://www.manubuild.org/downloads (2007)

[32] Manufactured Housing Research Alliance, (2003) "Technology Road Mapping for Manufactured Housing", March 2003.

[33] McGraw_Hill Construction (2007), Interoperability in the construction industry, SmartMarket Report, Interoperability Issue.

[34] "Quick Guide to Construction automation and robotics", http://adaptablehouse.vtt.fi/files/technology/robotics.doc.