

TECHNOLOGY DEVELOPMENT IN CONSTRUCTION: A CONTINUUM FROM DISTANT PAST INTO THE FUTURE

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Received 30 Nov. 2012; accepted 03 Dec. 2012

Abstract. This paper deals with the historical and current trends in the development of civil engineering and construction technologies. The authors demonstrate the continuity of creative thought and effort among early master builders and technology developers throughout the history of civilizations that created the most iconic structures remaining in the world heritage of the built environment to the contemporary times. Recent concepts and ongoing efforts in the development of advanced construction technologies based on automation and information sciences, materials science and systems engineering are highlighted in the context of historical ideas and achievements of past architects and construction engineers of the past century.

Keywords: civil engineering, construction technology, creativity, technology perspective.

1. Introduction

Technology is the making, modification, usage, and knowledge of tools, machines, techniques, crafts, systems, methods of organization, in order to solve a problem, improve a preexisting solution to a problem, achieve a goal or perform a specific function. It can also refer to the collection of such tools, machinery, modifications, arrangements and procedures. Technologies significantly affect human as well as animal species' ability to control and adapt to their natural environments (Wikipedia 2012). Technology plays an important role in the *science* → *technology* → *production* → *economy* chain (Fig. 1).

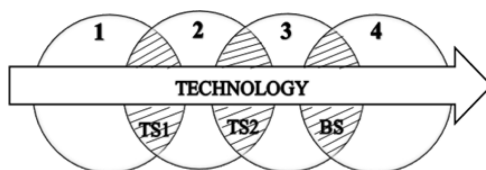


Fig. 1. Location of technology in the production chain of science-technique-trade-economics. TS-1 – technological sciences, TS-2 – technological systems, BS – business systems: 1 – science, 2 – technique, 3 – production, 4 – economics

Technology, as a scientific discipline, is determined to be transmission between the production and the fundamental sciences. Technology of construction processes analyses the separate elements of construction production (Fig. 2). The main objectives of technological sciences in the realm of construction are as follows:

- Systems-oriented analysis of construction processes with aspiration to determine their main components and relationships;
- Development of standard construction processes to be emulated throughout the industry;
- Research-based compilation of data for use in technology standards, directories and databases.

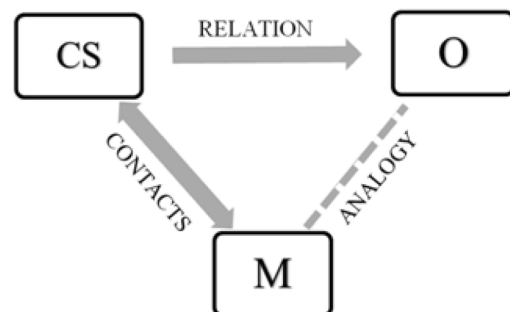


Fig. 2. The principal scheme of construction process modeling. CS – cybernetic system, O – object, M – model

A typical feature of most if not all construction technologies is their implementation of achievements originating from different scientific disciplines. The modelling of construction process is one prominent example of this fact (Fig. 3). The main components of the model are: pre-construction/ preparation processes (PP), construction site processes (CP) and management of the construction process (MP) (Fig. 4) (Fiedler *et al.* 1981).

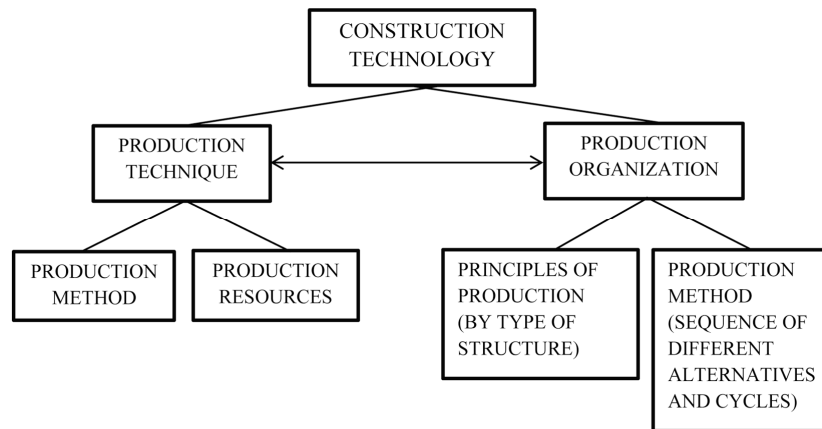


Fig. 3. Research objectives related to construction processes (technology)

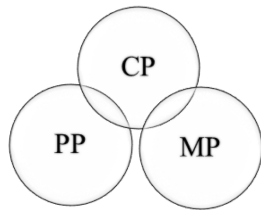


Fig. 4. Modeling components of construction technological processes: PP – pre-construction/ preparation processes, CP – construction processes, MP – management processes

Future development of construction technologies depends on the most pressing needs of sustainable built environment, economic and business fragmentation constraints characteristic for the construction industry, and the need to increase productivity and safety of construction workers. A systematic approach to the prediction of future trends has been provided by Zavadskas *et al.* (2007).

2. Creativity and Technology

What is creativity? According to a popular reference article, the term “refers to the invention or origination of any new thing (a product, solution, artwork, literary work, etc.) that has value. “New” may refer to the individual creator or the society or domain within which novelty occurs. “Valuable”, similarly, may be defined in a variety of ways. The range of scholarly interest in creativity includes a multitude of definitions and approaches involving [...] *psychology, cognitive science, education, philosophy (particularly philosophy of science), technology, theology, sociology, linguistics, business studies and economics*, taking in the relationship between creativity and general intelligence, mental and neurological processes associated with creativity, the relationships between personality type and creative ability and between creativity and mental health, the potential for fostering creativity through education and training, especially as augmented by technology, and the application of creative resources [...]” (Wikipedia 2012).

There are over 200 scientific descriptions of the process of human creativity due to the numerous aspects, domains and manifestations of this attribute. The role of creative minds in the construction industry will be of vital importance in the future, as this industry is most often the

largest contributor to the national economies of almost all developed nations and beyond (Langford, Dimitrijević 2002).

In construction, creativity has been associated in history in a large part with the intellectual and organizational capacities of the ‘master builder’ (Skibniewski 2012). Creativity remains unrealized unless it leads to the act of innovation. As construction knowledge, technology and experience progressed through the ages in the realization of major construction projects, various project-related specialties emerged: architects, building technicians and engineers, project sponsors and financiers, material and equipment suppliers, labor organizers, etc. This has often led to creative tensions among numerous project participants which either stimulated or hampered construction creativity and innovation.

As of 23 November 2012, more than 1200 scholarly papers related to the topic of “Technology & Creativity” can be found in the Thomson Reuters Web of Science database (Fig. 5). However, the number of related publications dealing with “civil engineering” and “construction and building technology” amounts to only several dozen. A sample of interesting examples of such papers is presented in Table 1.

3. Historical Retrospective

Construction is undoubtedly a product of human creativity which experienced its ‘peaks and valleys’ over the centuries. Building technologies and trades developed at first, most likely in ancient Mesopotamia (in the Tigris-Euphrates river system), dating back to year 3600 BC. According to Sumerian mythology, the Mesopotamians regarded the craft of building as a divine gift taught to men by the gods. *Ziggurats*, pyramid-like structures of that civilization, remain to this day in today’s Iraq. Similarly, ancient Chinese construction methods, utilizing both stone and timber, are as old as the Chinese civilization, dating back approximately to year 4000 BC. The Chinese were using elaborate wall-building techniques since approximately year 800 BC, culminating in the Great Wall of China built over an extraordinarily long period of approximately 2000 years. Ancient Egyptian pyramids of Giza, whose construction lasted only approximately 20 years and concluded in approximately year

2560 BC, were initially 147 meters in height and remained the tallest man-made structures for over 3800 years. The exact means and methods of their construction, ranging from ancient forms of *in situ* processes to those partially resembling offsite prefabrication, are subject to protracted speculations to date among archeologists and historians of technology. Ancient Maya construction of Central America, featuring ceremonial platforms, palaces, pyramids, temples, observatories and ball-courts had intricate carved stones and stair-step design, spanning a vast period of several thousands of years. Elaborate building methods were developed to include massive substructures made of stucco and cut stone interior, providing a solid foundation for the ensuing superstructures. External aesthetics took precedence over utility of many of these structures, as their purpose was

typically both religious and lay. Ancient Inca architecture in pre-Columbian South America featured in Cuzco and at the royal estate of Machu Picchu dates back to the 2nd century BC and has not been emulated for several centuries following the Spanish conquest and subsequent destruction of this civilization.

Ancient Greece and ancient Roman Empire borrowed a number of building techniques from the preceding civilizations while also developing unique techniques and architectural styles of their own, characterized by numerous temples, palaces and other public and private buildings, as well as world-renown structures such as *Parthenon* in Athens or *Colosseo* stadium in Rome. Construction techniques of parabolic stone arches subjected to compression forces only, with no bending moments, and the design and construction of elevated municipal

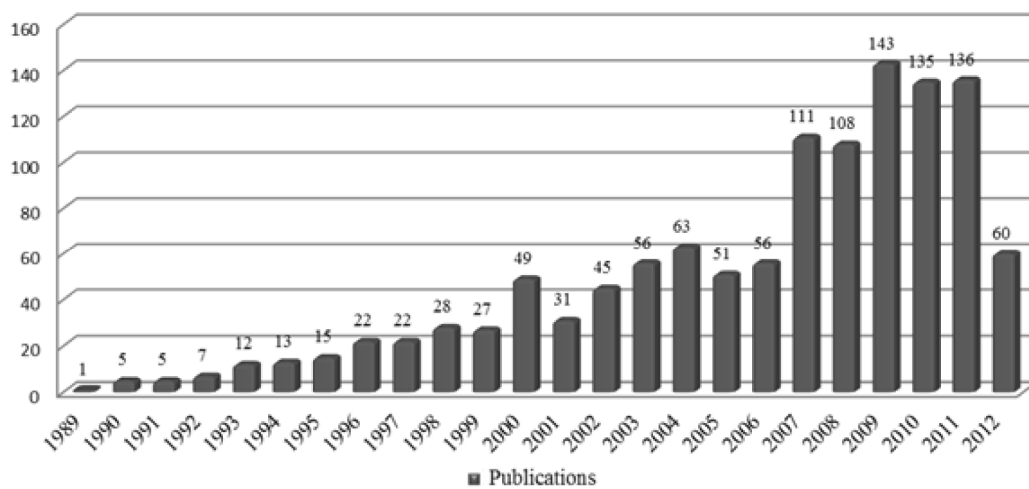


Fig. 5. Number of publications on the topic technology and creativity

Table 1. Sample publications on creativity and technology in civil engineering and construction

Reference	Main topic
Noor 2011	Intelligent adaptive Cyber-Physical Ecosystem
Ibrahim <i>et al.</i> 2010	Comparison CAD and manual sketching tools for teaching architectural design
Lainez <i>et al.</i> 2009	The Key-role of Eladio Dieste for Brickwork to Architectural design
Kicinger <i>et al.</i> 2005	Evolutionary computation and structural design
Srdic, Šelih 2011	Integrated quality and sustainability assessment
Peldschus, Zavadskas 2012	Equilibrium approaches for construction processes
Barrow 2006	Ideation and CAD/CAM
Holland 2006	Virtual school of architecture and design
Fan 2009	Exploration and Practice in Design
Negoescu, Axinte 2007	Engineering for strategic advantages
Seghedini 2007	Combinatorics in technical creation
Allen, Self 2008	Analysis of the integration of knowledge
Mackechnie, Buchanan 2012	Creative Laboratory Model for Large Undergraduate Engineering Classes
Zheng <i>et al.</i> 2011	Impact of Nanotechnology on Future Civil Engineering Practice
Brühwiler 2011	New Swiss Codes for engineering
Mashood <i>et al.</i> 2007	KB-GA-Based Hybrid System for Layout Planning
Ediz, Cagdas 2007	Computational Architectural Design Model
Sarrade <i>et al.</i> 2007	The GENHEPI Concept
Kaklauskas <i>et al.</i> 2011	Integrated model and system for passive houses
Zavadskas <i>et al.</i> 2011	Intelligent library and tutoring system at all stages of a building life cycle
Banaitienė <i>et al.</i> 2008	Evaluating the life cycle of a building

and rural aqueducts resulted in great architectural accomplishments existing in southern and Western Europe to the present day. The following European era of the Middle Ages, which lasted longer than all of the subsequent cultural periods combined, resulted in splendid Romanesque and Gothic architecture demanding new projects, undertaken both with the use of proven construction techniques from the bygone eras and new materials and techniques, including the production and implementation of building glass and an apparent use of organic mortars for stone masonry.

4. Linking the Present to the Past

The invention of Portland cement and the production of concrete revolutionized the use of construction materials and techniques and the ensuing construction methods dominate to this day. There is some historical evidence that this technology dates back to the ancient Romans and was used in the Roman Empire, e.g. for construction of the Roman Pantheon (Mukerji 2005). However, with the demise of that empire, the use of concrete was abandoned and almost forgotten, until its re-invention and slow re-emergence from the 18th century AD onwards. Currently the tallest building in the world, *Burj Khalifa* in Dubai (828 meters tall) is built with the use of this material.

Ingenuous creativity of construction craftsmen was exhibited throughout all of the architectural styles constituting the architectural and building engineering history of the last three centuries. Examples of ingenuity are too numerous to enumerate in a short presentation; it should suffice to mention the historically, technically, and artistically diverse select, short list of geniuses of Apollodorus of Damascus (2nd century AD), Abbot Suger (12th century), Villard de Honnecourt (13th century), Filippo Calendario (14th century), Leonardo da Vinci (15–16th centuries), Raphael Santi (16th century), Gianlorenzo Bernini (17th century), Nicolai Eigtved (aka Niels Madsen) and Domenico Merlini (18th century), Bela Lajta and Adolf Lang (19th–20th centuries), Frank Lloyd Wright (early 20th century), Renzo Piano (20th–21st centuries), Zygmunt Skibniewski (20th century), Frank Gehry (20th–21st centuries), and many others.

More than 20,541 scholarly papers published to date deal with the development of technology. The number of such publications is ever increasing (Figs 6 and 7). However, the number publications devoted to the subject of “civil engineering” or “construction and building technology” is only slightly more than 250, or about one per cent of the total. Several new examples of such publications are presented in Table 2.

More than 4,092 scholarly publications are devoted to future technological developments (Web of Knowledge - Web of Science, 12/11/2012) (Fig. 8). In the same realm, the number of publications dealing with development of construction technologies is only 130 (Fig. 9). Some of the latest such publications are presented in Table 3.

A new impetus to creativity in construction, and particularly to large earthwork projects and to tall buildings, was the progress of construction mechanization

Table 2. Publications in Web of Science by topic: technology perspective

Reference	Topic addressed
Yang <i>et al.</i> 2012	Web-based evaluation system housing
Arslan 2012	Web-Based Contractor Evaluation System for Mass-Housing Projects
Boukhatem <i>et al.</i> 2011	Application of new information technology on concrete
Podvezko <i>et al.</i> 2010	Complex evaluation of contracts for construction
Radziszewska-Zielina 2010	Selecting the best partner construction enterprise in terms of partnering relations
Zhang, Hu 2011	BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction
Dejus 2011	Safety of technological projects
Lee <i>et al.</i> 2012	A BIM- and sensor-based tower crane navigation system
Chow <i>et al.</i> 2012	Catastrophe model of withdrawal in construction project dispute negotiation
Razavi, Haas 2012	A Reliability-Based Hybrid Data Fusion Method for Adaptive Location Estimation in Construction
Hartmann 2011	Project Teams
AbouRizk <i>et al.</i> 2011	Construction Engineering Operations

Table 3. Examples of latest publications, topic: technology possible way

Reference	Considered problem
Clements-Crowne 2011	Sustainable intelligent buildings
Ghaffarian Hoseini 2012	Ecologically sustainable design
Bhatla <i>et al.</i> 2012	Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras
Promis <i>et al.</i> 2012	Effect of post-tensioning on the bending behavior
Gong <i>et al.</i> 2012	GPS/GIS method for travel mode detection in New York City
Zalama <i>et al.</i> 2011	An Effective Texture Mapping Approach for 3D Models Obtained
Chu <i>et al.</i> 2011	Development of Microbial Geotechnology
Marti <i>et al.</i> 2010	A multi-agent system for managing adverse weather situations
Bayart <i>et al.</i> 2010	A Framework for Assessing Off-Stream Freshwater
Yang, Lin 2011	Coastal Reservoir by Soft-Dam and its Possible Applications

spurred by the invention of steam engine. Much of such equipment has been preserved to this day, thanks to the efforts of the Historical Construction Equipment Association (Historical Construction Equipment Association 2012) based in Ohio, USA. A revolution in construction equipment was started with the invention of hydraulic pistons for the transmission of large forces. This led to a series of highly successful designs of the new types of

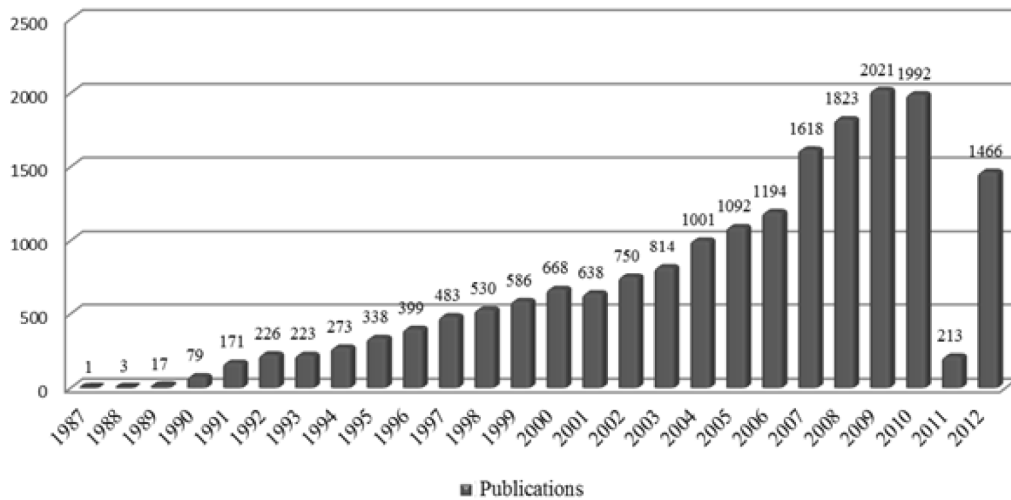


Fig. 6. Publications in Web of Science on topic: technology perspective

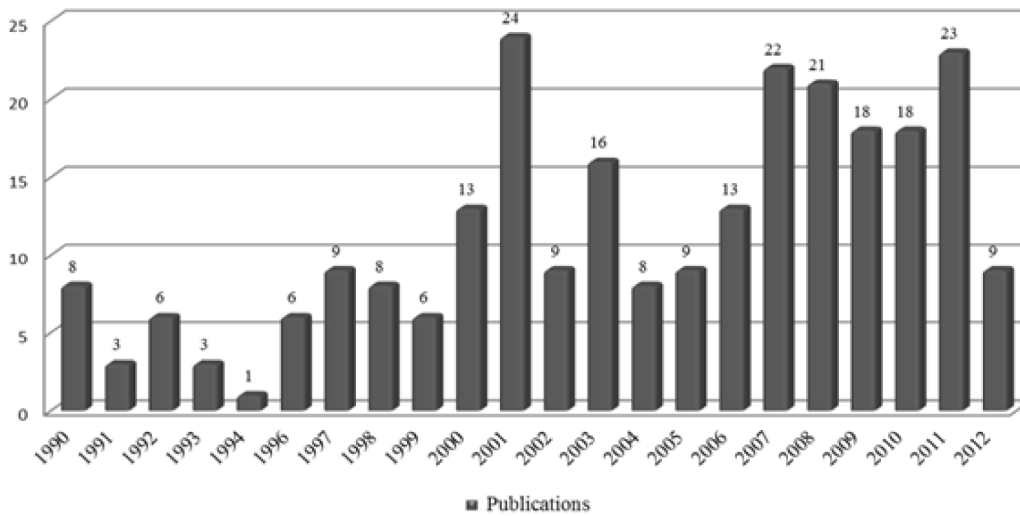


Fig. 7. Publications by topics: technology perspective (science categories – engineering civil or construction building technology)

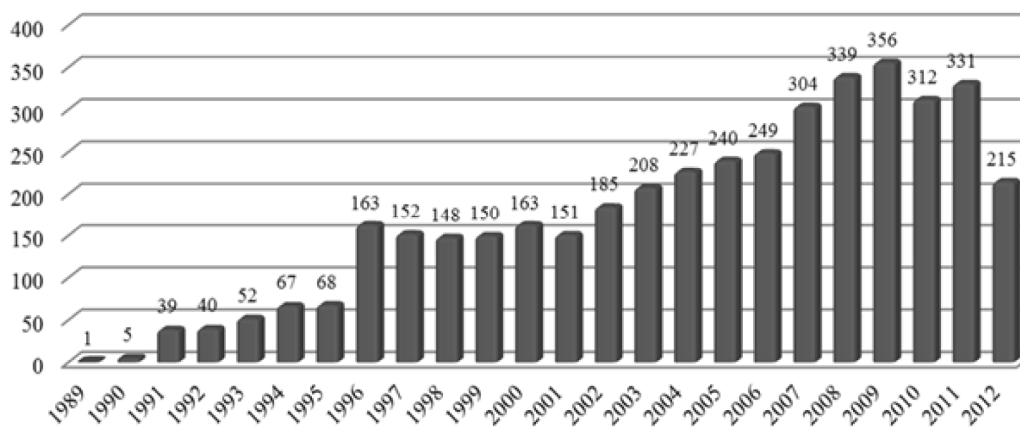


Fig. 8. Publications by topic: technology possible way

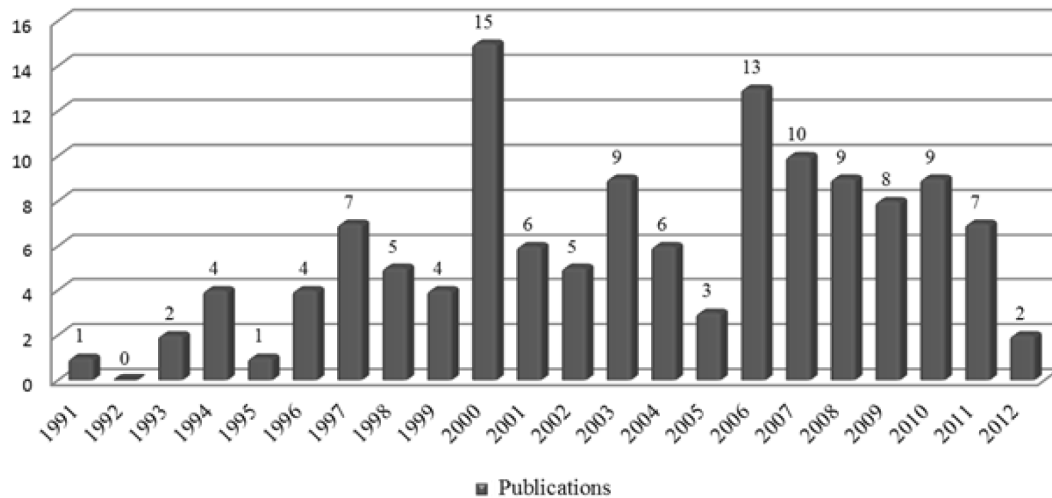


Fig. 9. Number of publications by topic: technology possible way (science categories: construction technology or civil engineering)

earthmoving equipment, surface finishing tools, and all terrain telescopic boom cranes (Skibniewski 1988a). What followed years later are improved equipment controls, intelligent sensors, laser-based telemetry and global positioning systems that led to marked improvement in the quality and productivity to many types of earthwork and allied construction tasks (Skibniewski 1993). Subsequently, construction robotics were designed and prototyped, initially in the early 1970's in the former Soviet Union on commission from the former Soviet armed forces (Springer Handbook of Mechanical Engineering 2009) (e.g. Dr. G. Frenkel at Moscow State University of Civil Engineering, formerly Moscow Civil Engineering Institute) and at VNIISTROYDORMASH), then in the late 1970's and early 1980's in Japan (Prof. Y. Hasegawa at Waseda University's Systems Science Institute, followed by several construction firms such as Obayashi, Shimizu, Kajima, Takenaka, Fujita, and others) and in the United States (Prof. W. Whittaker at Carnegie Mellon University's Field Robotics Center) (Haas *et al.* 1995). The idea was not entirely new, as already in 1910

a French artist Villemard produced a postcard illustration depicting his vision of a construction site in the year 2000, see Fig. 10 (BLDG BLOG 2011). International Association for Automation and Robotics in Construction (IAARC) (International Association for Automation and Robotics in Construction 2012) was created in 1993, continuing to organize annual symposia on this subject held around the world since 1984. (2012 and 2013 International Symposia on Automation and Robotics in Construction 2012). In its early years of existence, IAARC members unknowingly shared Villemard's early vision that robotics will become commonplace on construction project sites in the developed economies by the year 2000, which has not materialized not because of the lack of technical capabilities to implement them, but mainly due to the protracted economic crisis in Japan which led the development of robotic prototypes and automated systems for construction sites between in the 1980's and 1990's, and the persisting fragmentation of the industry in the United States and western Europe in their methods of the delivery of projects (Skibniewski 1988b).

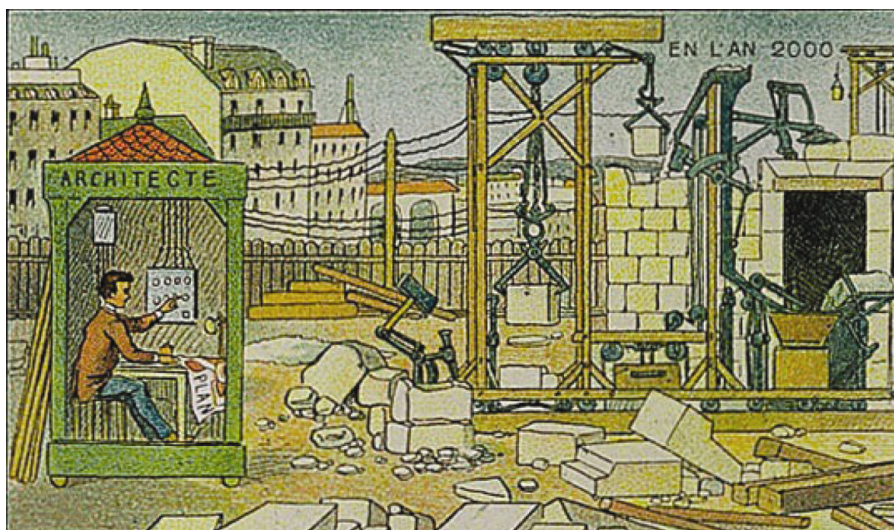


Fig. 10. Villemard's 1910 vision of a robot on a building construction site

Tall building construction presented yet another set of challenges to construction creativity, particularly related to vertical transport (National Institute of Building Science 2012) elevator technologies available today widely employ artificial intelligence and fuzzy-set-based controls to automate and optimize vertical transport of materials and people. This, combined with significant improvements in lifting crane equipment and operations, has led to increased efficiency, safety and improved productivity on the construction site, although accidents in this type of essential construction work as still relatively common (Crane Accidents 2012) There is a need redesign of many construction tasks based on sound ergonomic principles and aimed at further mechanization and automation of tasks that are simple, repetitive and inherently dangerous (Russell, Skibniewski 1990).

Recent advances in the implementation rapid prototyping, construction process simulation and accelerated implementation of Building Information Modeling (BIM) technologies are on their way to transforming building construction and allied project-based professions serving the construction industry (Building SMART International Ltd 2012; National Institute of Building Sciences 2012; Zavadskas 1991; Kanapeckiene *et al.* 2011; Zavadskas *et al.* 1995, 1994; Zavadskas, Kaklauskas 2007; Popov *et al.* 2010; Skibniewski, Jang 2009).

5. Innovation Environment in Construction Technology and Possible Way Forward

Innovation in construction project management benefitted much from the early advances in computational science and information technologies dating back to the late 19th century, particularly from work flow and networking techniques leading to improved project scheduling (Marsh 1975; Hajdu 1997). Program management to reshape the future built environment (Kaklauskas, Zavadskas 2009), particularly that of 21st cities, will depend on our ability to implement the latest advances of information and automation technologies in an integrated manner (Skibniewski *et al.* 1997; Sawaf, Skibniewski 2011; Kaklauskas *et al.* 2010, 2011, 2012; Zavadskas 2010).

Decision making will play a crucial role in construction management. Multi-Criteria Decision Making (MCDM) (Koksolan *et al.* 2011) is a sub-discipline of operations research that explicitly considers multiple criteria in decision-making environments, which can help the stakeholders: (a) assess the current situation, (b) find satisfactory solutions, and (c) take appropriate responses taking into account a set of objectives and criteria, that can be conflicting, multidimensional, incommensurable and incomparable. MCDM involves diverse methods leading to the prototyping and implementation of decision aid tools (Skibniewski, Chao 1992; Zavadskas *et al.* 1994, 2011; Yu, Skibniewski 1999; Zavadskas, Turskis 2011; Jiang *et al.* 2012; Bitarafan *et al.* 2012; Nieto-Morote, Ruz-Vila 2012).

It is widely acknowledged that the main barrier to an increased pace of innovation in construction is the fragmentation of this industry initiated in mid 1950's and

exacerbated throughout the remainder of the 20th century, creating adversarial and litigious project execution environments. Intense competition in most developed markets and the consequential low profit margins for construction contractors, designers and suppliers led to the commoditization of this industry. Additional severe challenges to the construction industries exist in the newly developing markets and in transition economies (Kocsis *et al.* 2011). Much of the process and quality improvement in construction utilizes proven management concepts from industries outside of construction (Tchidi *et al.* 2012). However, new project delivery systems such as Build-Operate-Transfer afforded an opportunity for new synergies among project owners, financiers, designers, constructors, suppliers and facility operators (Salman *et al.* 2007).

Supply chains in construction are being transformed thanks to implementation of successful ideas from retail trade industries (Li *et al.* 2008) and e-commerce platforms affording access to previously closed markets and increasing competitiveness among suppliers (Castro-Lacouture *et al.* 2007). Development of Internet-based collaboration tools, besides their overwhelmingly positive effect on project efficiency and productivity, created also a highly distributed construction project management environment (Nitithamyong, Skibniewski 2004; Urbana-viciene *et al.* 2009; Costa, Tavares 2012; Kaklauskas, Zavadskas 2002, 2010, 2012). Intelligent materials, distributed sensor systems and nanotechnology create new opportunities beyond the conventional solutions possible with traditional construction materials and systems (Mann 2006).

Schug and Watson of FMI argue for the need of construction innovation at three levels: tactical, operational and strategic (Schug, Watson 2012). They state that routine perspectives brought into construction from outside industries generate stimulation that drives innovation. Such innovation must be rewarded by recognition from industry peers (Construction Week Online 2012). All project participants should be made aware of their surroundings, enabling them to sense change and communicate the information to leaders of their organizations about technical and other related changes as seen from their perspective. Shared visions are essential to motivate and inspire construction organizations, propelling them to higher levels of creativity and innovation. Development of new skills, systems and strategic awareness creates a gradual change in attitude and behavior, resulting in improved organizational culture facilitating employee creativity. Changing the company culture to facilitate greater creativity takes time for most contractors due to organizational inertia and risk aversion created by the competitive and litigious work environment.

A number of organizations worldwide, such as Construction Industry Institute, (Construction Industry Institute 2012) FIATECH, (Fiatech 2012) Construction Innovation Forum, (The Construction Innovation Forum 2012) Building Smart Alliance, (The building SMART alliance 2012) and others strive to foster the culture of creativity and innovation in the construction industry

(Skibniewski, Chao 1992; Chao, Skibniewski 1995). Creativity unleashed by the use of innovative technologies can transform the entrenched relationships among project participants throughout the entire supply chain of this industry. This requires technology transfer from other branches of industry into construction and vice versa, (Skibniewski, Nof 1989; Pan *et al.* 2011; Kaklauskas, Zavadskas 2004) with a thorough technology feasibility evaluation prior to its implementation on construction sites (Gaultney *et al.* 1989; Jiang *et al.* 2012). Much of the current efforts focus on construction innovation aims at the challenges related to environmental sustainability and energy management in the built environment, (Kaklauskas *et al.* 2012; Zavadskas *et al.* 2008; Turskis *et al.* 2012) safety improvement, (Cheng, Teizer 2011) and productivity enhancement (Chao, Skibniewski 1994; Liao *et al.* 2012; Zavadskas, Vaidogas 2009). This trend, in addition to creativity manifestations in new architectural forms, is likely to continue well into the future, particularly over growing environmental protection concerns and sustainability of the current economic systems in the remainder of the 21st century.

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