THE ROLE OF COMPUTERS IN THE BUILDING LIFE CYCLE

What computers can and cannot do

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Abstract. The objective of this paper is to provide a conceptual framework that facilitates the development of integrated software environments that address the data and process needs of all building-related disciplines through the whole buil ding life cycle. The conceptual framework is based on a comprehensive analysis of the data and processes involved in d ecision-making, which is the common abstraction of all disciplines throughout the building life cycle. The role of computers is examined in every step of the decision-making process and through the building life cycle, focusing on what computers can and cannot do. The capabilities of computers are the used to present a vision for what the future of building design, construction and operation may be. 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.

1. Introduction

Computers have entered almost every aspect of the building life cycle, however in a fragmented way. Different building-related professionals, from building design through construction and operation, use specialized computer applications to proceed more effectively and efficiently. However, these applications address only specific tasks within specific disciplines and are not related to each other.

The objective of this paper is to provide a conceptual framework that facilitates the development of integrated software environments that address data and process needs of all building-related disciplines through the whole building life cycle. The conceptual framework is based on a comprehensive analysis of the data and processes involved in decision-making, which is the common abstraction of all disciplines throughout the building life cycle.

2. Decision-making

The main reason that we need and produce information at any phase of the building life cycle is to make decisions about what to do next. Understanding the decision-making process is critical to developing integrated frameworks that can accommodate all disciplines during the whole building life cycle.

2.1. THE DECISION-MAKING PROCESS

Decision making can be abstracted to *choosing among options*. The generation of options is based on the performance problems that we have identified and/or performance goals that we try to meet.

In building-related decisions there are usually several problems that we try to resolve and goals that we try to meet. The performance of the design alternatives that we generate varies with respect to the various performance considerations. Some designs are better than others in some respects and worst than others in other respects. Final decisions are always compromises between what is desirable with respect to performance considerations and what is possible with respect to available options.

The decision-making process involves iteration of four major activities: identifying problems or setting goals, identifying options towards resolving problems or meeting goals, estimating the performance of the identified options and evaluating the estimated performance.

Decision-making can also be seen as the process of answering questions, which may turn into issues when more than one answer becomes available. In this respect, the decision-making process can then be modeled as an argumentative process, i.e., 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).

2.2. THE DECISION-MAKING DATA

The data used in decision-making can be classified into three main categories of characteristics:

- *Design* characteristics, which are parameters that affect performance and can be controlled directly by the decision-makers, e.g., building geometry, materials, equipment, operation, etc.
- *Context* characteristics, which are parameters that affect performance but are not controlled directly by the decision-makers, e.g., weather conditions, building codes and regulations, characteristics of humans, animals and plants, properties of materials, etc.

- *Performance* characteristics, which are functions of design and context parameters and serve as performance indicators during the evaluation of design alternatives, e.g., images, comfort indices, energy requirement, cost, etc.

The differentiation between design and context parameters is a decision that indicates the scope of the decision-making. This differentiation varies not only among different building projects, but within the same project as well. Each decision becomes part of the context for the decisions to follow, e.g., the decision on the placement and orientation of the building on the site becomes part of the context for all following decisions.

Design parameters are often considered as context parameters in exploring what-if scenaria and then turned into design parameters again for exploration of alternative options. As context affects performance, each decision limits both design and performance options for the design decisions to follow, which makes early decisions increasingly important.

2.2.1. Quantitative and qualitative parameters

Design, context and performance parameters can be classified into two categories, which are very important when it comes to the consideration of evaluation and optimization, which are addressed later in the paper. Parameters can be:

- *Quantitative,* i.e. expressed as single values on continuous scales, i.e., in terms of real numbers, or
- *Qualitative,* i.e., expressed as sets of values on nominal scales, i.e., in terms of non-orderly entities.

The *width of the room* is an example of a quantitative design parameter, while the *glazing type* is an example of a qualitative design parameter. The *IES recommended level of illumination for reading and writing* is an example of a quantitative context parameter, while the *view to the East* is a qualitative context parameter. Finally, *work plane illuminance* is an example of a quantitative performance parameter, while an *East elevation image* is a qualitative performance parameter.

3. What Computers Can Do

Each of the four activities of the decision-making process can be decomposed into elemental steps. These are examined below with respect to what computers can do to assist in each step.

3.1. IDENTIFYING PROBLEMS

Problem identification relates to the values of performance variables and is intimately related to setting performance goals. A problem arises when one of the design participants is not pleased with the value of at least one performance variable. Problem identification can be seen as a two-step process, both of which can be facilitated by the use of computers:

1. Identification of performance variables, which is a prerequisite to defining problems. Performance variables are related to performance simulation tools, i.e., processes that compute their values. These are examined in detail below. Computers can certainly keep a list of all performance parameters considered. They can also help through searches on what others think we should be considering. The more performance variables considered the less possibility for unforeseen undesired effects.
2. Decision on which performance variables to check for problems. Determining and evaluating the values of all performance parameters at every single decision or what-if scenario can be cumbersome and time-consuming. Computers can help in two ways:
   - By supporting a mechanism that allows decision-making participants to *subscribe* to certain performance variables that they want to monitor, e.g., a daylighting or energy engineer can subscribe to the parameters related to windows and skylights and be automatically notified if their description is changed by another design participant, so that she can check daylight levels and/or energy levels again.
   - By supporting a *flag* mechanism to alert decision-makers when performance variables get values that are out of specified ranges (for quantitative variables) or sets (for qualitative variables), e.g., a decision-maker may wish to be alerted when energy requirements or cost exceed certain levels, such as code or budget constraints, respectively.

3.2. GENERATING OPTIONS

The generation of options is guided towards improving performance with respect to specific performance parameters. To improve on the value of a performance parameter, decision-makers need to change the value of one or more design parameters that affect the performance aspect that needs to be improved. In this respect, the generation of options can be seen as a three-step process:

1. Identification of the esign variables that affect the performance parameter value that needs to be improved. Computers can easily help by maintaining between performance parameters and the design (and context) parameters that affect them. All of the input parameters of simulation tools used to compute the values of performance parameters affect the values of the performance parameters that simulation tools produce as output. Simulation tools are addressed below.
2. Decision on which of the design parameters identified in step 1 to change for the generation of new options. Computers can help this step in three ways:
   - By a *flag* mechanism that allows design variables to be treated as context variables, which allows decision-makers to isolate the design variables that they are willing to change.
   - By sorting qualitative design variables with respect to their characteristics, e.g., sort all glazing options by transmittance, which allows selection of options that will influence the value of the performance parameter in the desired direction.
   - By prioritizing design variables according to their effect on the performance variable to be affected, to identify the ones with the most impact. This can happen through maintaining a list of *key* design parameters for each performance parameter, or through multiple parametric simulations, which is related to step 3.
3. Decision on how to change the identified design parameter in step 2, in which computers can help in two ways:
   - By finding qualitative design variables that meet specific criteria with respect to their characteristics, e.g., find glazing types with transmittance higher than a certain value, 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 multiple simulation processes, varying the value of the design parameter for each simulation in a systematic way. Simulation tools are examined in more detail below. If both variables (performance and design) are quantitative, then the relationship can be expressed as a 2-D plot. 3-D plots can be used to visualize the relationship among one performance and two design parameters. 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. Consideration of more than two design parameters is also possible, however raising visualization issues.

3.2.1. Optimization

In addition to the "exhaustive enumeration" of options for the understanding of the relationships between certain design and performance parameters, described above, computers can be used to automatically identify the combination of values for a set of design parameters that will offer the best performance with respect to a single quantitative parameter. Such algorithms are designed to find optimal combinations without need for exhaustive enumeration of options, thus saving significant computation time, especially when several design parameters are considered (Wetter, 2001). It should be noted that this type of optimization is valid only for single quantitative performance parameters. It should also be noted that these approaches cannot always find the optimal combination, depending on the algorithms used and the starting point of the search.

In addition to single-criterion optimization, computers can also help in multi-criterion optimization, i.e., the combination of values of a set of design parameters that offer the "best" performance with respect to more than one performance parameter. However, this can only be achieved up to a certain extent, because usually different combinations of values for design parameters offer better performance with respect to one performance parameter but worst with respect to another.

The limit to valid multi-criterion optimization is the identification of a *set* of "optimal" combinations, i.e., a set of sets of values for the selected design parameters, each of which offers the best performance for each of the performance parameters considered (Wright and Loosemore, 2001). As for the single-criterion optimization, multi-criterion optimization in the form of identifying a set of "optimal" options is valid only for quantitative performance parameters and may miss the true optima, depending on the algorithms and the starting point of the search.

3.3. ESTIMATING PERFORMANCE

Estimating performance involves the determination of the values of performance variables. This is the decision-making activity that computers offer the most! Through analytical models of physical phenomena, such as those addressing mass and energy transfer, computers 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.

Computers 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 computers, such as light levels, temperatures, air flows, cost, environmental impact, etc. Simulations of light propagation for example can be used to generate photo-metrically accurate images (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. Data visualization can vary from traditional business graphics, to enhanced visualizations of otherwise invisible data, such as colored 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 under various contextual situations.

Performance simulation can be seen as a five-step process. The second step is a repeat of step 3 of generating options, which is addressed above. The rest of the steps are already included in the development of the simulation tools and can be easily part of an integrated environment (Papamichael et al., 2000):

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.

3.4. EVALUATING PERFORMANCE

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:

1. Inspection of the values of performance variables. As explained above, various types of data visualization can be employed, from simple business graphics to virtual and augmented reality. This is another major area that computers can play a significant and most useful role throughout the building life cycle.
2. The only way to perceive value is through comparison. Computers can help in two ways:
   - By supporting maintenance of multiple design options and comparisons among them, and
   - By supporting comparison with the performance of actual buildings that are similar to the building under consideration.

Both involve the maintenance of databases and the display of information in ways that facilitate comparison. For quantitative performance variables, the performance of design alternatives and/or case studies can be displayed on the same plot. For qualitative performance variables the performance can be displayed for a side-by-side comparison. 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 and performance variables and alternatives across each dimension (Papamichael, 1999).

4. The Building Life Cycle

The above model of the decision-making process and the related capabilities of computers can serve 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. In fact building construction and operation can be seen as the continuation of the design process with most design parameters turned into context parameters.

A major difference between construction and operation is that they happen in real time, as opposed to design, which always refers to the future. Conceptually, however, they are identical, since design is the equivalent of 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. Potential changes in building construction and operation are equivalent to the design process. 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 an operational decision is now the context of the decision-making process. In this way, setting the thermostat or lighting controls in a building is the same process 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 and its context throughout the building life cycle 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 and operation with those used in design presents the following opportunities:

- All of the input required for the processes used in construction and operation are already available from the use of the integrated environment 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 continuum.
- 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, e.g., use construction-related criteria to influence design decisions.
- Deviations between values of performance parameters computed by simulation processes during design and values measured in real time can automatically trigger alerts for checking validity of simulation processes and/or proper operation of the building.

5. What Computers Cannot Do

As described above, computers can play significant and most useful roles throughout the building life cycle. However, there is one major task that computers cannot do. This task is related to the evaluation of qualitative performance parameters, which cannot be delegated and is certainly not computable.

One of the most common mistakes, especially in computer applications, is the development of algorithms that aggregate evaluation with respect to multiple performance parameters into overall levels of "goodness." The overall goodness is computed through the use of *transformation* and *aggregation* functions, both of which are arbitrary and thus meaningless.

When performance parameters are expressed on different scales their direct aggregation is meaningless, in the same way that it is meaningless to add apples and oranges. The purpose of transformation functions is to transform the values of performance parameters into values on a common scale of "goodness," which is usually defined as a continuous scale with arbitrary minimum and maximum values, e.g., -1 to +1, or -5 to +5, etc. The transformation function, i.e., the mapping of the potential values of a performance parameter onto the scale of goodness is also arbitrary.

Performance goals for individual performance parameters have meaning only in terms of direction, which can also be combined with constraints that define unacceptable performance. Comparison of alternative options with respect to a single performance variable is straightforward, valid and easy and requires only a sense of direction and/or constraints. It is valid to say that a with respect to energy requirements option A is better than option B. However it is meaningless to attempt to quantify how better it is, which is what transformation functions are used for.

Aggregation functions attempt to aggregate multiple values of "goodness" derived through transformation functions. Aggregation is usually achieved through the use of weighting factors that indicate the relative importance of the performance parameters considered. These weighting factors are also arbitrary and meaningless. Weighting factors are expressed as percentages and are used to weight the individual values of goodness into a single value of overall goodness. Just like transformation functions attempt to quantify goodness, aggregation functions attempt to quantify importance. However, goodness and importance cannot be quantified.

The evaluation of multiple performance parameters is the equivalent of a qualitative performance, because it operates on a nominal scale, defined by the sets of values of the performance parameters considered. Evaluation of qualitative performance parameters cannot be delegate to others, let alone computers. This type of evaluative aggregation is a process that is only partially rational and only humans can perform.

6. Integration Framework

Combining the decision-making process and data models described in the previous sections, decision-making can be defined as 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. The building life cycle can then be modeled as a semantic network of design, context and performance variables. The sources of these values are humans and either simulation processes (during design) or sensors (during construction and operation).

All variables are also issues and their values are positions. The values of performance variables, determined through simulation processes or sensors, can serve as arguments to support or negate the values of design variables. The assignment of values to any type of variable can be time-stamped and associated with its source, 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.

The need of a specific piece of information by humans or processes is the equivalent of the need for the value of one or more variables, which can come from another human, a process, or a sensor. This model presents significant opportunities to facilitating decision-making not only during building design, but during construction and operation as well (Papamichael et al., 2000).

7. A Vision of the Future

In conclusion, computers can certainly help in decision-making throughout the building life cycle and offer significant opportunities to improve the design, construction and operation of buildings. In principle we can specify any process we want in the form of a computer program. 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 and augmented reality formats.

Imagine putting on your virtual reality stereoscopic vision glasses or helmet and have real time meetings with clients and engineers at separate locations around the world, in a virtual building displayed in photo-metrically accurate images. You can talk in real time, move around in any direction, not only spatially but temporally as well, point to building components and systems, change them in real time to explore what-if scenaria, display invisible data, like temperatures, air flows, etc.

Imagine being able to simulate and visualize the construction process even during design 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 renovating or remodeling.

Imagine that the latest information about commercial building components and systems are quickly and easily accessible through the Internet, including all data required by simulation tools in formats that can be automatically used in the integrated software environment.

Imagine…

7.1. 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; 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 many 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 (www.iai-international.org) is underway during the last nine 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 photo-metrically 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 distributing data needed for simulation processes. 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 compatible with the decision-making tools of the future.

Due to these challenges, the realization of the vision may take sometime. It is, however, just a matter of time.

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