FUTURE DEVELOPMENTS OF ICT IN THE BUILDING SECTOR

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ABSTRACT: Developments in information and communication technology have an impact throughout the entire life cycle of a building, not only from the process and technical point of view but also from the creative design point of view. As a result of developments of advanced modelling software for architectural design, the gap between what the architect can envision and what the building technician or product architect can materialise is enlarging. Future developments in information and communication technology may help to narrow this gap. Internet technology will provide a closer link between the participants in the building process, their activities, knowledge, and information. Support software for the building designer will become object-oriented and tools will be integrated and be able to communicate with each other. Soft computing techniques such as artificial neural networks, fuzzy logic, and genetic algorithms will make contributions to the problem solving aspects of the design process. This paper provides an overview of these and other future developments of information and communication technology within the building sector.

KEYWORDS: building process, information and communication technology, object-oriented, decision support, advanced modelling, collaborative engineering, artificial intelligence

1. INTRODUCTION

In the last decade, the building sector has gradually seen the importance of Information and Communication Technology (ICT) developments for daily business. These developments impact the entire life cycle of a building, from initiative till demolition, and all aspects of the building process. When we look at the applications of ICT within the building process, we can distinguish four main categories of ICT use:

1. ***Creative design*** oriented ICT (applied in the conceptual design or inception phase)
2. ***Materialisation*** oriented ICT (building physics and building technology aspects such as calculating bearing structures and detailing)
3. ***Realisation*** oriented ICT
4. ***Process and management*** oriented ICT (linking the first three categories or activities)

When computers were first introduced in the building sector, these initial applications mainly concerned administrative tasks. Gradually their functionality has been extended to support repetitive tasks; nowadays, software applications are becoming essential tools for *creative* design, for *materialization* (building technical aspects), and also for the *management* of the entire building process. Already, for many architects, such as Peter Eisenman and Frank Gehry, the employment of computational programs is an instrumental, if indispensable, means, even if it holds no explanatory power over the results (Forster, 1996).

2. THE ROLE OF ICT IN THE DESIGN PROCESS

When we look at the role of the designer in the building process, we see that as a professional she has to deal with three main categories of sciences, sometimes called *alpha*, *beta,* and *gamma* sciences. Alpha sciences deal with the subjective world of beauty and moral, as expressed by the artistic, intuitive soul. Beta sciences bring in the objective world of facts and logic, represented by the rational mind. Gamma sciences consider the interest of the society and culture. The integration of these sciences makes the task of the designer more complex, but also extra-ordinary and unique. This means that the designer must have the skills to integrate the various disciplines of knowledge, involving besides the artistic form expression of the building also the dimensioning of the structure, building physics, applied mechanics, the calculation of structures, building materials and techniques, etc. The most famous designers, such as Santiago Calatrava, are the ones who have the ability to combine these various disciplines in their designs as architect and building engineer at the same time.

Technological developments have had remarkable influences on how people build and design. In the architectural practice, the old craftsmanship has been complemented with a new craftsmanship, in which the knowledge used in the architectural design process is coupled with the machine. Developments in ICT have been used to improve the quality and efficiency of the design process. However, computers have entered architectural design offices much later compared to other engineering disciplines. At the same time, the first CAD applications were mainly developed for other engineering disciplines such as mechanical engineering and aerospace engineering. Only later did the architectural community also recognize the power of these tools and adopt them, though initially only for two-dimensional drafting purposes.

Looking back at these historical developments, we can conclude that computers were first put into practice as a tool, as an instrument for achieving a specific result, whether to produce a final drawing, an animation, a simulation, or an interactive visualisation. Nowadays computers have taken on a slightly different role as a new medium besides the existing media within the architectural design process. Especially the widespread use of Internet and the developments of the Web have pushed the computer into the role of a medium. The tasks assigned to the computer however have more or less remained the same:

1. Information processing
2. Communication
3. Interactive Visualisation

In the very near future, we can expect another shift in the role of computers in the design and building process, namely, as a partner (Schmitt, 1999; Sarıyıldız *et al.*, 1998; McCullough, 1996). We are now at a stage that ICT allows us to develop new techniques and methodologies to use the computer as a partner by means of knowledge integration, decision support, and artificial intelligence. Decision support systems allow the computer to support the user through knowledge provided by experts or by the user herself. The computer can also be a partner when we teach it things it can reason with. It can even be a valuable and reliable friend when we let it solve problems that are not clearly defined, fuzzy, or uncertain. Here, artificial intelligence techniques such as fuzzy logic and neural networks play an important role. From this viewpoint we can add the following tasks, in addition to the ones above, where the computer can be seen as a partner:

4. Knowledge Integration
5. Decision Support
6. Design

Buildings are becoming more and more complex nowadays, not only in their form and functions, but also in their infrastructure: their techniques and communications. Naturally, the design process is also becoming more complex. It is complex in the sense that many, often conflicting, interests and criteria are involved, and that many different types of expertise are required to find an optimal solution. Additionally, there is the uncertainty of the future use of the building, requiring the meeting of new criteria that are not defined explicitly at the moment of design. That means that a designer must have the ability to meet a certain range of criteria in a flexible way so that future demands are also met to a certain degree. The outcome of the design process has to fulfil different requirements of functional, formal, and technical nature. These requirements concern aspects like usability, economics, quality of form and space, social aspects of architectural design, technical norms or laws, and technical and mechanical aspects of the design.

Building design is a multi-actor, multi-discipline, and multi-interest process. Design is a teamwork among architects, designers, and consultants for various fields, e.g., building physics, construction, material science, electrical engineering, acoustics, geotechnics, building economy, and environmental engineering. The process of decision making is often intuitive and based on experience. Tedious discussions may occur in committees where all or many of the criteria are represented. The resulting decision obviously is a compromise, but it is often unclear how the decision was reached and whether better solutions exist. In this respect, the ICT tools and their integration form an essential component in the *knowledge integration* process of the various disciplines. As such, they are increasingly becoming a valuable and, hopefully, reliable partner in the design process.

3. AN OBJECT ORIENTED APPROACH TO THE CREATIVE DESIGN PROCESS

In the *conceptual design phase* or *inception phase* we deal with the creative process of form finding. In this phase the architect starts by making a spatial perception of the design in her mind, then expresses these spatial ideas onto a medium, e.g., sketches, for reflection and communication to others, and for evaluation. When a computer is deployed in this phase, the machine serves as a means to render ideas directly into three-dimensional forms. Conventional techniques for three-dimensional spatial design include models, holograms, and red-green line drawings offering a three-dimensional impression. Computer software presents us with modellers, virtual reality, interactive walkthroughs, and cyber space. A primary condition for creativity to be present in the design process is the ability to express ideas of form unrestricted by medium or software. For this purpose, the software tool must be able to handle complexity and flexibility, enabling the designer to express her ideas in all their dimensions, while supporting creativity in reformulating forms and ideas.

The concept of an architectural design shows similarities with the real object, the building. The design process results in a virtual object that shares geometrical and morphological qualities with the physical object. As such, the design can be regarded and expressed in all its complexity as a conceptual object, computationally represented in an object-oriented way. However, such an object-oriented approach should never suppress the flexibility that is characteristic to the creative process. That is, the representational objects must be able to reformulate themselves, nut just on their own, but as a dynamic composition of objects that combine or dissolve in order to reflect on the designer's current interpretation (figure 1). In other words, the overall representational structure must borrow from a self-organizing system, adapting itself to the intentions of the designer at any time.

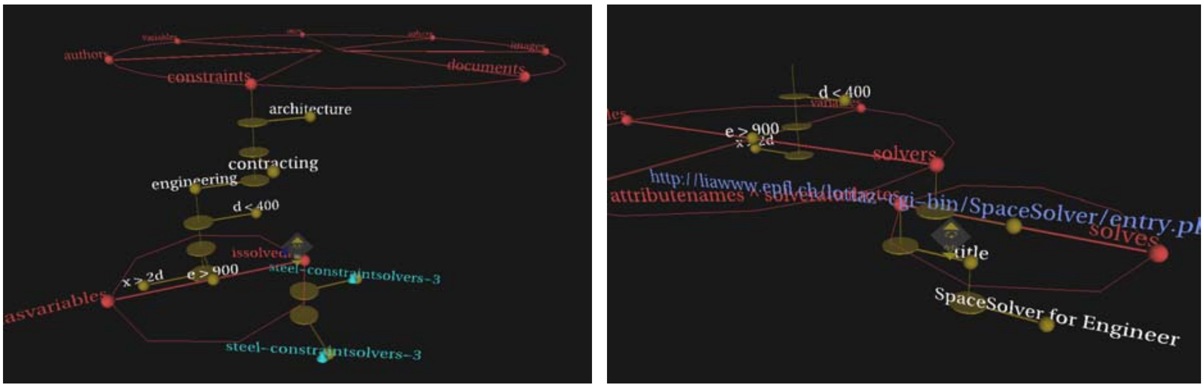

Figure 1. Alternative (re)presentations of a same structure: A constraint satisfaction problem from a hierarchical point of view and from a collaborator's view.

Such dynamic behaviour seems far removed from the conventional object-oriented approach and closer to an interpretation of elements as individuals (Leonard and Goodman, 1940). However, this coupling of the strength of a computational structure, on the one hand, and the fluidity of the mental image, on the other hand, is a prerequisite for capturing and supporting creativity in the computational design process: "Continuity of computation requires anticipation of the emergent shapes that are to be changed" (Krishnamurti and Stouffs, 1997). At the same time, a dynamic structure can overcome some of the limitations of current product models, in support of a representation of design artefacts with respect to different disciplines and throughout the entire life-cycle of the building (Stouffs and Krishnamurti, 1997).

4. DECISION SUPPORT TOOLS IN THE MATERIALISATION PHASE

Once the concept of a building has been determined, it must be materialised, that is, the geometrical model has to be transformed into components and materials. Here, questions arise as to which material, element, or detail best satisfy all the requirements regarding cost, aesthetics, physics of construction, applied mechanics, installations, dimensions of load-bearing structures, etc. A lot of ad hoc software exists to support such decision making for specific knowledge domains, e.g., building physics, lighting, calculation of structure, finite element methods. However, a lot less support is available for the integration of decisions made on various components or aspects, including the necessary negotiation when partial solutions conflict. During such negotiation it is entirely the responsibility of those involved to ensure consistency, to consider all important alternatives, and to inform each other of important justifications for decisions (Lottaz *et al.*, 2000). Furthermore, such justifications often do not find their way into the design or documentation, though their impact may weigh heavily on issues surfacing at later moments in the building process.

The greater part of knowledge required to make these decisions is expert or domain knowledge. This can be stored and made accessible by means of an expert system or knowledge based system, or plugged into specific tools for calculation and evaluation. There is also a need for integrated knowledge on a higher level embedded in design decision support tools that can assist the designing architect in a 'first step materialisation' (Sarıyıldız and Schwenck, 1996), or support communication and negotiation between architect, engineer, and contractor. Factors such as time and data losses during information exchange, misunderstandings because of ill-defined information, and iterative negotiation over integration conflicts, further complicate such collaboration. Much trouble is caused during negotiation due to the practice of participants suggesting only single solutions; ranges of possible values for variables are usually not determined. Instead, by using mathematical constraints for specifying requirements, computational tools can approximate the space for potential solutions, thus providing means to detect conflicts and to guide negotiation (Lottaz *et al.*, 2000).

Aside from decision support, there is also a need for databases of three-dimensional graphical building components to achieve a detailing system for materialisation (figure 2). Even the EU concedes that at a European level there is a need for building component databases that can be used for graphic information. Currently, manufacturers mainly provide two-dimensional graphic information on building products, if any, which is often the same information as present in paper catalogues. Its two-dimensional nature makes this information ill-suited for design, unless for inclusion in final production drawings. Research still needs to be carried out on the establishment of databases of building components that would link this information to three-dimensional object-oriented software.

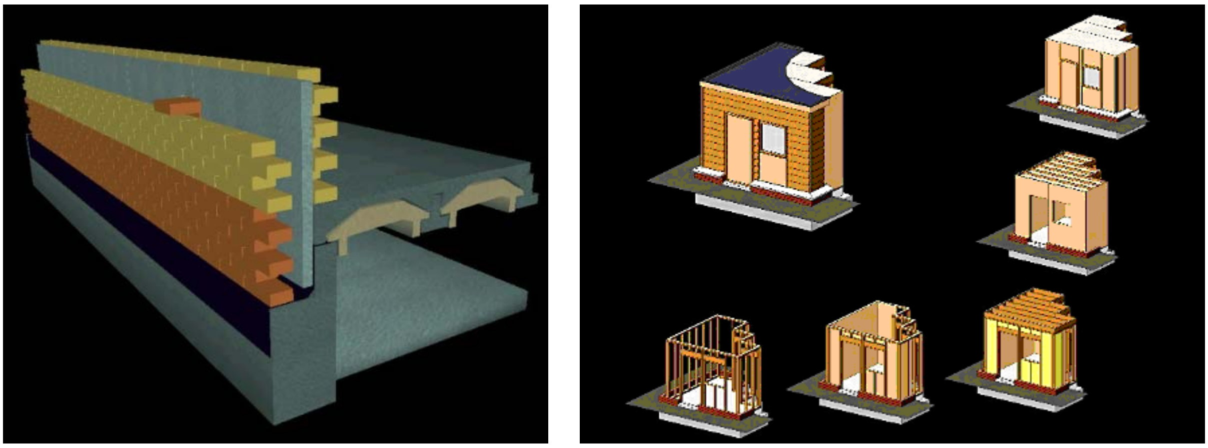

Figure 2. 3-D graphical information for inclusion in building component databases.

5. ADVANCED MODELLING SOFTWARE AND ITS IMPACT ON PRACTICE

As a result of developments in advanced modelling software, and its use for architectural design, the gap between what the architect or designer can envision on the one hand and what the building technician or product architect can materialise on the other hand is enlarging. The Guggenheim Museum (figure 3) in Bilbao, Spain, designed by the Frank Gehry, is a prime example. Designed using Catia, a modelling software first developed for the aerospace industry, it is a fact that the form of this design would be much more difficult to establish using traditional tools and methods of designing than using this or other advanced modelling software. With such tools, the architect is provided with a richer form vocabulary and more flexibility to realise her spatial ideas on the computer. Design software has reached a point where it can stimulate the designer's creativity rather than impeding it as has been argued in opposition to the use of CAD software. Also in Europe, we can see many architects who have adopted advanced modelling software for their creative design, such as Dutch architects Kas Oosterhuis and Lars Spuybroek (Schwartz, 1997).

Figure 3. Guggenheim Museum, Bilbao, Spain.

The developments in the field of building technology and building materials have not followed these advances in modelling software, such that they can no longer answer all the requirements and demands of the new architectural forms. ICT may play an important role in narrowing this gap. CAD/CAM already counts heavily in the realisation of such buildings as the Guggenheim Museum. Electronic form information is transferred directly from the design model to computer-controlled manufacturing machines, as in the case of stone cutting for a curved wall. Unlike straight or even cylindrical surfaces, free-formed surfaces cannot be composed simply of standardized components; potentially each element may be of different size. This strongly complicates the manufacturing process and causes astronomical costs. Numerically or computer-controlled equipment enables custom components to be produced at a lower cost. Connecting such equipment to the Internet such that these can be controlled directly from the design model further cuts cost. As custom manufacturing increasingly replaces standardized production, these costs will further decrease. Furthermore, as electronic catalogues are extended to include information on custom manufacturing techniques, possibly allowing designers to check manufacturability and price in the design phase, custom production will become more accessible and common.

6. COMMUNICATION AND COLLABORATION OVER THE INTERNET

As the Web and Internet technologies are filtering into every aspect of society, so will they have an enormous impact on the building practice. Already, architectural offices are using the Internet to communicate with partners across the globe, discussing their designs using whiteboard software and teleconferencing. As distances become smaller, architects are empowered to take on a global role. Examples already abound, such as the world's highest skyscraper in Kuala Lumpur, Malaysia, designed by Cesar Pelli Associates in the US. The use of Islamic geometric patterns in the design nevertheless shows a strong influence of the local culture.

Such global access requires new ways of managing the design process. Building projects are increasingly becoming teamwork, where no one person is solely responsible for a design. Well-defined control hierarchies and relationships are making place for more intricate collaborative processes that are not as easily planned and controlled. This requires an increasingly networked thinking that brings partners to closer interaction but, without appropriate computational support, impedes the ease of overview and understanding (Lottaz *et al.*, 2000). Web-based document management systems serve as media for the exchange of information between the collaborative partners and provide facilities for organizing, viewing, and redlining drawings and images (Roe, 1999). These systems can also serve the development and dissemination of tools that support specific needs and processes (Lottaz *et al.*, 2000), leading to integrated software environments as platform for various applications to communicate with each other over the Internet (figure 4).

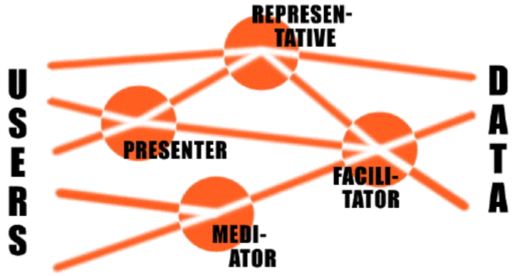

Figure 4. Four types of functionalities to support information processing in an integrated environment. Image by David Kurmann.

This evolution is founded on several universal Internet technologies, such as TCP/IP, HTML, Java, and XML. Using these technologies, it is pretty straightforward to create a Web application that runs on any platform. The role of XML is as a universal data interchange format among applications, freeing "Internet content from the browser in much the same way as Java frees program behaviour from the platform" (Johnson, 1999). XML also simplifies communication and improves agent technology (Tidwell, 1999). When exchanging XML-structured data, the only thing the partners need to agree on is the XML tag set used to represent the data. No other information about each other's systems is required. This makes it simple for new organizations to join an existing structure of data exchange. Similarly, XML-structured data makes it much easier for an agent to understand exactly what the data means and how it relates to other pieces of data it may already know, thereby easing one of the challenges when writing an agent, that is, to interpret the incoming information intelligently and respond to it accordingly. Another advantage to the use of XML for structuring data is that it can easily be applied to existing data and information, for the purpose of archiving or indexing such information. Unlike product model representations, XML structured data is easy for a human to read and understand, is flexible in its application, and can easily be applied for specific purposes (Tunçer and Stouffs, 2000).

Many disciplines are in the process of developing a framework for using the XML standard for electronic communications and data interchange in their domain (Cover, 2000), including the building industry (aecXML, 1999). Considering the complexity of building projects and the unstructured and interrelated nature of the project data, it is sure that the building community can benefit from a unifying strategy for data interchange. This will not only make the current data exchange and reuse practices more efficient, but will also result in great savings through streamlining the worldwide transactions in the Architecture, Engineering, and Construction (AEC) community.

7. THE IMPACT OF ARTIFICIAL INTELLIGENCE ON ICT ENHANCED BUILDING TECHNOLOGY

Design requires more comprehensive attention than ever before. This is mainly due to the fact that the building sector involves multi-dimensional aspects to be considered with conflicting criteria to be reconciled for optimal design solutions where cost effectiveness and efficiency are becoming dominant requirements, particularly in a hard competitive environment. In this respect, there is no doubt that the available building information must be used effectively, and

ICT can play a role in eliciting this information in a timely and exhaustive manner. Several emerging technologies have important relevance to the use of ICT in the building process and, ensuing, important implications. Various implications of these advances in communication technology have already been pointed out in the preceding sections. In particular, due to these advances, design information is now communicated over the Internet and a start is being made of storing information and knowledge in databases and knowledge bases, respectively. At the same time, the volume of information to be processed is exponentially growing.

As information and knowledge are being stored at a continuously growing pace, buried in gigabytes of records, these are becoming far less comprehensible. Faced with difficulties of retrieving them and making them available in an easily comprehensible format at higher levels of summarisation, this information becomes less and less useful. No human can use such data effectively and be able to understand the essential trends in order to make rational decisions. With reference to this phenomenon of overwhelming information, the emerging technologies of knowledge discovery and data mining offer a prospect of help. Knowledge discovery is inherently connected to databases: in an interaction with a database, a search for patterns or objects is performed, eliciting meaningful pieces of knowledge. Data mining provides the means or methods to attain this knowledge. Among the most promising methods for data mining are artificial neural networks, fuzzy logic, and heuristic search methods such as genetic algorithms. Collectively, these are referred to as soft computing methods; heuristic search methods are also referred to as evolutionary algorithms. Artificial neural networks are invoked toward processing numeric data and building non-linear relationships. Fuzzy sets concentrate on the representation of data at a nonnumeric level. The symbiotic cooperation of these two technologies results in an effect on the granularity of information.

These soft computing methods are receiving growing importance in almost every field, including building technology, though here at a relatively slower pace. Presumably, the basic reason for this is the difficulty of formulating building technological problems in a way that these become convenient for artificial neural treatment. However, these methods are especially important in the building sector, as they can handle information in various forms such as numerical specifications as well as linguistic qualifications, thus, information coming from all three alpha, beta, and gamma sciences. At present, a unified representation for artificial neural networks and fuzzy logic is already established (Jang et al., 1997). From this, it can be anticipated that the communication between building technology and soft computing technology will be much easier than before. This is due to the possibility of processing information at hand more human-like in the coming years than is achieved today. Currently, such information processing, in combination with knowledge base systems, is mostly introduced in the form of expert systems or decision support systems. So far, these are in most cases unsatisfactory. In the future, however, we can expect such computational intelligence systems to play an important role in decision-making support.

Intelligent systems are increasingly replacing conventional systems, as exemplified by intelligent manufacturing and intelligent design technologies. Some basic Artificial Intelligence (AI) fields associated with the emerging technologies connected to the developments of ICT are indicated in figure 5. In order to cope with the demands of information acquisition and information handling of these intelligent technologies, new methodologies and techniques are being developed. Besides knowledge discovery and data mining technology, agent technology is another example of such emerging software technologies. An agent is a software program designed for a specific purpose or functionality, that acts autonomously to some extent, and may be intelligent too (Jennings and Wooldridge, 1998). Agent technology is closely associated with ICT in the sense that agents are generally conceived for communication with other agents or software and for transmission to a distant computer if the task requires it. The Internet allows this distant computer to be any machine on the globe. Agents are especially promising for mining databases as they act autonomously. As an example, a fuzzy engineering agent can interact with a building design database in order to identify various trends of engineering or architectural nature. In connection with virtual reality (VR), agents can assist in design by providing sufficiently realistic feedback early in the design process. This should ease the early integration of design components, in particular, in collaborative design (Abarbanel *et al.*, 1997). Especially for collaborative design, agents have an important role to play to assist participants in their task or communication, or to offer additional functionality in project-management applications (Stouffs *et al.*, 1998).

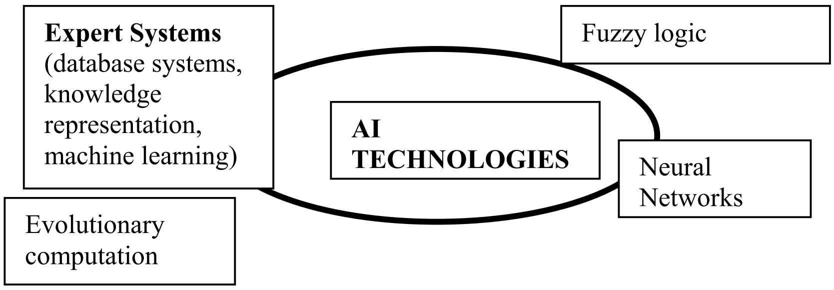

Figure 5. Some basic AI fields of importance to ICT developments with impact on building technology.

Here, it is important to point out that alongside the advancements of intelligent systems, also software is inevitably getting more intelligent, especially in the form of agents and the associated technology. Therefore, soft computing technology, together with agent technology, is going to play an increasing role in ITC enhanced intelligent design and it is to be anticipated that they will provide substantial contributions in the problem solving tasks of architectural and building design processes.

8. FUTURE ICT TOOLS FOR THE BUILDING SECTOR?

We are still dealing with the material world for which ICT is highly appropriate. But what will happen to the immaterial world? Can we 'teach' computers immaterial values?

Early developments of information technology in the field of architecture involved two-dimensional applications; subsequently, the significance of the third dimension became manifest. Nowadays, people are already speaking of a fourth dimension, interpreting it as time or dynamics. And what, for instance, would a fifth, sixth or Xth dimension represent?

In the future we will perhaps speak of the fifth dimension as comprising the tangible qualities of the building materials around us. And one day a sixth dimension might be created, when it will be possible to establish direct communication with computers, because direct exchange between the computer and the human brain will have been realised. The ideas of designers can then be processed directly by the computer, and we will no longer be hampered by the physicality of screen and keyboard.

This is mere speculation, and seems to be far-fetched, but even 50 years ago nobody could even imagine that today everybody could be walking the streets with a wireless telephone.

9. CONCLUSIONS

The ongoing developments in the field of ICT have an important impact on the design and building process. Designers can allow ideas and intuitions to take physical shape in ways that have not been possible before (Forster, 1996). At the same time, building technical developments are lagging behind and alternative, innovative solutions have to be adopted. In Eisenman's Aronoff Center at the University of Cincinnati, "all of the building trades (plumbing, tiling, painting) were carried out through a three-dimensional coordinate numerical control system implemented by an electronic laser transit on the site" (Zaera-Polo, 1996). Future ICT developments for architecture and the building sector will be in the field of knowledge integration and decision support environments leading, finally, to ICT support in the entire building process, from initiative until demolition. Collaborative engineering will pervade the building design process. By means of these technologies, the various branches of scientific disciplines will come closer than ever before into an integration of their disciplines. In the future, each participant in the design process will need to be able to make her own computer model in order to build up her specific knowledge within this computer model and to use it for her own support as a partner in the design. Developments in the software industry already show that if software firms provide the software core, architects and building engineers will be able to develop their own application tools according to their specific requirements and needs. Independent of the existing tools, they will be even more free to create their own language of activities.

REFERENCES

Abarbanel R., Brechner E. and McNeely W. (1997). FlyThru the Boeing 777, *Formal Aspects of Collaborative CAD* (eds., M.L. Maher, J.S. Gero and F. Sudweeks), Key Centre of Design Computing, University of Sydney, Sydney, 3-10.

aecXML. (1999). aecXML: A framework for electronic communications for the AEC industries, IAI aecXML Domain Committee.
http://www.aecxml.org/technical/

Cover R. (2000). The XML Cover Pages: Extensible Markup Language (XML), Organization for the Advancement of Structured Information Standards (OASIS), Billerica, Mass.
http://www.oasis-open.org/cover/xml.html

Forster K.W. (1996). Rising from the land, sinking into the ground, *Eleven Authors in Search of a Building* (ed., C.C. Davidson), The Monacelli Press, New York, 114-119.

Jang J-S.R, Sun C-T. and Mizutani E. (1997). *Neuro-fuzzy and Soft Computing; a computational approach to learning and machine intelligence*, Prentice-Hall, Upper Saddle River, NJ.

Jennings N.R. and Wooldridge M.J. (1998). *Agent technology: foundations, applications, and markets* (ed. Jennings, N.R. and Wooldridge, M.J.), Springer, Berlin.

Johnson M. (1999). XML for the absolute beginner: A guided tour from HTML to processing XML with Java, *JavaWorld*, April 1999.
http://www.javaworld.com/javaworld/jw-04-1999/jw-04-xml.html

Krishnamurti R. and Stouffs R. (1997). Spatial change: continuity, reversibility and emergent shapes, *Environment and Planning B: Planning and Design* 24, 359-384.

Leonard H.S. and Goodman N. (1940). The calculus of individuals and its uses, *The Journal of Symbolic Logic* 5, 45-55.

Lottaz C., Stouffs R. and Smith I. (2000). Increasing understanding during collaboration through advanced representations, *Electronic Journal for Information Technology in Construction* 5 (1), 1-24.
http://www.itcon.org/2000/1/

McCullough M. (1996). *Abstracting Craft: The Practised Digital Hand*, MIT Press, Cambridge, Mass.

Roe A. (1999). New digital products boost collaborative design, *CADENCE* 14 (2), 26-29.

Sarıyıldız S. and Schwenck M. (1996). Integrated support systems for architectural design, Architecture proceedings of *3rd Design and Decision Support Systems in Architecture and Urban Planning Conference*, Eindhoven University of Technology, Eindhoven, The Netherlands, 375-384.

Sarıyıldız S., van der Veer P., Schwenck M. and Çiftçioğlu Ö. (1998). Computers as reliable and valuable partner, *Cyber-real Design*, 5th Conference on Computer In Architectural Design, TU Bialystok, Poland.

Schmitt G. (1999). *Information Architecture: Basics of CAAD and its future*, Birkhäuser, Basel.

Schwartz I. (1997). A testing ground for interactivity, *Archis*, September 1997.
http://www.archis.org/archis_art_e_1997/archis_art_9709_ENG.html

Stouffs R., Kurmann D., Tunçer B., Mieusset K.H. and Stäger B. (1998). An information architecture for the virtual AEC company, *Product and Process Modelling in the Building Industry* (ed. R. Amor), Building Research Establishment, Watford, UK, 479-486.

Stouffs R. and Krishnamurti R. (1997). Sorts: a concept for representational flexibility, *CAAD Futures 1997* (ed. R. Junge), Kluwer Academic, Dordrecht, The Netherlands, 553-564.

Tidwell D. (1999). XML and how it will change the Web, IBM.
http://www-4.ibm.com/software/developer/library/xml-web/index.html

Tunçer B. and Stouffs R. (2000). Modeling building project Information, Proceedings of *Construction Information Technology 2000*, 28-30 June 2000, Reykjavik, Iceland.

Zaera-Polo A. (1996). The making of the machine: Powerless control as a critical strategy, *Eleven Authors in Search of a Building* (ed., C.C. Davidson), The Monacelli Press, New York, 28-37.