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A Knowledge-Based Layout Generation System

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Abstract

This paper describes a layout generation project which emphasizes the potential for using knowledge-based methods in architectural layout generation. This project focuses on the development of a heuristic-based layout generation system which works in cooperation with a designer to produce conceptual layouts. It is intended that the system will complement the expertise of the designer by using experiential knowledge provided by the designer, in conjunction with its own knowledge base, to generate conceptual layouts. The project incorporates several objectives including the development of a model for the representation of layout knowledge and information, the identification of heuristics used by designers during layout conceptualization, and the implementation of a control structure which facilitates the generation of knowledge-based layouts. The paper will address these objectives through a description of the overall layout generation project and a detailed explanation of the knowledge model developed in the initial project stages.

Keywords: Architectural Design, Artificial Intelligence, Computer-Aided Design, Knowledge-Based Systems, Knowledge Representation

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Introduction

The development of architectural layout generation systems has represented a primary research focus for Architectural-Engineering-Construction (AEC) researchers for over twenty years. These researchers have recognized the potential impact of integrating computer-aided architectural design techniques into the preliminary stages of design including a reduction in the time required to generate preliminary plans and an increase in the quality of generated layouts. The layout generation project introduced in this paper diverges from these earlier efforts, which have failed to yield a system acceptable to architectural designers, by focusing on a knowledge-based approach to layout generation. This approach emphasizes the incorporation of design methodologies utilized by designers in developing conceptual layouts.

The emphasis on a knowledge-based approach to layout generation will be addressed in this paper through a description of the overall layout generation project and a detailed explanation of the knowledge model developed in the initial project stages. First, the overall description of the project will provide a background into the objectives and primary focus areas of the project. Secondly, the explanation of the knowledge model will provide an introduction to the knowledge organization concept developed for this project. Finally, the implementation environment chosen for this project will be reviewed.

Project Overview

The layout generation project has been undertaken to explore the knowledge used by designers in developing conceptual layouts. Based on this overall focus, a prototype of a heuristic-based layout generation system is being developed. The system will be developed as a support tool working in cooperation with a designer to develop conceptual layouts. It is intended that the system will complement the expertise of the designer by using experiential knowledge provided by the designer, in conjunction with its own knowledge base, to generate conceptual layouts.

The primary research goal of developing a heuristic-based support tool for designers incorporates several objectives including the development of a design knowledge model, the identification of layout heuristics used by designers, and the implementation of a control structure which facilitates the generation of knowledge-based layouts. In addition, the project incorporates secondary issues such as graphical representations, user interface, and the relationship of this project to other design research.

The first of these objectives, the development of a design knowledge model, represents a central concern due to its relevance to the overall project. The knowledge model is required to provide a framework for the design knowledge in the system. This framework impacts the representation of the knowledge, the organization of the knowledge, and the inferencing procedures which access the knowledge. The importance of the knowledge model led to it receiving the initial focus of the three project objectives. A detailed description of this knowledge model will be presented later in this paper.

The second objective, the identification of layout heuristics, focuses on the identification of heuristics and guidelines which a designer employs during the design process. Throughout the design process, a designer addresses various issues in relation to a layout, such as user requirements and space planning. In many of these areas, a designer will use heuristics and guidelines to assist in the generation of a layout. The identification of this design process knowledge is important to defining the design heuristics which may be used to generate a conceptual layout.

The final objective, the implementation of a structure to facilitate the layout generation process, is required for the control of the overall system. The necessity to coordinate various types of design knowledge during the design process sequence requires a control structure which provides a high degree of flexibility. In addition, the control structure must permit the various types of design knowledge to be used as they are needed during the design process. Based on these requirements, a blackboard control system has been selected as the central control structure [Hayes-Roth 1985]. The blackboard system will include the knowledge necessary to coordinate the design process and the tasks associated with this process. In addition, the blackboard will allow the user to interact with the system as the generation of the layout progresses.

Based on these objectives, it is intended that the system will provide a framework for satisfying the overall goal of assisting a designer in the generation of conceptual layouts. Additionally, the system will demonstrate the potential for using a knowledge-based structure as the basis for providing useful layout recommendations.

System Domain

Design Attribute Focus Areas

The creation of a layout configuration requires the input of various design experts from diverse areas within the architecture-engineering-construction domain. Although it is the intent of this project to simulate the conceptual design process, it is beyond the scope of the project to include the entire realm of design expertise. However, a vertical slice of the information required to generate a layout will be incorporated in the system. In addition, the first version of the system will be confined to the design of university computer research buildings. However, even with these restrictions, the system will provide a basis from which to validate the essential concepts introduced in this project. The design domain attributes which will be addressed in the initial system implementation are as follows.

> *Space Planning* - The system will require general knowledge concerning the principles of space planning for university computer research buildings. These principles include knowledge about typical adjacencies, typical design object locations, and typical access requirements. This general space planning knowledge represents the first level of knowledge from which a conceptual layout may be developed.
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> *User Requirements* - One of the areas of design knowledge which has been largely overlooked in previous layout generation projects is the incorporation of user requirements. In this project, a segment of user requirements will be included to model the requirements of the typical building occupants. These requirements include daylighting needs, security factors, and acoustic requirements. The inclusion of this area of knowledge will extend the layout requirements beyond the typical physical constraints found in most layout systems.
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> *Daylighting Knowledge* - An important aspect of building design, at the present time, is a focus on daylighting requirements. In addition to the algorithms associated with daylighting requirements, daylighting heuristics have been developed in relation to energy consequences, building orientation, location, and configuration. The system will include knowledge concerning the impact of layout configurations on the daylighting requirements within a building.

Design Objects

In addition to restricting the building type and design attribute domains, the project restricts the design object focus. Architectural design objects may be thought of as the various components which comprise an overall design. These objects are typically defined as Neighborhood, Site, Building, Floor, Space, Workstation, Wall, and Window [Pohl et al. 1989]. Although each of these objects must be addressed during the course of a design project, it is feasible to restrict this view during the layout generation process. Therefore, this project restricts the design object view to the requirements of floors and spaces. Specifically, the project focuses on the types of spaces and floors in a university computer research building.

The Knowledge Model

While previous work by researchers such as Flemming [Flemming et al. 1988] and Gero [Gero and Coyne 1985], has explored heuristic-based design, requirements for representing the full range of knowledge which a designer uses in layout conceptualization has received less attention. The following model illustrates one potential framework for this knowledge representation. This model represents a characterization of the design process knowledge and the layout information used by a designer.

The characterization of design process knowledge consists of the categories of knowledge employed by a designer during layout conceptualization. These categories incorporate the experience and intuition of the designer which focuses on the coordination of layout requirements and features. The characterization of layout information features the categories of information required to identify typical layout features. This information is used to support the decision making process involved in developing a conceptual layout. These two characterizations form the model's premise that, the consolidation of both design process knowledge and layout information are essential to the successful generation of a knowledge-based layout.

Knowledge Categories

A protocol analysis of the design process, combined with examinations of previous work completed by such researchers as Akin [Akin 1978] and Woodbury [Woodbury 1987], has revealed that the primary framework of design process knowledge and layout information may be modelled as a series of individual categories. These categories include topological attributes, design attributes, and spatial ordering concepts for the layout information framework. Concurrently, designer expertise, design attribute heuristics, spatial ordering heuristics, and knowledge selection heuristics provide the framework for design process knowledge.

The knowledge model centers on the premise that the layout information and design process knowledge categories must not be focused upon independently (Figure 1). If a system focuses strictly on design process knowledge, then it reduces the capability to use layout information as constraints and guidelines for the evolving layout. The lack of these constraints and guidelines renders the eventual solution inferior in terms of the actual layout requirements. Conversely, if the system focuses entirely on satisfying design constraints, then the system loses the capability to examine solutions based on the experience and intuition of the designer. This pure synthesis form of design results

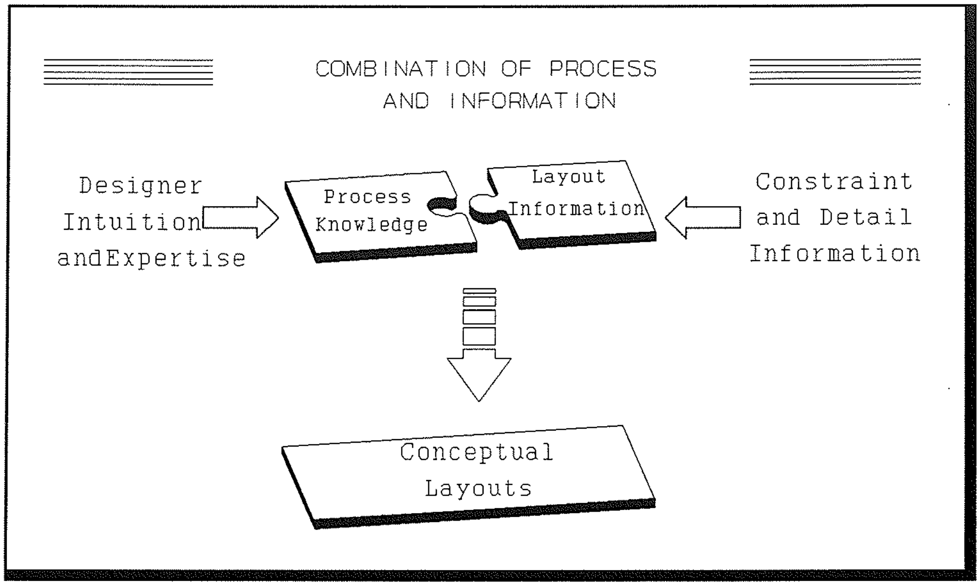

Figure 1: A combination of layout information and design process knowledge is necessary to produce useful conceptual layout assistance.

in a layout considered feasible by the system, rather than one considered acceptable in terms of design qualities.

Layout Information Categories

The classification of layout information into topological attributes, design attributes, and spatial ordering concepts, expresses the framework from which layout information may be stored within the knowledge model. Based on the protocol analysis used to define these information categories, the following definitions of each category have been developed.

> *Topological Attributes - The information relevant to the physical appearance and specific location of an individual design object.* The layout information represented in this category provides the topological constraints and guidelines for the design of individual objects such as spaces or floors. These attributes include square footage requirements, typical dimensions, typical length-width ratios, and other information related to the physical dimensions of a design object. This information category is necessary due to the tendency of designers, at various times, to address design objects based primarily on their topological requirements.

Design Attributes - The information related to each attribute which is relevant to the design of an appropriate object. The multiplicity of information associated with the design of a layout requires a designer to organize the information into categories which facilitate the use and retrieval of specific information. A natural organization of this information is in terms of the attributes related to the design of the layout, such as daylighting or space planning. In this way, the designer may retrieve information related to an attribute for an individual design object. This information may then be used as the constraints or guidelines for the design object in a particular design process circumstance.

Spatial Ordering Concepts - The spatial ordering paradigms which are relevant to a particular building type. In addition to requiring information relating to topological attributes and design attributes, a designer utilizes information related to typical spatial ordering concepts such as linear or clustered concepts. These concepts provide the designer with an ordering paradigm from which to develop a layout. This information category contains the standard ordering paradigms for a particular building type and the circumstances under which each type is appropriate for inclusion in a layout.

Design Process Knowledge

The layout generation design process referred to in this model is based on the analysis-synthesis-evaluation cycle frequently documented as the process used by architectural designers [Hyde 1989, Magee 1987]. The model proposes that the phases within this iterative cycle form the underlying focus for the design process knowledge categories. Through this focus, the design process knowledge categories may be refined to concentrate on the analysis and generation of relationship constraints, the synthesis of constraints into spatial placement alternatives, and the evaluation of placement alternatives.

The categories of designer expertise, design attribute heuristics, spatial ordering heuristics, and knowledge selection heuristics, provide the framework for the design process knowledge within in the model. The following definitions provide a further description of each category.

Design Attribute Heuristics - The knowledge required to transfer general design attribute information such as lighting levels and typical adjacencies, to specific design objects such as floors and spaces. The layout information related to individual design attributes may be used in different forms depending on the specific design phase which is being considered. For example, during analysis, design attribute information may be used to generate relationship requirements between different spaces. While during evaluation, the same information may be used to determine if a spatial placement option is valid according to the design attribute constraints. This category comprises the design process knowledge necessary to utilize the appropriate design attribute information as it is required in each design process phase.

Spatial Ordering Heuristics - The design knowledge necessary to generate potential placement options related to an individual spatial ordering concept. The generation of spatial placement options requires knowledge of the spatial ordering concept being employed by the designer. For example, the generation of placement options for a clustered layout will vary from those generated for a linear layout. Thus, specific knowledge is included in this category to facilitate the generation of possible placement options according to the spatial ordering concept under consideration.

Knowledge Selection Heuristics - The knowledge focusing on the central design process and the conditions under which specific types of design knowledge should be selected to assist in the layout generation process. An aspect of design process knowledge which serves a specific purpose during the evolution of a layout, is the knowledge which assists the designer in determining when to alternate between various phases of the design process and when to use different sources of layout knowledge. This knowledge serves to determine when analysis of constraints should be completed, when synthesis of spatial options should commence, when evaluation of options should be invoked, and finally, when these phases should iterate to refine the evolving layout.

Designer Expertise - The experience and intuition of a designer required to determine the overall design emphasis and focus of the evolving layout. An important aspect which a designer brings to a problem is his expertise developed over a period of time addressing a particular building type design. As a result of this experience, the designer develops intuition concerning the proper focus for an evolving layout. A segment of this knowledge which addresses the **typical** selection of spatial ordering concepts and the overall evaluation of an evolving layout will be incorporated in the system. However, the remainder of this knowledge must be incorporated into the layout generation process through direct designer intervention. This latter knowledge is required when the designer prefers to make decisions which go against what the system advises. At this point, the designer will invoke his own expertise to control the evolution of the layout.

Knowledge Model Representation

The representation of the knowledge model categories includes frame hierarchies, rule sets, and design object instances. These representations have been selected based on the necessity to relate information and knowledge from each category to individual design objects. Specifically, each component of information and knowledge must be represented in an appropriate manner which permits the information to be applied to an individual design object. For example, daylighting information in the design attributes category must be represented in a manner which permits the information to be related to the faculty offices design object. The following descriptions will provide an overview of each representation format in the model.

Frame Hierarchies

The layout generation process requires that various attributes of a design object be addressed according to the current design stage. However, a designer does not view these attributes as independent pieces of information. Rather, the designer views these attributes as components of the design object to which they belong. For example, a designer does not address the daylighting requirements of a faculty office as an independent piece of information. Rather, the designer addresses that piece of information as one attribute of an overall faculty office. Thus, a designer requires that information related to a design object be contained within the context of that object.

The use of a frame hierarchy representation facilitates the requirement to address information at the design object level. The capability to combine attributes into a single frame as one component, parallels the requirement to address design objects as one component containing multiple attributes. In addition to this information collection capability, the inheritance capability of frame structures permits the hierarchies to be described as a series of class specializations [Fikes and Kehler 1985]. Thus, faculty offices may be described as offices plus a set of properties that distinguish faculty offices from other kinds of offices. In this way, both general and specific design information may be used according to the requirements of the design object. Based on these capabilities, a frame-based representation was selected as the primary representation format for the layout generation project. The knowledge model hierarchies are introduced in the following sections.

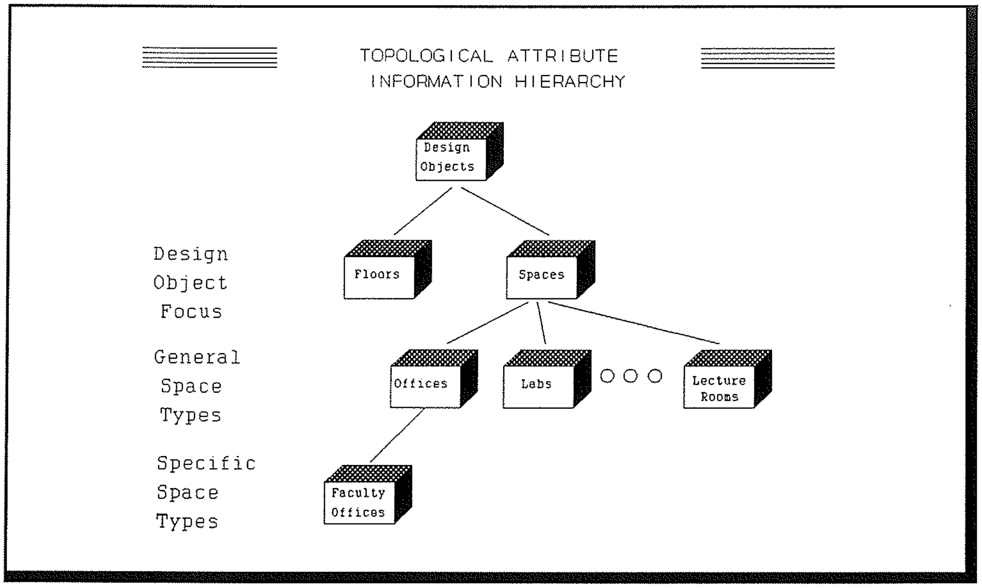

Figure 2: An example of one section of the topological attribute frame hierarchy.

Topological Attributes Hierarchy - The topological attributes hierarchy represents the fundamental design object organization in the knowledge model (Figure 2). The second level of the hierarchy, the design object focus level, separates the design objects into the typical categories found in an architectural design. Below that level, the hierarchy specializes into a definition of the types of spaces and floors found in a particular building type. At the lowest level of the frame hierarchy, the complete set of design object types found in this building type will be represented by individual frames.

Within this hierarchy, typical topological attributes such as dimensions are stored at the appropriate level of specificity. For example, default office dimensions are stored in the offices frame and more specific faculty office dimensions are stored in the faculty offices frame. In this way, default information may be inherited down through the hierarchy if more specific information is not known. However, if more specific information is contained in the lower level frames, then it will override the information inherited from the parent frames.

Design Attributes Hierarchy - The design attributes hierarchy has been developed to relate the information in this category to specific design objects (Figure 3). The design attribute categories level of the hierarchy represents the various types of design

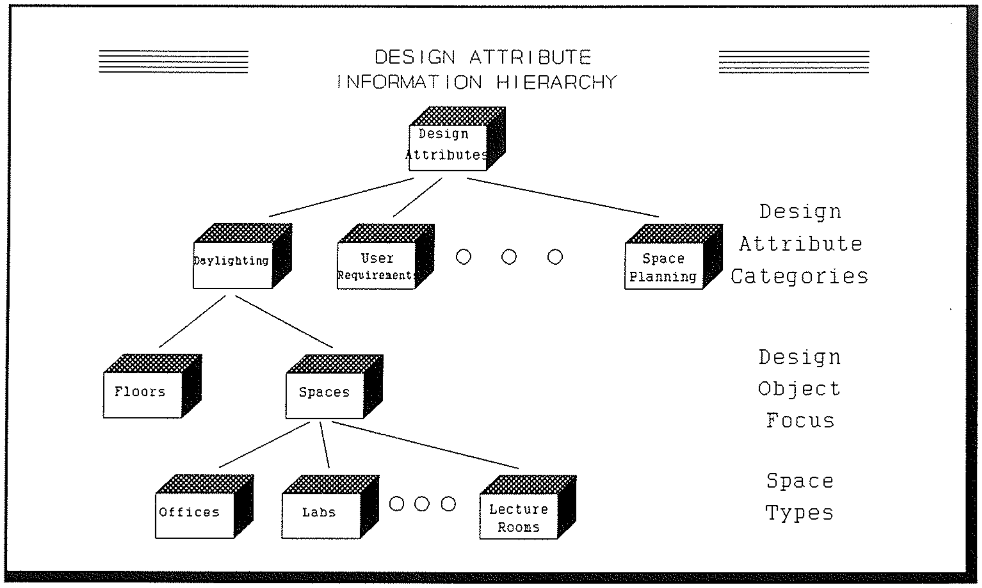

Figure 3: An example of one abstraction of the design attributes frame hierarchy.

attributes which affect design objects. The relationship between these attributes and design objects is then facilitated in the lower levels of the hierarchy. Below each design attribute, a series of frames is given which duplicates the frame representation hierarchy given in the topological attributes hierarchy. This representation enables each typical component of design attributes information to be related to the appropriate design object. For example, the offices frame below daylighting contains the typical daylighting requirements related to generic offices.

Solution Concepts Hierarchy - The solution concepts hierarchy represents the various types of ordering paradigms available to the system (Figure 4). In this hierarchy, the conditions under which an individual paradigm is applicable are stored in the frame representing that paradigm. To illustrate, the typical security level associated with the linear ordering paradigm would be stored in the linear paradigm frame. The hierarchy thus permits the general attributes required to evaluate each paradigm to be defined at the top level of the hierarchy and the individual values of those attributes associated with each concept to be stored in the appropriate frame.

Design Attribute Heuristics Hierarchy - The final hierarchy focuses on the design attribute heuristics category (Figure 5). This hierarchy comprises frames which represent the various design attributes in the system. The organization of the design attribute categories level of this hierarchy parallels the organization of the same level in the design attributes hierarchy. This parallel permits the model to partition the

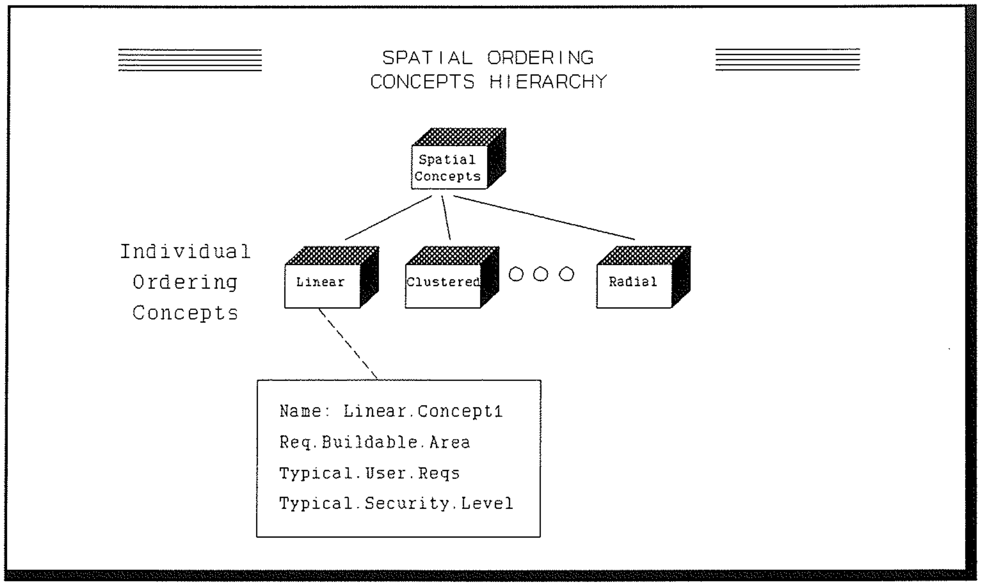

Figure 4: An example of the spatial ordering concepts frame hierarchy and the typical slots defined for each concept.

design attribute heuristics into rule sets which focus on individual design attributes. Each frame in this hierarchy contains the conditions under which a design attribute rule set is relevant. For example, the space planning frame may store information which indicates the space planning rule set is applicable during the analysis stage to generate adjacency constraints. In this way, the system may limit the number of rule sets which are fired at any particular stage in the layout generation process.

Rule Sets

The rule set representations focus on the heuristic knowledge associated with the design process knowledge categories. The heuristics which are obtained by the designers for each knowledge category are translated into corresponding rules. The rules may then be viewed as small expert systems focusing on a particular stage of layout generation. For example, heuristics obtained for space planning may be translated into a rule set which represents the acquired space planning knowledge. This form of representation permits the heuristics to assist in providing solution generation explanations and facilitates future expansion of the knowledge base. An example rule from the design attribute heuristics category is as follows;

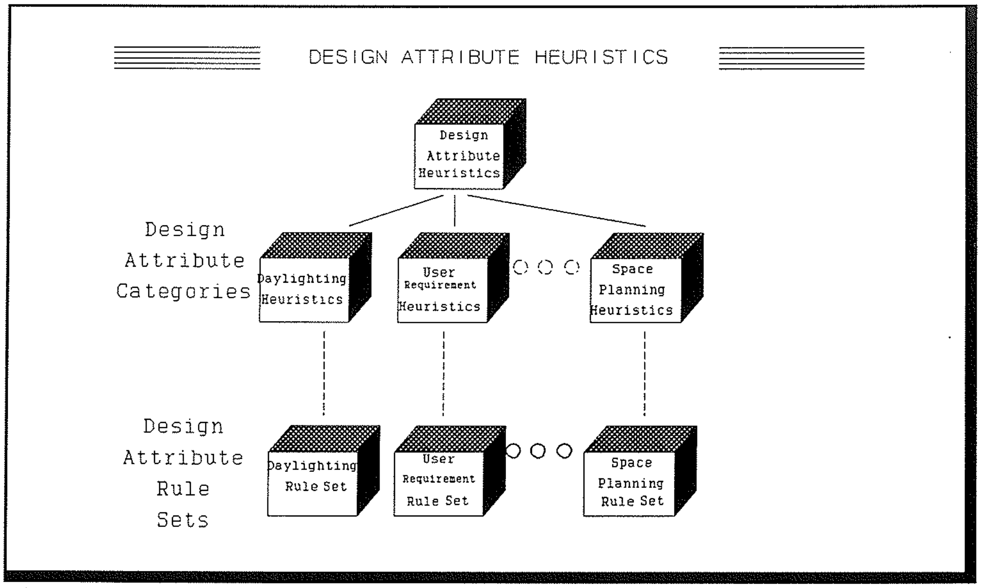

Figure 5: An example of the design attribute frame hierarchy with the associated design attribute rule sets. The dashed lines indicate that the frames reference the rule sets and subsequently activate the rule sets.

Space Planning Analysis Rule

IF

A space is a member of the seating areas class AND
The number of seating areas in the layout > 1 AND
A second space is a member of the administrative spaces AND
Space2 is a positive adjacency of space1

THEN

Set all administrative spaces to be adjacent to space1 AND
Remove all additional seating area adjacencies from the administrative spaces

In this rule, the system determines if there are multiple seating areas in the layout, and then, sets one of these seating areas to be adjacent to all of the administrative offices. It then eliminates all other seating areas from being adjacent to the administrative areas. This frees the system to use the other seating areas in other parts of the layout.

The rule sets are represented in the model as individual groups according to their focus. Each one of these rule sets is referenced by a frame which contains information concerning the circumstances under which the rule set may be executed. This

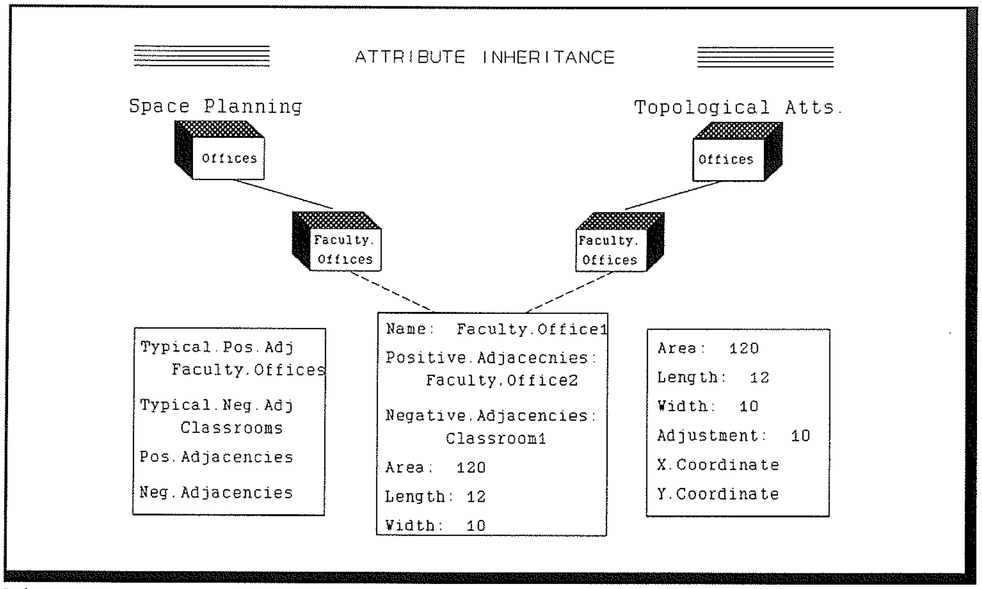

Figure 6: The multiple inheritance of attributes permits individual design objects to inherit topological attributes and design attributes from multiple parent frames.

referencing technique permits the system to reduce the number of rules which need to be fired at any given time. Subsequently, the system reduces the attempts to fire rules which will not be applicable at the current design stage. An example of this frame-rule set relationship is given in figure 5. In this example, the design attribute rule sets are referenced by design attribute frames. At the appropriate time, the frames will initiate the firing of their associated rule sets.

Design Object Instances

The final model representation focus is on the design object instances created for a particular layout generation problem. These objects fulfill the designer requirement to address a design object as one component containing multiple attributes. The object instances represent the actual spaces and floors which will be manipulated during the layout generation process. This representation is derived from the topological and design attribute frame hierarchies.

Each design object instance is instantiated as a child frame of the appropriate design object class defined in the topological hierarchy. Thus, a faculty office is instantiated as a child of the faculty offices frame in the topological attributes hierarchy. In addition, each design object instance is given a link to the appropriate frame in each design attribute category. This multiple inheritance provides each design object with both topological information and design attribute information. Figure 6 illustrates one section of this multiple inheritance scheme. In this illustration, faculty office1 inherits typical dimensions from the faculty offices frame in the topological attributes hierarchy and typical adjacency information from the space planning faculty offices frame in the design attributes hierarchy. In this way, the user may address all information related to a single design object through one frame, while the knowledge base retains its modularity.

Model Summary

In summary, the definition of the layout generation knowledge model serves a primary function of providing a structure from which the design knowledge necessary to generate a conceptual layout may be organized. The model enumerates the primary design process knowledge and layout information categories within the layout generation process. Additionally, the model permits comparison with and evaluation of other design systems that generate conceptual layouts. This classification by knowledge categories is necessary in a research environment where new systems consistently appear with varied claims and premises. Finally, the model represents a framework on which further layout generation research will continue.

Implementation Platform

The selection of an implementation platform for the layout generation system required the platform to provide the capability to incorporate various types of knowledge in a framework providing flexible control throughout the design process. Based on these requirements, the KEE environment has been selected as the implementation platform for the knowledge-based layout generation project. The primary issues leading to this determination include the standardization of the platform, the user interface, and the flexibility of representation.

The standardization of the platform is an essential aspect of this project due to the concern for knowledge exchange at the completion of the project. One of the underlying objectives of this project is the ability to let other design researchers review the project at its completion. The KEE system facilitates this objective due to its portability and rapidly increasing recognition within industry and academia.

The user interface issue involved with this project covers a spectrum of issues from ease of use to built-in graphics capabilities. The commercial status of KEE provides an interface which facilitates an ease of system building and an ease of graphics integration. These aspects of the environment facilitate rapid prototyping and system expansion. In addition, the KEE interface reduces the learning curve involved with the environment due to the ease of use factor which the interface provides.

The KEE system provides the fundamental tools required to develop the level of control required in this project. The object-oriented base of KEE provides the tools from which the blackboard system of control is being developed. In addition, the capability to combine rules with objects in KEE permits the control system to incorporate designer expertise heuristics which will assist the overall control of the design process. Based on these factors, the KEE system provided the necessary framework to most effectively implement the system.

Summary

In summary, the main emphasis of the knowledge-based layout generation project is on the definition and representation of design information required to generate conceptual layouts. This knowledge will be combined with an analysis-synthesis-evaluation cycle to provide support for a designer. In addition, the system will demonstrate the potential of using a blackboard framework to coordinate the design knowledge associated with developing a layout. Based on these emphasis areas, the system will provide useful layout recommendations.

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