LBNL-43080
LC - 475

LBNL Report

Digital Media in Architecture: Opportunities and Challenges

Kostantinos Papamichael
Building Technologies Division
Lawrence Berkeley National Laboratory
One Cyclotron Road, MS 90R3111
Berkeley, CA 94720

April 1999

This work is supported in part by the by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. CIEE is a consortium of the CPUC, the CEC, and California utilities, including LADWP, SCE, SCG, SMUD, and PG&E. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. This work is also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Systems, Office of Building Systems, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Digital Media in Architecture: Opportunities and Challenges

Kostantinos Papamichael
Lawrence Berkeley National Laboratory

Abstract

This paper is about a theoretical framework of the relationship between digital media and architecture. The objective of the paper is to better understand the nature of change that digital media bring and the ways they affect architecture, leading to a vision of how the profession might be practiced in the future.

Three design models are presented, addressing the design tasks, the types of information used and the interaction among design participants. Digital media are examined with respect to the fundamental nature of their contribution to society in general and architectural practice in particular, concluding that, at an abstract level, the main contribution of digital media is increased speed in the production of analog media. This increase in speed, however, is so large that it presents significant opportunities to greatly improve the way we design, construct and operate buildings.

The three design models are combined into one that facilitates the development of digital applications. The opportunities that digital media present are then described in detail, within the theoretical framework of the new model and a vision is presented for what is possible not only for building design, but for construction and operation as well.

While the vision is based on technologies that are already available, its realization requires significant research and development efforts. Conceptual, technical and strategic challenges to realizing the vision are presented and discussed.

Introduction

The objective of this paper is to provide a theoretical framework that will facilitate the identification of opportunities that digital media present and assist with the development of digital applications that will address the data needs of the whole building life cycle.

Three design models are presented along with a discussion on the use of analog and digital media in architecture. The three models are then combined into one that facilitates development of digital applications. Digital media opportunities are then presented in detail within the framework of the combined model. They are then used collectively to paint a vision for how buildings may be designed, constructed and operated in the future. Finally, main challenges to realizing the vision are discussed.

The models and concepts described are valid for any type of activity that involves decision-making. In this paper they are focused on architectural design and extended to address decision-making throughout the whole building life cycle.

Design models

Three design models are presented: one for the design process, one for the types of information used in design and one for the interaction among design participants.

Design process

The design process can be modeled as the iteration of four major tasks: identifying problems, generating ideas towards resolving them, simulating the performance of the ideas and then evaluating it for the identification of problems (Figure 1). Design presupposes a discrepancy between a situation “as is” and a situation “as it ought to be,” that is the identification of at least one problem with respect to a certain performance aspect. To resolve the problem, designers generate ideas aimed to improving the situation with respect to specific performance aspect(s). Then, they “try out” their ideas in the form of simulations, which are processes that support performance prediction, e.g., construction of drawings and scale models, computations, etc. Simulation results are then evaluated, not only with respect to the performance aspect(s) that triggered the idea, but with respect to other performance aspects as well, to make sure that there are no undesired side or after effects (Papamichael and Protzen 1993).

The frequency of design iterations varies through the design process. Usually, it is very high in the early, schematic phases of building design, when iterations are almost instantaneous. Ideas are generated, simulated and

Figure 1. The design process as an iterative cycle of identifying problems, generating ideas towards resolving them, simulating the performance of the ideas and then evaluating it for identification of problems.

evaluated for problems very fast within the mind of the designer. The simulation process is in the form of sketches that are evaluated while being drawn, generating new ideas to address identified problems. As the design process continues, the iterations become slower. Simulation processes require more time, as design and performance specifications become more detailed. The process eventually becomes a refinement of the original ideas as it reaches the level of construction specifications.

Design information

The information used in design can be classified into three main categories of characteristics used to describe environments or situations (Papamichael and Protzen 1993):

- *Design* characteristics, which are parameters that affect performance and can be controlled directly by the designer, such as building geometry, materials, equipment, etc.
- *Context* characteristics, which are parameters that affect performance and cannot be controlled directly by the designer, such as weather conditions, building codes and regulations, characteristics of humans, animals and plants, etc.
- *Performance* characteristics, which are functions of design and context parameters and serve as performance indicators during evaluation, such as images, comfort indices, energy requirement levels, etc.

The differentiation between design and context parameters is a design decision that indicates the level at which the designer is willing to control the situation. It varies not only among architectural design projects, but within the same project as well. Each design decision becomes part of the context for the design decisions to follow. The decision on the placement and orientation of the building on the site, for example, becomes part of the context for the decisions on the arrangement of the spaces. As context affects performance, each design decision limits both design and performance options for the design decisions to follow, which, along with the cumulative nature of design decisions makes the initial, schematic decisions most important.

Design, context and performance parameters can be classified into two categories (Papamichael 1999):

- Quantitative parameters, which are expressed as single values and are measured on continuous or ordinal scales[1], and
- Qualitative parameters, which are expressed as distributions of values and are measured on nominal scales[2].

The "Width of the room" is an example of a quantitative design parameter, while the "Glazing type" is an example of a qualitative one. The "IES recommended level of illumination for reading and writing" is an example of a quantitative context parameter, while the "Site" is a qualitative one. Finally, the "Work plane illuminance" is an example of a quantitative performance parameter, while the "North elevation" is a qualitative performance one.

Design communication

Design participants perform "design iterations" either in isolation, or through interactions with others. The process is usually initiated by the clients, who have already "evaluated the situation," "identified the problem," "generated the idea of a building as a list of spaces," "evaluated it" and "identified the problem of putting the spaces together," which they pass to architects. The architects continue the process by coming up with ideas on how to put the spaces together, simulate and evaluate performance through drawings, scales models, computations, etc.

While architects may move through the iterative tasks of the design process in isolation for sometime, they often contact the clients to better understand needs and desires, which are essential for the evaluation task. As design ideas progress they are communicated back to the client for further discussions, towards refining wants and needs with a continuously enhanced understanding of what is possible. The design process in this respect can be seen as a two-way communication between parties expressing what is desired and parties expressing what is possible, towards finding an acceptable compromise, usually within certain time and economic constraints.

Eventually, engineers and other professionals get involved in the process, as the design proceeds to further considerations and more detailed specifications of building components and systems, towards the preparation of construction documents. While the engineers address structural, mechanical and electrical issues, other design professionals are employed to address lighting, interior design, etc. Each participant goes through the iterative cycle alone and with everybody else, depending on how problems are identified and ideas occur. Moreover, each task in a single iteration can be performed by different design participants. An idea generated by architects, for example, may be simulated by mechanical engineers for potential mechanical problems, which may be evaluated and accepted by the clients, while the structural engineers identify a new problem.

Communicating information can be seen as the process of answering questions, which may turn into issues when more than one answer becomes available. In this respect, the design process can then be modeled as an argumentative process, that is as a network of *issues* (questions) each of which can have any number of *positions* (answers), which in turn can be supported or negated by any number of *arguments* (Kunz and Rittel, 1970, McCall et al, 1998).

Media

The word "media" is the plural of "medium," a Latin word, which, as a noun, means "means," "vehicle," "channel," "mode," "method," "way," "avenue," "form," etc.

---

[1] Continuous (or ratio) scales are expressed as real numbers, while ordinal scales are expressed as integers or orderly expressions, e.g., small-medium-large.

[2] Nominal scales are expressed as non-orderly expressions, e.g., wood, steel, concrete.

The "essential" architectural media

Based on the above definition of the word "media," *architectural media* may refer to anything used in architectural practice, not only with respect to documents, but equipment used for their production as well, such as papers, pencils, computers, printers, plotters, etc. Moreover, they may refer to equipment used for communication among design participants such as phones, fax machines, e-mail, etc.

If we exclude the equipment used for document production and communication, we are left with the *essential* architectural media that can be abstracted into *images* and *messages*. Images come in the form of pictures, drawings, paintings, scale models, plots, etc.   Messages can contain three information elements:

- *Text*, in the form of letters, memos, reports, etc.
- *Sounds*, mostly in the form of speech.
- *Gestures*, mostly accompanying and supporting speech.

The sound of a person's voice conveys more informative than the "text" version of the message. Gestures and expressions accompanying the sounds convey even more information.

Digital media

Based on the general definition, digital media may refer to anything used for the storage, transfer and manipulation of digital information, not only with respect to electronic documents and computer programs, but computers, hard disks, printers, plotters, telephones, etc.   At the level of the *essential* architectural media, however, digital media refer to representations of text, sound, images and video in digital format, e.g. sequences of zeros and ones. In this sense, humans cannot interpret digital media directly. Through appropriate input devices, e.g., keyboard, mouse, tablet, glove, helmet, etc., humans use computers to encode analog information into digital format, or "data." Through appropriate output devices, e.g., screen, printer, plotter, helmet, etc., humans use computers to convert digital media into analog, that is "data" into "information," which they can interpret (Figure 2). Digital media, then, are not directly related to humans. They merely serve the purpose of producing the same analog media that have traditionally been used in architectural practice in particular and business in general.

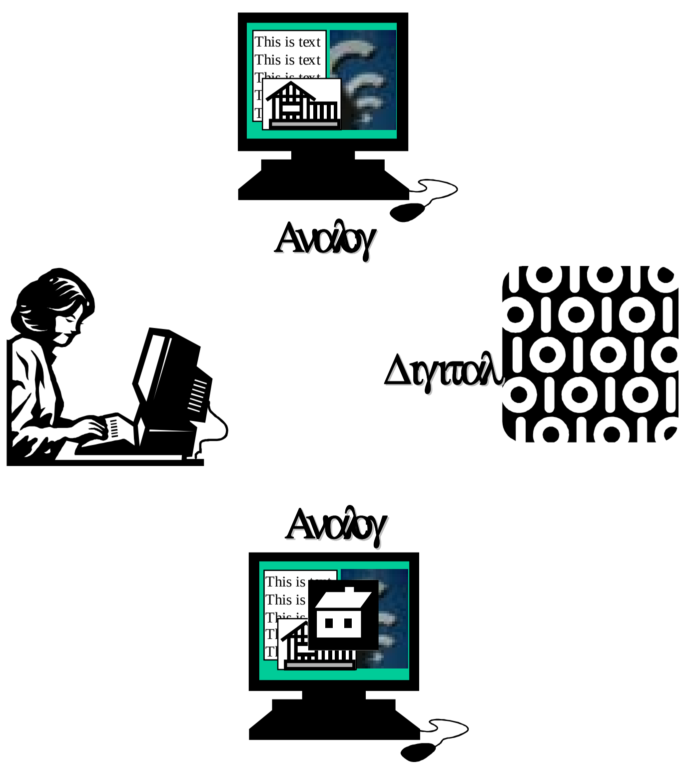

Figure 2. Humans can interpret analog media. Digital media are manipulated by computers to produce analog media that. Humans interpret. Digital information can me used by computer programs to generate new information very fast and produce it in analog formats for human interpretation.

Advantages of digital media

At a very basic level, digital media can be processed to produce analog media that are identical to the ones humans enter as input. The initial 2-D CAD systems, for example, allowed the production of 2-D drawings, such as plans, elevations, sections, etc., with the same amount of information and format that they were entered. The main advantage at this level is the quick and easy modification and extension of the information entered, e.g., making modifications to digital drawings does not require starting all over again.

The real value of digital information, however, lies in the ability to manipulate it very fast for the generation of new information, following specific instructions in the form of computer programs or applications. The 3-D CAD and solid modeling systems, for example, receive as input the geometric characteristics and material properties of surfaces to automatically produce new images, such as perspectives, 3-D sections, etc. What used to take hours, days and even weeks is now possible almost instantaneously! Moreover, it is very accurate with respect to geometry, shadow casting, etc., and much more realistic with respect to illumination levels and material textures. The speed in generating images has opened new opportunities in experiencing buildings through virtual walk through and fly over sequences. Through the use of specialized input and output devices, such as movement sensors and stereoscopic displays, we can even experience the building in "virtual reality."

Through analytical models of physical phenomena, such as those modeling mass and energy transfer, digital media can be used to predict performance with respect to a large variety of performance aspects, which are usually prohibitively expensive due to the magnitude of the required computations. These include prediction of light levels, temperatures, energy requirements, etc., through appropriate computer-based *simulation* processes. Prediction accuracy can reach levels that are humanly impossible without the use of digital media. Analytical simulations of light propagation for example can be used to generate not only photo-realistic, but photometrically accurate images, as well (Ward and Shakespeare, 1998). Other types of numerical information, such as energy requirements and comfort levels, can be computed and displayed very fast and in various forms to facilitate interpretation (Birdsall et al, 1990). These can vary from traditional business graphics, to enhanced visualizations of otherwise invisible data, such as "infrared display" of surface temperatures and "vectored" display of airflow. Quick generation of data can result in animations that show performance over time, which is most essential in understanding the operation and behavior of the building.

Finally, digital media can be transferred very fast over very long distances (Figure 3). Through the Internet, digital media can be used to produce the essential media not only in record speeds but at any distance as well. The continuous increase in computing power and data transfer rates will eventually reach the level of producing any type of computable information anywhere in the world at the "speed of thought." The potential of this new reality of "analog media on demand" opens up opportunities to significantly improve the way we design, construct and operate buildings.

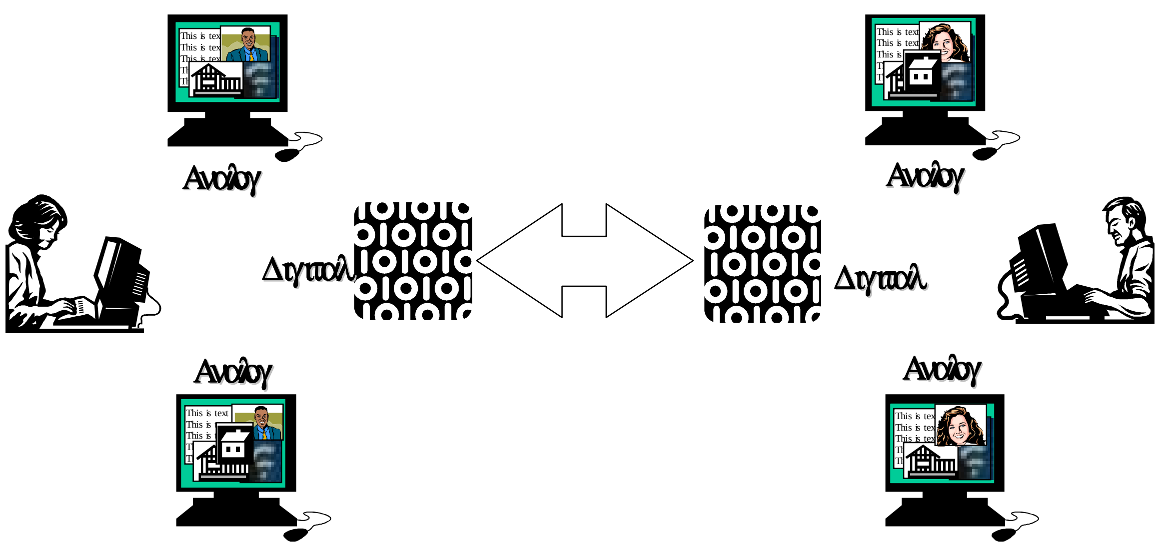

Figure 3. Digital media can be transferred electronically very fast, allowing real-time communication among humans, which include the all forms of the essential media.

A design model for digital media

The manipulation of digital information requires the use of computer programs, or processes, which are developed by humans using *computer languages*. The common characteristic of computer languages is that they allow the *assignment* of values to *output* parameters through *processing* of the values *assigned* to *input* parameters. The three design models describe earlier can be combined and expressed in terms of assigning values to parameters, or "variables," for the formulation of a design model that is most suitable for digital applications, or "programming:"

Design is the argumentative process of assigning values to design variables, in order to control the values of performance variables, for a given set of values for context variables.

All variables are issues and their values are positions. The values of performance variables are determined through simulation processes and serve as arguments to support or negate the values of design variables. The assignment of values can be time-stamped and stored, thus greatly facilitating tracing decisions with respect to who decided what, when and why.

At the level that humans operate, design and context variables are either in the form of geometric attributes, or objects. The characteristics of objects are in turn context variables as well, whose values are determined through *search processes*, e.g., retrieving data from databases. For example, designers do not usually specify the optical or thermal properties of materials or the weather data directly. Rather, they specify them indirectly, choosing among available options for materials and locations. Finally, performance variables can also serve as input to simulation processes, e.g., the energy requirements can serve as input to an operating cost model (Figure 4).

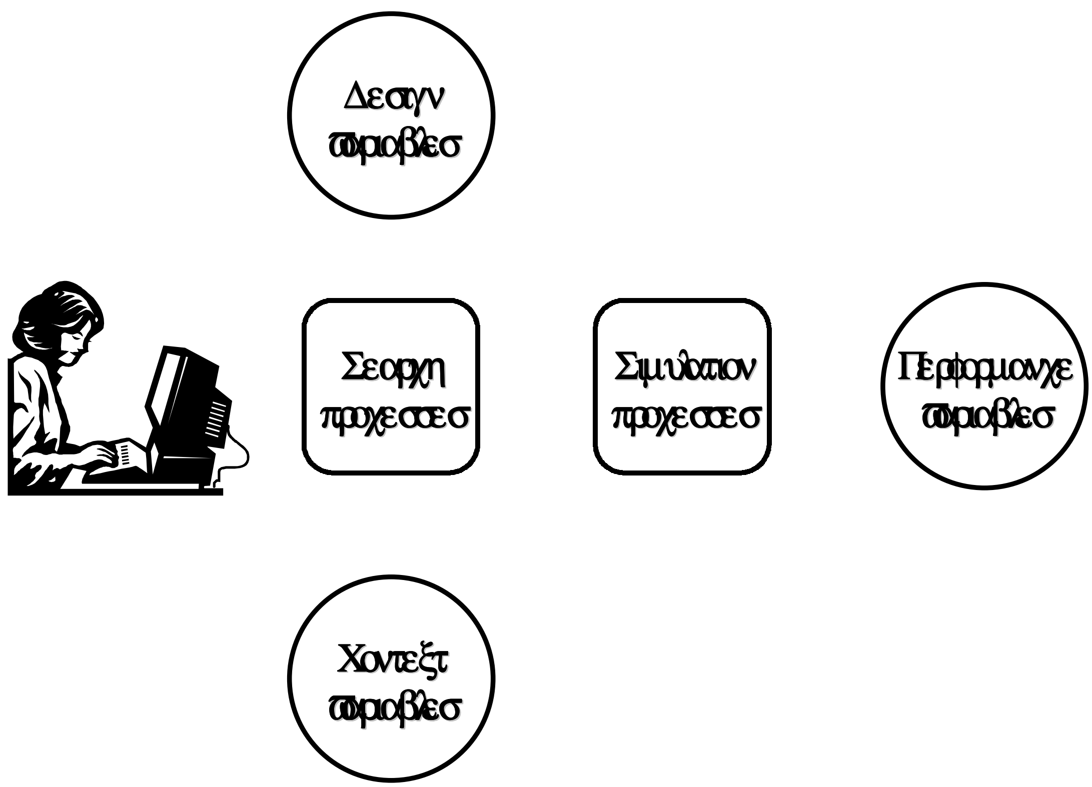

Figure 4. Design can be seen as the assignment of values to design. Context and performance variables by humans, search and simulation processes.

Based on the above, the building and its context can be modeled as a set of variables, whose values are assigned by humans and processes through a single recursion (Figure 5). When humans need the value of a variable, the computer can identify the processes that can produce it as output. If no process is found, then the computer asks all, or specific design participants, e.g., structural engineers for the height of a beam, or mechanical engineers for the

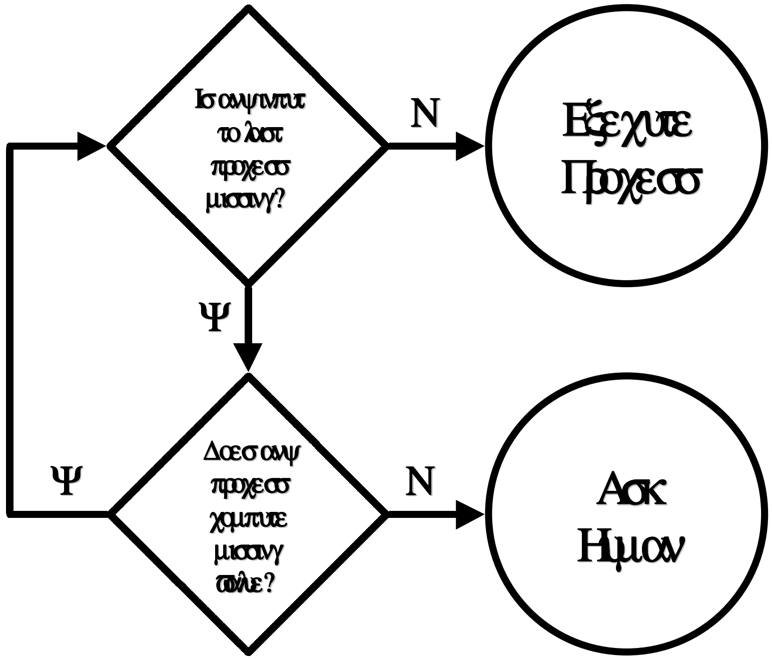

Figure 5. The generation of information by processes and humans can be handled through a single recursion.

capacity of the chiller. If a process is found, then the computer checks to see if all of the variables that serve as input to the process have values. If they do, the computer executes the processes and displays the requested value. If one or more of the variables that are required as input to the process does not have a value, then the computer "stacks" the process and looks for other processes that can provide the required value as output, in a recursive mode. The stacked processes are eventually executed and removed off the stack, when their input is provided either by processes of humans (Papamichael 1999).

This model presents significant opportunities to facilitating decision-making not only during building design, but during construction and operation as well. These opportunities are discussed in detail below for each of the four tasks of the design process and for the whole building life cycle.

Digital media opportunities

Assuming that digital media can reach the level of producing information at the "speed of thought," the potential of digital media in decision-making is to provide instantaneous answers to all questions raised. The types of possible questions are examined below for each of the main design tasks, decomposing each task into its elemental steps.

Problem identification

Problem identification relates to the values of performance variables. A problem arises when one of the design participants is not pleased with the value of at least one performance variable, which is the direct result of the evaluation process examined in more detail below. Problem identification can be seen as a two-step process, both of which can be facilitated by the use of digital media:

1. Identification of performance variables, which is already part of the model.
2. Decision on which ones to check for problems, which can be facilitated in two ways:
    - By supporting a mechanism that allows decision-makers to "subscribe" to certain performance variables that they want to monitor, and

- By supporting a "flag" mechanism to alert decision-makers when performance variables get values out of specified ranges (for quantitative variables) or sets (for qualitative variables).

Idea generation

Ideas are directed towards improvement with respect to specific performance variables. To affect the value of a performance variable, designers need to change the value of one or more design variables that affect the performance that needs to be improved. In this respect, idea generation can be seen as a three-step process, all of which can be facilitated by the use of digital media:

1. Identification of design variables, which is already part of the model.
2. Decision on which one(s) to change, which can be facilitated in three ways:
    - By a "flag" mechanism that allows design variables to be treated as context variables, which allows designers to isolate the design variables that they are willing to change, and
    - By sorting qualitative design variables with respect to their characteristics
    - By prioritizing design variables according to their effect on the performance variable to be affected, to identify the ones with the most impact.
3. Decision on the value(s) to be changed to, which can be facilitated in two ways:
    - By finding qualitative design variables that meet specific criteria with respect to their characteristics, and
    - By supporting the computation and display of the relationship between the design variable(s) to be changed and the performance variable to be affected. This can be achieved though execution of simulation processes, examined in more detail below. If both variables are quantitative, then the relationship can be expressed as a 2-D plot. 3-D plots can be used to visualize the relationship among three variables. If one of the two variables is qualitative, then the relationship can be expressed in the form of a table that can be sorted by the quantitative variable. If both variables are qualitative, then the relationship can be shown on a table that cannot be sorted.

Performance simulation

Performance simulation involves the computation of the values of performance variables. Digital media can greatly facilitate such computations to produce values for both, quantitative and qualitative performance variables. Analytical computations can produce values for performance variables that are prohibitively expensive or even impossible without digital media, such as light levels, temperatures, air flows, cost, environmental impact, etc. Performance simulation can be seen as a five-step process, all of which are already supported by the model:

1. Identification of input parameters.
2. Specification of values for input parameters.
3. Submission of the input to the simulation processes.
4. Execution of the simulation process.
5. Assignment of results to performance variables.

Performance evaluation

Performance evaluation requires comparison among at least two options and is intimately related to what is possible. It can be seen as a two-step process, both of which can be facilitated by the use of digital media:

1. Inspection of the value(s) of performance variable(s), which is directly related to the conversion of digital information into analog formats for human interpretation.
2. Comparison with the corresponding performance of alternatives, which can be facilitated in two ways:
    - By supporting maintenance of multiple design options and comparative comparisons among them, and
    - By supporting comparison with the actual performance of existing buildings that are "similar" to the one under design. Both involve the maintenance of databases and the display of information in ways that

facilitate comparison. For quantitative performance variables (e.g., work plane illuminance), this can be the display of the performance values of all options in a single plot. For qualitative performance variables (e.g., north elevation) this can be an array of side-by-side displays.

Since performance evaluation usually requires the consideration of more than one performance variable, the information for many options and many variables can be displayed in tabular form, with options and performance variables across each dimension.

The building life cycle

The above model can be used as the foundation for the development of processes that can greatly facilitate not only the way we design buildings, but also construct and operate them. The building life cycle can be modeled as a sequence of decisions that are identical in nature to design decisions, following the same iterative tasks. In fact, building construction and operation can be seen as a continuation of the design process with most design variables turned into context.

A major difference between construction and operation is that they happen in "real time," as opposed to design, which refers to the future. Designing is "living" in one's imagination (Papamichael and Protzen 1993). Another major difference is that sensors, rather than simulation processes, determine the values of performance variables. Any idea for a change in construction or operation moves us into imaginary time just like in design. The context, of course, is dramatically different.

Usually, performance parameters are still the same, e.g., comfort, energy, cost, aesthetics, etc. The main difference is that all of the construction and operation up to the moment of the "design decision" is now the context of the design problem. In this way, setting the HVAC or lighting controls in a building is the same processes during operation as it is during design. Different options have to be identified, simulated and evaluated.

The maintenance of a digital model of the building throughout its life cycle can greatly facilitate decision-making in construction and operation, by allowing use of simulation techniques to predict the effects of potential changes. Something that was already considered during the design process can be readily available as an option for reconsideration during construction and operation. If the arguments against and for it have been maintained, they do not have to be regenerated, which otherwise may not be possible if the same participants are no longer available.

The integration of processes used in construction, commissioning, etc., with those used in design presents the following opportunities:

- All of the input required for processes used in each phase are already available from the use of the system in the phase before, which eliminates information transfer from one phase to another. In a way the phases of the building life cycle become part of one continuous process.
- Criteria related to the performance of alternative options during construction and operation can be used to evaluate the options during the design process and affect design decisions.
- Deviations between values computed by simulation processes for imaginary time and values measured in real time can automatically trigger alerts for checking validity and proper operation. Agreements and deviations can serve as arguments to support or negate the validity of results from simulation processes in future projects.

A vision for the future

Since in principle we can specify any processes we want in the form of a computer program, and assuming the same rate of increase in computing power, it is just a matter of time until we put everything together for "information at the speed of thought" and in "virtual reality" formats.

Imagine putting your virtual reality stereoscopic vision glasses or helmet on and have real time meetings with clients and engineers, who may be anywhere in the world, inside the imaginary building under design. The virtual building is displayed in photometrically accurate images. You can talk real time, move around in any direction, not only spatially but temporally as well, point to building components and systems, change them on the spot, display invisible data, like temperatures, air flows, etc.

Imagine being able to simulate and visualize the construction process, and explore what-if scenaria for changes during the operation of the building, either at the level of changing operational characteristics or at the level of renovation processes. Digital media will be able to support a virtual model of the building not only during design, but through construction and operation as well. Imagine being able to fast forward or rewind time, simulate emergency situations, like earthquakes and fires, and compare different evacuation plans.

Imagine that the latest information in appropriate digital formats is available for every building component and system in the market, quickly and easily accessible through the Internet. Imagine discussing the simulated performance of a building component or system with the manufacturer in virtual meetings inside the virtual building, and be able to try alternatives on the spot, immediately checking their performance.

Realizing the vision

Most of the pieces required for the realization of the vision described above are available in one form or another today (Davidson and Cambell, 1996; Brady, 1997; Faucher and Nivet, 1998; Gross, 1996; Papamichael et al, 1997; Kalay, 1997; Mahdavi et al, 1996; Pinet, 1997; Seebohm and Wallace, 1997; McCall et al, 1998; Kolarevic et al, 1998; Cambell, 1998; Clayton et al, 1998). Putting them together is a major challenge that requires a significant collaborative effort by many programmers, architects and engineers, over several years, along with active participation of the whole building industry.

Currently, as most pieces are produced by individual efforts in a fragmented way, they do not fit with each other. There is no common general plan and only small fractions of individual plans are being explored. The most prominent challenge to shaping the pieces and putting them together is the development of a “central entity” to guide and coordinate multiple efforts by both, academia and industry.

A major effort by the International Alliance for Interoperability is underway during the last several years to define an object-oriented representation of the building and its context that will serve the data needs of all disciplines involved with buildings. This effort may successfully address the main issue of a commonly accepted model that will be instrumental in accelerating progress.

Another major challenge is the development of faster computers and faster networks. Even today’s supercomputers are not capable to producing enough frames of photometrically accurate images per second for virtual reality purposes. Considering the dramatic increase in computing speed, however, it is just a matter of time until computers are fast enough and the input/output hardware evolves to the level required for the realization of the vision.

Finally, manufacturers of building components and systems need to participate by producing and making available the required data for the simulation of the performance of their products. Standard procedures and formats need to be defined to allow for production and availability of required data. Manufacturers will overcome their hesitation to publishing detailed technical specifications about their products to make sure their products are considered with the design tools of the future.

Due to these challenges, the realization of the vision may take sometime. It is, however, just a matter of time, which may be shortened through establishment of appropriate collaborations by government, academia and industry.

Conclusions

The main change that digital media bring is speed in producing analog media that humans can interpret. The increase in speed, however, is so large, that it offers unique opportunities to drastically changing the way we design, construct and operate buildings. All opportunities are based on the potential for “information at the speed of thought,” which will allow us to answer questions that involve massive computations instantaneously. Virtual reality has the potential to allow us to live and experience the building in virtual worlds, simulating its complete operation and allowing visualization of otherwise invisible data about temperature, illumination, air movement, etc. Simulations of “what if” scenaria will move us through time to anticipated events that we need to examine and understand, such as worst case scenaria for equipment response, emergency evacuations, etc. While the technical and professional challenges are tough, the potential for high rewards is generating the necessary excitement to realizing it. Collectively organized research and development efforts may have the potential to significantly increase progress.

Acknowledgements

This work is supported in part by the by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. CIEE is a consortium of the CPUC, the CEC, and California utilities, including LADWP, SCE, SCG, SMUD, and PG&E. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. This work is also supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Systems, Office of Building Systems, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

References

Birdsall, B.; Buhl, W.L.; Ellington, K.L.; Erdem, A.E.; and Winkelmann, F.C. 1990. "Overview of the DOE-2 Building Energy Analysis Program, Version 2.1D," Lawrence Berkeley National Laboratory Report No. LBL-19735, Rev. 1, 1990.

Brady, D.A. 1997. "The mind's eye: movement and time in architecture," *Proceedings of ACADIA '97 Conference*, Cincinnati, Ohio, October 3-5, 1997.

Cambell, D.A. 1998. "Architectural construction documents on the Web: VRML as a case study," *Proceedings of ACADIA '98 Conference*, Quebec City, Canada, October 22-25, 1998, pp. 267-275.

Clayton, M.J.; Johnson, R.E.; Song, Y.; and Al-Qawasmi, J. 1998. "Delivering facility documentation using intranet technology," *Proceedings of ACADIA '98 Conference*, Quebec City, Canada, October 22-25, 1998.

Davidson, J.N.; and Cambell, D.A. 1996. "Collaborative design in virtual space – Greenspace II: A shared environment," *Proceedings of ACADIA '96 Conference*, Tucson, Arizona, October 31 – November 2, 1996.

Faucher, D.; and Nivet, M. 1998. "Playing with design intends: Integrating physical and urban constraints in CAD," *Proceedings of ACADIA '98 Conference*, Quebec City, Canada, October 22-25, 1998.

Gross, M. 1996. "Elements that follow your rules: constraint based CAD layout," *Proceedings of ACADIA '96 Conference*, Tucson, Arizona, October 31 – November 2, 1996.

Kalay, Y.E. 1997. "P3: An integrated environment to support design collaboration," *Proceedings of ACADIA '97 Conference*, Cincinnati, Ohio, October 3-5, 1997.

Kolarevic, B.; Schmitt, G.; Hirschberg, U.; Kurmann, D.; and Johnson, B. 1998. "An experiment in design collaboration," *Proceedings of ACADIA '98 Conference*, Quebec City, Canada, October 22-25, 1998.

Kunz, W.; and H. Rittel. 1970. "Issues as elements of information systems (IBIS)" Working paper 131, Institute of Urban and Regional Development, CED, UC Berkeley.

Mahdavi, A.; Mathew, P.; Lee, S.; Brahme, R.; and Kumar, S. 1996. "On the structure and elements of SEMPER," *Proceedings of ACADIA '96 Conference*, Tucson, Arizona, October 31 – November 2, 1996.

McCall, R.; Holmes, S.; Voeller, J.; and Johnson, E. 1998. "World wide presentation and critique of design proposals with Web-Phidias," *Proceedings of ACADIA '98 Conference*, Quebec City, Canada, October 22-25, 1998.

Papamichael, K. 1999. "Application of information technologies in building design decisions," *Building Research and Information Journal*, January 1999.

Papamichael, K.; La Porta, J.; Chauvet, H. 1997. "Building Design Advisor: automated integration of multiple simulation tools." *Automation in Construction Journal*, Vol. 6, No. 4, pp. 341-352, August 1997.

Papamichael, K.; and Protzen, J.P. 1993. "The limits of intelligence in design," Proceedings of the Focus Symposium on Computer-Assisted Building Design Systems of the 4^{th} International Symposium on Systems Research, Informatics and Cybernetics, Baden-Baden, Germany.

Pinet, C. 1997. "Design evaluation based on virtual representation of spaces," *Proceedings of ACADIA '97 Conference*, Cincinnati, Ohio, October 3-5, 1997.

Seebohm, T.; and Wallace, W. 1997. "Rule-based representation of design in architectural practice," *Proceedings of ACADIA '97 Conference*, Cincinnati, Ohio, October 3-5, 1997.

Ward, G.; and Shakespeare, R. 1998. *Rendering with Radiance: The Art and Science of Lighting Visualization*, Morgan Kaufman, 1998.