INTEGRATING ENERGY DESIGN INTO CAAD TOOLS:

Theoretical Limits and Potentials

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Abstract. The study is part of a research aims to establish theoretical grounds essential for the development of user efficient design tools for energy-conscious architectural design, based on theories in human factors of intelligent interfaces, problem solving, and architectural design. It starts by reviewing the shortcomings of the current energy design tools, from both architectural design and human factor points of view. It discusses the issues of energy integration with design from three different points of view: architectural, problem-solving, and human factors. It evaluates theoretically the potentials and limitations of the current approaches and technologies in artificial intelligence toward achieving the notion "integrating energy design knowledge into the design process" in practice and education based on research in the area of problem solving and human factors and usability concerns. The study considers the user interface model that is based on the cognitive approach and can be implemented by the hierarchical structure and the object-oriented model, as a promising direction for future development. That is because this model regards the user as the center of the design tool. However, there are still limitations that require extensive research in both theoretical and implementation directions. At the end, the study concludes by discussing the important points for future research.

1. Shortcomings of Current Tools

In a previous study, Al-Sallal and Degelman (1995) attempted to clarify the shortcomings of current energy-integrated design tools by categorizing them into two main groups, those that concern design and those that concern human factors. It should be noted that these shortcomings are not clear cut;

on the contrary they have complex relationships among each other. They can be listed as follows:

1. Lack of integration between design tasks and the design process
2. Disregard of research knowledge
3. Reliance on approximate methods
4. Failure to aid the designer in the early stages of the design process
5. Complicated and time consuming
6. Isolation among design tools
7. Lack of standard means of evaluating design decisions
8. Focus on the machine control
9. Poor access to information

The first four shortcomings (i.e., from 1 to 4) are the ones that have direct impact on design. They belong to one category; that is the *design concerns* shortcomings. The last five shortcomings (i.e., from 5 to 9) are the ones that have impact on the user interface, which indirectly affect design. They belong to another category; that is the *human factors concerns* shortcomings. The human factors group is related to the problems of the intelligent interface explained below. The fifth shortcoming through the seventh one are related to the *communication* problem. The eighth shortcoming is related to the *automation*, or *control*, problem. The ninth shortcoming is related to the *accessibility* problem.

Card (1989) categorized the problems of the intelligent interfaces into two main types: the role problem and the automation problem. The question of role is related to the question of the design of the persona of a machine. Young (1984) pointed out that the choice of role might influence the acceptance of the program by users quite independently of the program's performance expertise. The automation problem is related to the problem of control mentioned below. The range of automation possibilities runs from direct control by the human, to complete control by the machine, to some of the many other combinations of paths (Card, 1989; Sheridanand and Verplank 1978.) Realizing the many automation dialogue possibilities raises the question: how should the human and the machine cooperate?, rather than, which tasks should the human do and which the machine? Chignell and Hancock (1989) believed that all interfaces face three fundamental problems: communication, control, and accessibility. Communication means communication of the user's intent to the system and of the system's response and its effects to the user. Control centers on the issue of who does what and when. Accessibility is that of making the full range of machine capabilities accessible and useful.

2. Integration Issues – Different Views

The architectural design process involves tasks that are performed by several members of the design team and phases through which the design evolves until its final form. This process becomes more complex every day with the introduction of new building technologies, new research findings, and more stringent codes. Without appropriate design tools, the integration of the different tasks of the design team throughout the different phases of the design process becomes very tedious or almost impossible. The issues of integration are discussed from three different views.

2.1. ARCHITECTURAL VIEW – ISSUE OF INTEGRATION WITH THE DESIGN PROCESS

There are two types of integration in the computer-aided design environments, vertical and horizontal integration (Mitchell and McCullough, 1991.) The vertical integration relates to the development and flow of data systematically organized to support work at successive stages-sketch design, design development, documentation, construction management, and in-use facility management. The horizontal integration relates to the access of data that support the different design team members, representing different design disciplines (architecture, landscape architecture, urban design, structural engineering, mechanical engineering, interior design, and so on). The issue of integration of computer-aided architectural design (CAAD) tools is very complex and has multiple levels (Mitchell and McCullough, 1991.) These levels are hardware integration, file transfer and translation, databases, coordinated software tool kits, and modifying and customizing the tool kit. The vertical type of integration, for energy design, would produce a single-domain user tool type. This type is usually much easier to develop and less expensive than the one that provide both types of integration.

2.2. PROBLEM-SOLVING VIEW – ISSUE OF DESIGN SEARCH

CAAD tools that are designed for a single domain use such as energy might help to produce promising solutions for that purpose. Its success comes from the concept of focus of attention that was discussed by Akin (1986) and was part of his discussion of search methods in design. The single-domain user tool is related to the method of Depth-first search. Akin described the depth-first search as follows:

> "Depth-first search can be characterized as the allocation of designer's attention to the siblings of a parent node before moving to the next parent node of the same depth in a tree-like search space.... As a search method in tree-like or lattice-like networks, depth-first search (a) does not guarantee optimal search of the tree, (b) does not insure

> finding a solution, and (c) does not insure a balance of emphasis between multiple issues of equal priority that may be implied by the levels of the tree structure."

Based on this discussion, one could conclude that although the single-domain user tool could find the best solution in only one aspect of the problem, its use becomes increasingly less useful when other aspects of the design problem are considered. Accordingly, these types of tools can be useful in either of two cases:

1. when the designer knows that the purpose served by such tool has much larger relative weight than other aspects of the problem; or
2. when the designer needs to evaluate his design (and not to use it for synthesis especially in the early stages.)

2.3. HUMAN FACTORS VIEW – ISSUE OF THE USER INTERFACE

It is much easier to design a user interface for a certain group of people who come from the same domain (e.g., architects) than it is the case with another who come from different domains (e.g., architects and civil engineers). That is because people of the same domain share similar knowledge and experiences. For instance, architects need different considerations in the design of the user interface from civil engineers. As mentioned previously, all interfaces face three fundamental problems: communication, control, and accessibility. Regarding the communication issue, architects would prefer flexible input description that is more concerned with design qualities than accuracy whereas civil engineers would prefer numerical description that provides high levels of accuracy. Regarding the control, architects would prefer the human control over the machine control because most of the architectural tasks cannot be automated; they are complex and involve diverse and non-measurable issues such as esthetics' consideration. Civil engineers, on the other hand, could prefer the inclusion of some levels of machine control (automation); optimization in engineering can be applied, due to the limited number of design variables and the capability to quantify them. Regarding the accessibility problem, both groups need to access all the capabilities of their programs but the way of facilitating that is different for each group. This problem is partly related to the design of metaphors. Each group needs metaphors that match its domain experiences. From this discussion, one can conclude that developing a user interface for a multiple-domains user tool is more complex than that of a single-domain one and requires a highly adaptive user interface.

3. Potentials and Limitations of Current Approaches

This section evaluates theoretically the potentials and limitations of some current approaches and technologies toward achieving the notion "integrating energy design knowledge into the design process" in practice and education based on research in the area of problem solving and human factors and usability concerns. Within this framework, it also presents the ideas of some potential models in implementing the current approaches and technologies.

3.1. HUMAN-COMPUTER INTERACTION – COGNITIVE APPROACH

Considering that most of the problems in the current tools are related to human factors leads us to realize the critical need for new approaches that are based on human-computer interaction theories, such as the cognitive approach. The cognitive approach employs theories in cognitive science and psychology to make the process of information in the computer similar to that of the human or to help the computer "understand" the user's need so that intelligent help can be given. The well-established theories and models of the cognitive science and psychology provide a strong foundation for the development of intelligent interfaces. In particular, the attentional resource theories can be used to decide intelligently how the displayed information can be distributed between the sensory modalities. However, very few research efforts have given consideration to the cognitive approach and theories (Al-Sallal and Degelman, 1994; 1995.) Other developed models that have shown indication of some relationship to the cognitive approach – although it is not stated clearly in their research is the BDA model (Papamichael et al., 1996; Papamichael, 1999; Papamichael et al., 1999.) The research efforts in both models indicated that in order to support decision-making, the tool must not only provide a means for performance prediction but for performance evaluation as well.

3.1.1. Potentials

The advantage of the cognitive approach as seen by Al-Sallal and Degelman (1994; 1995) is that it views the user as an intelligent information processor who is actively trying to solve problems with help of computer, which also must be intelligent to deal with the user. It appears intelligent because it gives the user the appropriate analogy to learn how to perform a task, helps the user solve problems with the use of graphics, and evaluates the user's plans and goals and providing error feedback dependent on that evaluation.

The BDA model supports the evaluation of concurrent design solutions, as well as links to a Case Studies Database of actual buildings to allow performance evaluation through comparison among alternatives. This is achieved by its graphical user interface that consists of two main elements:

the Building Browser and the Decision Desktop (Papamichael et al., 1999.) The Building Browser allows building designers to quickly navigate through the multitude of descriptive and performance parameters required by the simulation tools linked to the BDA. Through the Building Browser, the user can edit the values of input parameters and select any number of parameters for display in the Decision Desktop. The Decision Desktop allows multi-criterion decision-making, through comparison of multiple alternative design solutions with respect to multiple performance parameters. The Decision Desktop supports a variety of data types, including 2-D and 3-D distributions, images, sound and video.

3.1.2. Limitations

The research on the area of human-computer interaction (i.e. HCI) on the whole is still in the evolving stage and lacks the existence of well-established models. This is especially true in architectural applications, whose HCI research is still in the infancy, when compared to other areas of applications. This can be attributed to the fact that architectural design is a very complex process by nature, since it involves many issues with unlimited number of interdependent variables. The integration of all aspects of architectural design in one tool with effective interaction with the user is still believed to be ambitious goal, and it might be hard to imagine its accomplishment in the near future.

3.2. HIERARCHICAL STRUCTURE AND BUILDING REPRESENTATION

In discussing the activity of design description as part of the design process, Papamichael (1991) wrote, “Control variables are usually specified in an object-oriented fashion. The will-be situation is defined in terms of objects, which have attributes and may be children or parents of other objects, and can be seen as hierarchical, treelike structures.” Applying this to the energy building design, one can say that the real system consists of objects such as spaces, walls, windows, floors, and roofs. Each object has a set of variables (or attributes) to which designers assign values in order to describe it as part of the whole system. Some of these objects are subsets of others -- like a wall as a subset of a space and a window as a subset of a wall. In this treelike structure, the lower level objects cannot exist unless the higher level ones exist (e.g., no window without a wall).

Depending on the performance aspects being addressed (e.g., energy, esthetics, cost, etc.) simulation tools use different building modeling representations. To address this problem, the BDA uses a single, object-oriented building representation, which allows building designers to describe the building in terms of real world objects such as spaces, walls, windows, etc (Papamichael et al., 1996.) The BDA then automatically “translates” these objects into thermal barriers, geometric solids, etc., as required by the simulation tools linked to the BDA, thus relieving building designers from the modeling complexities associated with each simulation tool.

3.2.1. Potentials

The hierarchical structure is also supported by the theory of information chunking that was discussed by Akin (1986.) According to this theory, The human memory organizes pieces of information into chunks that have common relationships binding them together. The chunking of information allows larger numbers of units of information to be processed at one time. A primary strength of this theory is that it accounts for the limitations of short-term memory span and supports the hierarchic and multirelational organizations of information.

Accordingly, in order to improve the user's mental model of the energy-integrated CAAD tool, it is believed that the conceptual model and its display representation should support the hierarchical organization that exists in the nature of building design (Al-Sallal and Degelman, 1994; 1995.) Al-Sallal and Degelman (1994) considered the hierarchical structure shown in Fig. 1, as an appropriate structure for organizing project information of energy design due to the potential benefits of the information chunking theory mentioned above. Another cognitive benefit gained from using the hierarchical structure from the educational side is that it provides a mental model to the student in the design studio that is consistent with the methodology of energy design in other courses (e.g. environmental control).

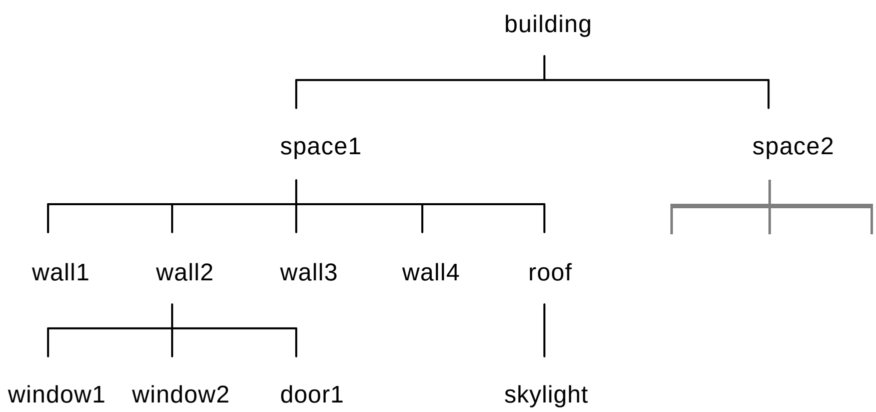

Figure 1. Class hierarchy of building components.

Although other research projects have implemented the hierarchical structure model, there is no clear indication if their primary objective was the consideration of human factors. Some significant examples of such research projects are S2 project (S2 is a developed version of the original project SEMPER) (Mahdavi et al., 1999) and BDA (Papamichael et al., 1996; Papamichael, 1999; Papamichael et al., 1999.) Yet, if the user is to be considered as the center of the tool design, this means that every part in the tool, including its model structure and interaction, has to be designed from the start based on human factors. When this is done, one could definitely realize great improvements in supporting the architectural design process.

3.2.2. Limitations

Modeling buildings with complex spatial organization using the hierarchical structure is somewhat difficult because of the complexity of relationships among the different spaces and objects of the building. This kind of complexity is seen, for example, in universal spaces where several spaces and building elements can merge into one large space. In some designs a thermal zone can include several spaces; whereas in others, a large space can include several thermal zones. This inconsistency can cause serious errors when building information is modeled. Also, the hierarchical structure is not helpful in modeling building forms in which it is difficult to distinguish among its different building objects and object's classes (e.g.; walls and ceilings.), such as those of sculptural or organic quality.

3.3. OBJECT-ORIENTED MODEL

In the object-oriented model, new objects can be formed by extending functionality and data attributes supported by existing object definitions. Similarly, new object definitions can serve to refine or tailor existing object behavior in order to support specific applications. This process is called Inheritance in the object-oriented programming terminology and provides a framework by which object behavior and/or data can be utilized by other objects in the system (Kacmar, 1990.) Another process, called Polymorphism, allows a common message to be sent to all objects within a class and its subclasses such that each object knows how to respond to this message. The ability to use the same message for a similar operation on different kinds of objects is consistent with the way human beings think about solving problems. Hence, this process can contribute to improving the user interface.

The BDA uses a generic object-oriented representation of the building (Papamichael et al., 1996.) It is generic in that it is not focused towards any specific domain or application, but instead models the actual physical components of the building. An object-oriented representation is based on the notion of objects (e.g., windows) that have parameters (e.g., U-value, visible transmittance), relations (e.g., composed of) to other objects (e.g., frame, glazing), and methods (e.g., display), which describe their behavior. The advantage of an object-oriented approach is that each object has not only a description of itself, but also an explicit behavior built into it, which enables it to manage its own actions. In BDA, for example, a Wall object contains a Construction object (which defines its materials), and two Surface objects (one for each side) describing the characteristics of the final finish. If the room on one side of an interior wall is deleted, the Wall object can automatically change its Construction and exterior Surface objects to match the requirements for an exterior wall. This kind of interaction is possible because each object in the BDA system has knowledge about itself and its actions.

One of the key features of SEMPER is that a user can input a building description and run simulations in multiple domains without having to manually create domain-specific building representations for each simulation tool (Mahdavi et al., 1999.) S2 facilitates this through the use of a Shared Object Model (SOM), from which the domain object models (DOM) for each simulation module can be automatically derived without any additional user intervention. To achieve this S2 depends on a process of SOM-DOM mapping and information flow.

3.3.1. Potentials

Al-Sallal and Degelman (1994), attempted to solve the problem of the user interface by representing the basic components of the design with objects and encapsulating their characteristics and methods within these objects. By doing this, the user can easily view the principal components of the system and specify their behaviors and interaction. Objects provide both data abstraction and information parsimony that helps to modularize a problem in its earliest stages of analysis. Another important point in the object-oriented model is related to the graphical representation of its components. Their model supported easy and effective user interface by providing natural pictorial (iconic) representation of real objects in the physical environment. Icons, which look like the components of the system being modeled, are placed on the screen to show the spatial relationships. This is especially important in modeling architectural systems where the spatial relationships are as important to designers as the internal information of objects.

3.3.2. Limitations

The attributes related to energy design of an object can be determined with certainty due to the existence of well-established models in predicting the thermal performance of buildings. However, there are other important aspects related to architectural design that have no such concrete models because of their subjective nature. Without definitive models, representing the information of such aspects of design as part of explicit objects is still not discernible. The behavior of an object and its interaction with other objects should be controlled by specific rules in order to assure the validity of the model as a whole. However, the integration among many aspects of design that usually has contradictory variables make the definition of these rules very difficult.

3.4. HYPERTEXT/HYPERMEDIA INFORMATION STRUCTURES

Hypermedia draws knowledge and makes powerful association to produce useful results based on the complex interaction of many factors that must be considered as a whole. As indicated by Scown (1985), AI-based programs not only manipulate symbols but they also control the relationships among them which, in turn, can represent real-world entities. Bielawski and Lewand (1991) stressed two key factors in intelligent systems:

- the ability to use knowledge to perform certain tasks or solve problems and
- the capacity to exploit the powers of association and inference in attempting to deal with complex problems that resembles the real world.

For computers to be "intelligent", they must possess at least subset of the human intelligent abilities such as solving complex problems, making decisions, and connecting thoughts and ideas in non-linear, associative ways. Equally important to these activities is the human ability to adapt or modify behavior based on reason and employ several skills given the situation at hand. Correspondingly, the intelligent systems must be adaptive according to type of situation or level of user.

3.4.1. Potentials

Some characteristics of intelligent hypermedia systems are as follow (Bielawski and Lewand, 1991):

- they provide nonlinear program navigation;
- they make effective use of existing information; and
- they are user-friendly and highly interactive.

As an organizational tool and information retrieval tool, hypermedia does provide a highly flexible context for representing energy design knowledge. Retrieving information of design objects and accessing knowledge bases depends on information access structures. Access structures provide tools for following links from node to node.

Al-Sallal and Degelman (1994) developed a design creation module that creates access nodes and embeds them in the plan view representations of design objects. When a new object is created, the program automatically builds the required links to connect it to the different knowledge bases and databases, as shown in Fig. 2.

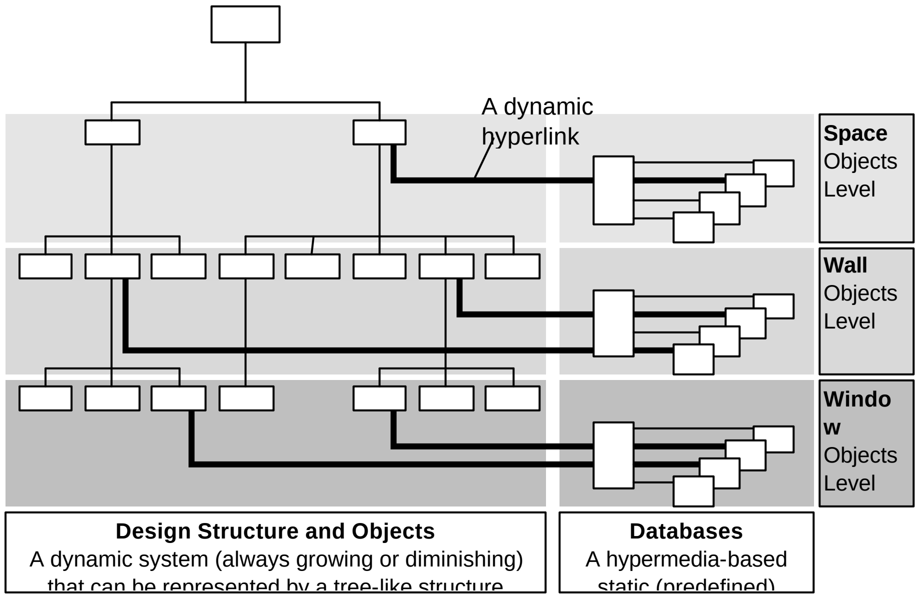

Figure 1. The design creation module automatically builds hyperlinks from the dynamic design structure to specific locations of construction databases when a new object is created.

The access and end nodes of these links depend on the type of object being created. While the user attention is focused only on design issues, the intelligent synthesis module generates the information structures of objects (i.e. designs) represented by two-dimensional plans on the screen. They also implemented the analysis module (i.e. design and results revision sub-modules) in a hypermedia structure, to allow non-sequential access to information. The result revision module allows the user to review the results produced by the energy simulation program non-sequentially by using navigational tools. It facilitates the use of the Building Energy Performance Standards BEPS (1979) to set criteria for the yearly total whole-building energy consumption.

The BDA supports the review and modification of the building specifications through a graphical user interface element called Building Browser, which is very similar in concept to the Window 95's Explorer (Papamichael, 1997.) In the same way that the Explorer allows navigation through directories and files, the Building Browser allows navigation through building objects and parameters. Moreover, it allows modification of the values of objects and parameters, and automatically maintains a record of who changed what and when. The values of building objects are modified by selecting from expandable libraries of alternatives. In addition to viewing the building model and modifying the values of descriptive parameters, the BDA users can use the Building Browser to specify which variables (descriptive or performance) they want to consider for decision-making and display their values in the Decision Desktop module.

3.4.2. Limitations

Navigation – Navigation, where the user alone is responsible for finding his way around a complex undefined structure, cannot be sufficient for efficient access to the information contained in a large hypermedia system (Waterworth, 1992.) It is unclear how to reduce the cognitive load this responsibility places on the user, without sacrificing the freedom of exploration that is such an attractive feature of hypermedia. Hierarchical organization of information like the one shown on Fig. 1 might be an acceptable solution for this problem in the architectural design when the access nodes of information, such as buttons or icons, are embedded in the different components of a building.

Disorientation – The disorientation problem can be viewed easily in the context of the architectural design process due to the complexity of acquiring design information from multiple levels of access in the design process. For instance, the architectural designer may need to access the general design strategies of daylighting (i.e., an issue related to the design of form level) then he/she might want to check if one (or some) of the strategies conflict(s) with the space heating recommendations (i.e., an issue related to the design of envelope level); should the system allow him/her to go directly to these recommendations before finishing what he/she was doing in the design of form level? It might be confusing and affect the usability of the system if the system allows it. Perhaps providing a map of the structure of information can help.

4. Summary and Discussion of Future Research

From the preceding analysis, one can deduce that there are two directions of future research in the area of intelligent interfaces in energy-integrated CAAD tools. The first direction should focus on how to adapt the well-established theories and models of the cognitive science in order to develop more suitable ones that satisfy our needs and problems. The points of research in this direction can arise from concepts that are related to the following:

Cognitive approach of HCI – the well established theories and models of the cognitive science and psychology provide foundation for the development of intelligent interfaces. The fact that research of educational technology area is largely established on theories in cognitive science makes the cognitive approach an appropriate vehicle to explore methods of integrating energy design into the design studio based on educational benefits. However, the integration of all aspects of architectural design in one tool with effective interaction with the user is ambitious goal and it is hard to imagine its accomplishment in the near future. The comprehensive integration requires extensive research on the area of human-computer interaction in architectural applications, which is still undeveloped if compared to other application areas.

Hierarchical structure – the hierarchical structure provides a mental model that is clear to the user and also consistent with the methodology of energy design; this indirectly encourages the user to start the design with issues that have greatest impact on energy. The hierarchical structure however has limitations in modeling buildings with complex spatial organization or complex geometrical forms.

The second direction is related to the implementation of theories and models. It should focus on how to overcome the limitations of the current approaches and technologies and how to exploit their potentials. The points of research in this direction can arise from concepts that are related to the following:

Object-oriented model – the object-oriented model helps to reduce the mental load on the user by helping him/her to form design objects while avoiding highly detailed procedures and to avoid risky designs that can result from inexperienced users by generating the design from prototype objects. This is especially important for students who have limited experience in energy design in buildings. Moreover, its potential of providing data abstraction and problem modularizing creates locations for linking concepts and projects taught in energy design courses with the design studio. It also provides information parsimony that helps to improve the user's focus of attention. However, the complex nature of the architectural design puts a limitation. The integration among many aspects of design, which usually involves contradictory variables, makes the definition of explicit objects with rules that control their behavior and interaction with other objects very difficult.

Intelligent hypermedia systems – intelligent hypermedia systems provide nonlinear program navigation, make effective use of existing information, and are user-friendly and highly interactive. As an organizational tool and information retrieval tool, hypermedia does provide a highly flexible context for representing energy design knowledge. Yet, in large hypermedia systems the freedom of exploration is not sufficient for efficient access to information and might be sacrificed in order to reduce the cognitive load this responsibility places on the user. Navigation in large hypermedia systems for architectural design might cause disorientation due to the complexity of acquiring design information from multiple levels of access in the design process.

5. Conclusion

The lack of providing appropriate building performance simulation tools for designers is a significant topic that has been investigated by many researchers. The failure to provide an appropriate tool that integrates well with the designer thinking during the design process, especially in its early stages, is a major problem. It is believed that this problem cannot be solved as long as the user is not regarded as the center of the tool design. The human computer interaction theories such as the cognitive approach can help us to understand this issue and provide us with the required theories on which we can build appropriate models. This paper presented two directions of future research. The first direction should focus on how to adapt the well-established theories and models of the cognitive science in order to develop more suitable ones that satisfy our needs and problems. The second direction is related to the implementation of theories and models. It should focus on how to overcome the limitations of the current approaches and technologies and how to exploit their potentials.

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