Evaluating the Complexity of CAD Models as a Measure for Student Assessment

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Abstract

The feasibility of a proposed CAD project is often judged in terms of two conceptions of complexity: design complexity, based on visible features of the object to be modeled; and CAD complexity, based on the actual CAD embodiment of the design. The latter is suggested as a more useful guide. Clearer articulation of this underutilized concept is proposed for use in both educational and industrial settings. A formal model of CAD complexity is introduced, and initial experiments to determine the complexity of CAD models are described.

1 Introduction

A frequent culmination of computer aided design (CAD) teaching is the self-directed project, for which a student produces a CAD drawing or model. Each student selects a suitable design and develops and implements strategies to produce and display their model. During discussions with students on choice of project and general approach, matters of complexity inevitably arise. For any individual there is an optimal range of complexity. A too modest project may fail to challenge and extend, if the potential to extend the individual's technical knowledge is not exploited. An overly complex undertaking, if not recognized and corrected early, may consume many fruitless hours of effort, leaving the individual frustrated, demoralized and mistrustful of CAD technology.

Two interpretations of complexity are often discussed at the outset. One is based on the appearance of the object to be modeled; we call this *design complexity*. The second, *CAD complexity*, is based on the actual CAD embodiment of the design.

Design complexity is the more popular indicator of manual drafting task magnitude, because it is visible before work commences. Appearances can be misleading, however, especially in CAD production, where the magnitude of a task is highly dependent upon the designer's interpretation, what is modeled, and methods of representation. Superficial aspects of drawings and photographic images can mislead and short-circuit a designer's detailed analysis and planning at the commencement of their CAD task unless they are balanced by equally clear notions of the intended model.

CAD complexity is associated with the actual CAD embodiment of the design. It derives from the strategic use of CAD functions applied to both organization and production of the completed model. It is potentially a more useful notion than design complexity, because it directly concerns task outcomes, but it appears to have been underutilized. There are several reasons why this may be so. First, the concept of complexity is not entirely clear (Corning 1998). Although there is an abundance of published literature on complexity (e.g., Garey and Johnson 1979; Shannon and Weaver 1963; Simon 1996), much is about complexity in nature and relatively little is relevant to CAD. There is a need to clarify the sense of the term as it applies to CAD.

Another difficulty is that CAD complexity is not evident from the appearance of drawings generated from a completed model. Other indicators, such as the number of files or file sizes are no more revealing, unless some account is taken of the file contents. There is a need to identify the essential components of complexity.

Informal observations of students undertaking CAD courses in the Faculty of Architecture at the

University of Sydney indicate that many find it difficult to appreciate broader organizational aspects of CAD until their work is well advanced. A likely reason for this is a need to experience the consequences of different strategies in order to understand their significance. The possession of a tangible model-in-progress to see and discuss is obviously helpful as well. To bring tangibility to the start of projects there is a need to develop a consistent and coherent nomenclature of CAD complexity in a form that can be presented and understood before modeling commences.

Greater understanding of CAD complexity may also be useful to performance of a range of management activities in educational and other settings. Educational tasks could include

- matching project complexity to student knowledge and skill levels more accurately at the onset of a project;
- developing bases for modulating complexity during the course of a project; and
- developing objective criteria of use in comparison and assessment of completed CAD models.

Other strategic uses could include support for the development of

- bases for evaluating and coordinating the integration of CAD and related software;
- improvements to specific CAD techniques; and
- a general CAD methodology.

The remainder of the paper is structured as follows. Section 2 identifies concepts of complexity we consider in our study. Section 3 describes the subsystems of CAD organization that form the basis for our model of CAD complexity. Sections 4-6 describe ongoing experiments in testing the formal model of CAD, and future work. Section 7 offers some conclusions.

2 Concepts of Complexity

We begin by defining concepts considered important in understanding CAD complexity. In this paper the term "CAD model" refers to one or more computer files that are intended to describe or represent visual or other properties of a design.

2.1 Properties of Complexity

Corning (1998) identifies properties commonly associated with the term 'complexity'. He states that complexity often implies the following attributes:

- A complex phenomenon consists of many parts;
- There are many relationships/interactions among the parts;
- The parts produce combined effects that are not easily predicted and may often be novel.

2.2 Interpretations of Complexity

Although complexity has been described above in a broad sense, we offer some common interpretations of the term and select those that are relevant. These are described below.

Degree of Difficulty. It is recognized that complexity of a CAD task can influence its difficulty. Since many other factors also influence task difficulty, we do not explore this relationship.

Real Complexity. There is a difference between 'real' complexity, objectively measurable and substantially irreducible, and 'apparent' complexity, a matter of perception and interpretation, varying from one person to another. Our interest here is in measuring real complexity.

Necessary Complexity. Human artifacts typically contain both necessary and unnecessary elements, both intended and unintended. The CAD complexity of this study is that which may be regarded as intended and necessary. We do not consider here the area of CAD intentions, but acknowledge that CAD models produced for one purpose are frequently put to other uses.

Organized Complexity. Weaver (1948) distinguishes between disorganized and organized complexity. Since CAD models can be considered ordered systems, we focus here on organized complexity.

2.3 Complex Systems

CAD models are systems, in that they combine any of the above attributes of complexity within some integrated form. Complex CAD models are complex systems, based on the Simon's description that complex systems are "made up of a large number of parts that have many interactions." (1996, p. 183)

Research into complex systems has been stimulated in recent years by studies of chaos. One outcome of this research has been a greater interest in the study of complexity in its own right (Simon

1996, p.181; Salingaros 2000), including the study of ordered complex systems.

CAD models, at least as we currently understand them, can be considered ordered complex systems, in both: a) design complexity, since order can be considered an objective of design; and b) CAD complexity, since the CAD model is an embodiment of some form of order. This need not always be true; some aspects of design complexity, and some functions of CAD modeling, such as surface representation, may involve the intentional use of chaos, e.g., for artistic purposes.

Simon (1996) makes the following observations about complex systems:

- Complexity of a system depends critically upon how it is described.
- Most complex systems contain a lot of redundancy.
- Simplicity of description can be achieved by finding the right representation.
- Hierarchies of complex systems can often be described in economical terms.

In applying these observations to CAD models we conclude that a first step towards achieving an economical description of CAD complexity is the identification of CAD hierarchies.

2.4 Complexity Criteria for Graphic Systems

A number of different criteria have been identified and used as measures of complexity for graphic objects. One of the earliest measures was developed by Birkhoff (1933), who based shape complexity on the number of sides of a polygon, leading to a formula for measuring aesthetic values. Attneave (1957) used matrix grain, curvedness, symmetry, number of turns, degree of compactness and angular variability as parameters in his experiments. Stiny and Gips (1978) suggested that the lengths of shape descriptions and generative specifications define shape complexity, following similar work in information theory (Chaitin 1975). Salingaros (1997) has used an analogy with thermodynamic complexity to describe the complexity of drawings of buildings by measuring thermodynamic temperature and architectural harmony. A recent Ph.D. thesis (Cha 1998) develops measures for shape complexity using pattern representations.

2.5 CAD vs. Design Complexity

The complexity of a CAD model is influenced by design complexity to the extent that properties of the design or modeled object are represented in its CAD embodiment. It may be inferred that the distinguishing elements of CAD complexity derive from something other than these properties. An object may be interpreted and represented in different ways by designers for a number of reasons, and in different ways by CAD systems due to variations in system functionality. One could also observe that distinctions between a CAD embodiment and the designed object arise from the fact of representation. We therefore believe that distinguishing elements of CAD complexity can arise from characteristics of CAD interpretation and representation.

2.6 Sources of CAD Complexity

Three possible sources of CAD complexity can be distinguished: CAD data, or the information content of the CAD model; CAD structure, associated with the model's file organization; and properties associated with application software functionality.

CAD data. Here we consider element type and differentiation (variety) within a model. Items in this category include the actual components of the CAD model, i.e. shapes and annotations:

- Shapes or figural information includes vectors and inserted raster images. Graphic symbols, such as North points and hatch blocks may also be considered as belonging to this category.
- Annotation includes dimensions, other numeric data, and drawing notations, such as headings, notes or title blocks. Also included is documentation to facilitate communication, but not necessarily part of the model.

Measures of CAD data include quantities such as numbers and variation of objects, shape complexity and non-geometric properties. In measuring the complexity of notation, fonts, scales and other properties that fulfill specific presentation requirements become relevant. Further distinction can be made between data that is part of the design and data that is part of its presentation. It should be noted that raw CAD data may appear to be repetitious, difficult to analyze and reflect design complexity more than CAD complexity.

CAD structure. Here we consider the organization of the CAD data in a model. Items in this category include file variables and inter-file variables:

- File variables include functions that support differentiation and organization of data within individual files, such as colors, line types, layers and complex objects. Complexity measures may be similar in principle to those used for measuring CAD data.

- Inter-file variables include functions that support organization and inter-file referencing of data. Typically files are of the same type; use of different file types may require data translation.

CAD model structural elements are highly capable of analysis and decomposition by reference to CAD functions. Many support hierarchical organization, making them suitable for use in describing CAD complexity based on organizational subsystems (described in Section 3).

Application software. CAD software varies significantly in the extent and manner of its support of CAD production, editing and display functions. This influences not only how models are created, but also what is created. Given the large number of different CAD products, this is beyond the scope of our project.

We do offer some indication of the manner and extent of software variations by using as reference two different CAD applications, AutoCAD and ArchiCAD. Significant differences of approach and function are highlighted where appropriate in the description of each of the organizational subsystems.

3 Subsystems of CAD Organisation

At this point we identify and describe various CAD model hierarchies, categorizing five subsystems of CAD organization, on the basis of organizational processes. There are four categories described, in order from low to high level of organization. This order coincides with the least to most technically advanced, with the least to greatest potential to provide high levels of efficient model realization. We include a fifth category (pre-sets) that incorporates peripheral factors, which are integral to the communication of a model, but are not part of it.

3.1 Object Differentiation

Differentiation is a simple, non-hierarchical structuring that implies grouping within a model file. It may be achieved by varying one or more appearance characteristics, enabling one to visually identify different classes of element, or particular parts of a model. Its main characteristics include:

Shape. Different shapes can represent different objects. Proximity and orientation of shapes to each other or to some ordered form, such as a grid, may also be employed to assist recognition.

Color. Variation in hue, saturation and other object color properties enable different classes or conditions of objects to be visually distinguished regardless of shape. Typical CAD software allows association of colors with pens, thus enabling plotted line thickness to be modulated by means of color.

Figure 1. Object differentiation: varying shape, colour, line type

Line type. Particular repeating patterns of shorter lines, dots, symbols and spaces facilitate the visual distinction of linear objects, such as centerlines, particularly when they overlay other objects.

3.2 Object Grouping

Grouping is a method of relating objects within a model file, to act as one, by means of one or more of the following functions:

Informal or unnamed grouping. CAD software supports informal, one level groupings in different ways, e.g.:

- AutoCAD 'polylines' may be drawn as a continuous string of lines or formed by converting a series of end-to-end objects into a complex polyline.
- The ArchiCAD 'Drafting Modifier' option allows a designer to draw a continuous string of lines. These may be converted into one continuous object, through use of one of the ArchiCAD building tools, e.g. the Slab tool.

Formal object-class grouping. CAD applications support open ended class groupings by allowing designers to assign elements to named layers. The use of layers enables designers to control display properties, such as color and line type, and selection properties of different classes of design elements. Layer hierarchies, of two or more levels, may be a feature of the system, or can be created implicitly by the use of layer naming conventions.

Formal or named-object grouping. The ability to group objects and build complex hierarchies of nested objects has long been associated with drawing applications. Use of named 'blocks' in AutoCAD to 'modularize' a design enables designers to achieve significant economies of file size and simplify the production of a CAD model.

Patterns. An additional grouping is the pattern, generally not supported in commercial CAD systems currently available. A pattern can describe such relationships between objects as translation and rotational symmetry; these may be intentionally created by the user, but are not explicitly stored in the CAD model. Sophisticated pattern recognition routines are typically utilized to identify such relationships in a design (Cha 1998); however, the complexity of most CAD models would likely prohibit effective utilization.

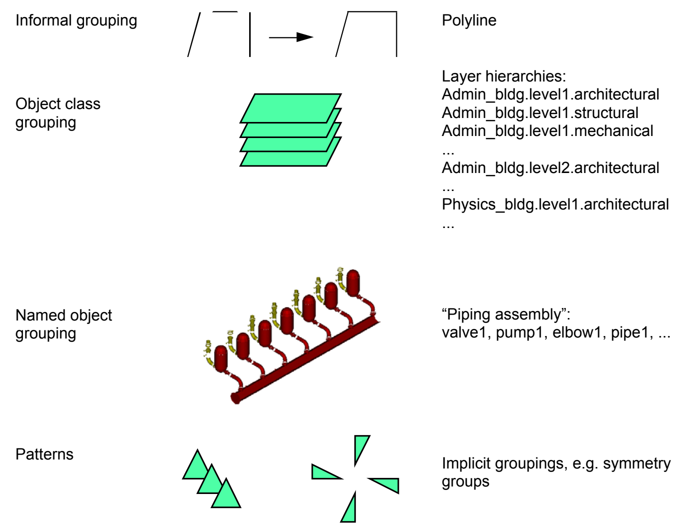

Figure 2. Different types of object grouping

3.3 *File Grouping*

Complex CAD models that require a significant amount of production time, or more than one author, generally warrant the organization of design objects into multiple files. AutoCAD External Referencing allows a drawing file to be 'attached' to another. ArchiCAD supports file grouping by means of Library files, an alternative to AutoCAD blocks. On large projects external references may be used instead of blocks as a means of reducing inconsistencies among files. Both systems allow hierarchies of attachments to be developed and include validation procedures to prevent circular referencing.

3.4 *Application Grouping*

A trend in the evolution of computer applications is toward increasing functionality and complexity. This is indicated by the number of additional functions, increasing memory and disk space requirements with each new version of software. Associated with the general growth is the growing mobility of data among applications.

Linking CAD software to external database or spreadsheet applications is now commonplace. Recent trends toward the development of sophisticated dynamic models, capable of simulating complex facilities, will further stimulate multiple file and application structuring, making this a fertile source of new hierarchies.

3.5 *Pre-sets*

Predefined settings (pre-sets) that control object display can facilitate communication of a model of substantial complexity. While not part of the model, pre-sets can be considered agents for the expression of the model's organizational hierarchy. We therefore consider them as part of an overall strategy to manage complexity. Examples of pre-sets include

- *Filter lists*. Filter options in AutoCAD permit designers to limit the display of different classes of object, based on color, line type and other properties, such as location, current in-use status, or their association with externally referenced files.
- *Layer Sets*. Combinations of layers in ArchiCAD files may be defined, named and saved, as named layer sets in the Layer Menu.
- *Named Views*. The View command in AutoCAD permits designers to store combinations of viewpoint coordinates, orientation and zoom in the form of named views.
- *Other Display settings*. There are many other useful pre-sets, e.g. page layout functions, which include ArchiCAD Plotmaker and AutoCAD Paperspace/Layout.

4 CAD Model Construction

Here we describe a number of experiments in constructing of CAD models, to be later evaluated according to the complexity criteria. There are a number of ways that model construction can be varied in order to test our model of complexity. We describe them below, noting which ones are examined in our pilot project and which could be explored in further research.

4.1 *Modelling techniques*

A building can be modeled using 2D representations such as plan, section and elevation, or by 3D representations such as wireframe, surface or solid representations. Model organization can also be varied by the use of devices such as layers, blocks, external references, and single vs. multiple file organization. We focus here on the organizing devices.

4.2 CAD systems

This can have profound effects upon the representation of the model. For example, AutoCAD is a generic CAD system, requiring the user to model with geometric primitives such as lines, surfaces and solids. ArchiCAD uses a very different modeling paradigm, oriented toward the architectural user, who primarily models higher level architectural elements such as walls, doors and roofs. We therefore expect that a model constructed with one system will have different measures of complexity to one constructed with another system.

4.3 Design complexity

How does one compare the two designs in Figures 3a and 3b? 3a depicts the design of a student residence that has many components, with heavy use of repetitive elements. Does this produce a more complex model than that in 3b (Rietveld-Schröder house), a smaller building with fewer components but little repetition?

Measures of design complexity could stem from the measures of shape complexity described in Section 2.4. Stiny and Gips *(1978)* define aesthetic value of a design as the ratio length of its description: length of its generative specification.

The length of a description is analogous to the size of a CAD model file, as information such as color tables, block descriptions and instances are often stored internal to the file. The generative specification is analogous to the sequence of commands used to construct the model. A generative specification is precise, while a designer's CAD construction methods will vary from person to person, and even session to session. Protocol studies could, however, be useful in generating specifications for CAD model development (Flemming, Bhavnani, and John 1997).

We note that design complexity may also influence the choice of CAD system and modeling technique. Experience has shown that, for a design consisting of curved surfaces and 'freeform' shapes, students are more likely to choose a CAD system such as FormZ, which allows easier modeling of such objects than AutoCAD.

4.4 Individuals

Each individual develops her or her own style and modeling technique. Part of our study consists of comparing models of the same design, but constructed by different individuals.

As an example, compare two AutoCAD models of the same building (Figures 3d and 3e), developed by different students. The modeling techniques varied, with a significant difference in CAD file size (file D is more than twice the size of file E). Analysis of these models and similar ones are described in the Appendix.

While we use multiple subjects to construct the models, measuring the variability of the results by user requires a larger number of subjects and models constructed than possible for our initial study. We therefore give our subjects specific guidelines for model construction in order to control the variability of technique. Our goal is to develop data extraction and analysis techniques that can be applied to any CAD model, thereby enabling recognition of particular patterns or inclinations in student modeling.

5 Measurement of Complexity

At this point, data is extracted from the CAD models and analyzed. The results give us measures of the complexity of the models. Among the criteria used in comparison are:

- counts of element types;
- use of blocks, external references and layers;
- other types of repetition and differentiation.

As an illustration of the some of the analysis issues, results from a group of student produced AutoCAD files are described below, with a small number illustrated in the Appendix.

Our initial studies have involved examination of models produced by students using AutoCAD in introductory courses. The work of the architects Glenn Murcutt and Tadao Ando are popular modeling choices for students in our Faculty. The designs often contain a large number of repeated elements, thus serving as a good basis for design and model analysis. We have a small but useful sample of models that can be used as a basis for comparison.

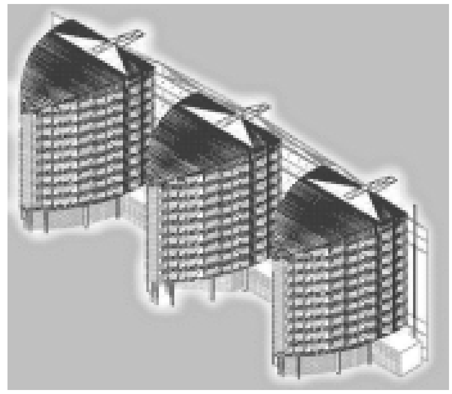

Figure 3a. Clingancourt student residence

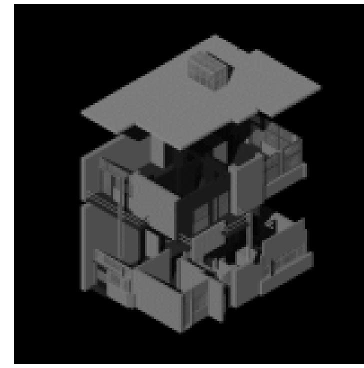

Figure 3b. Rietveld-Schröder house.

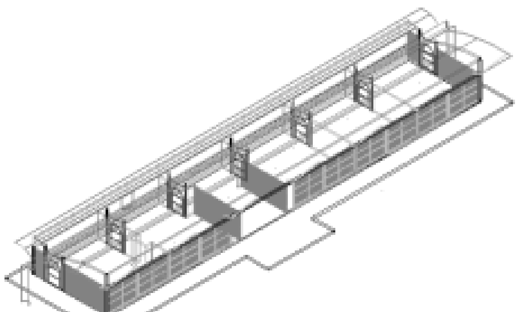

Figure 3c. Magney house (Glenn Murcutt).

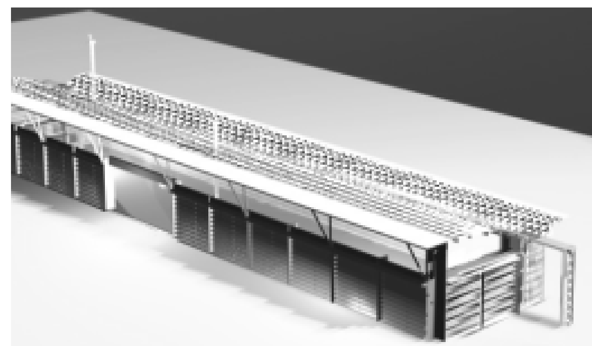

Figure 3d. Magney house (Glenn Murcutt).

Figure 3e. Magney house (Glenn Murcutt).

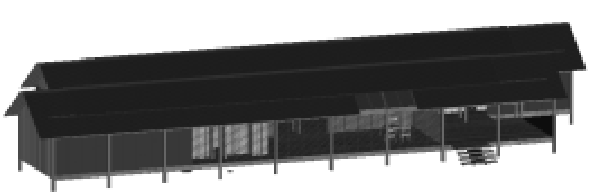

Figure 3f. Marie Short house (Glenn Murcutt).

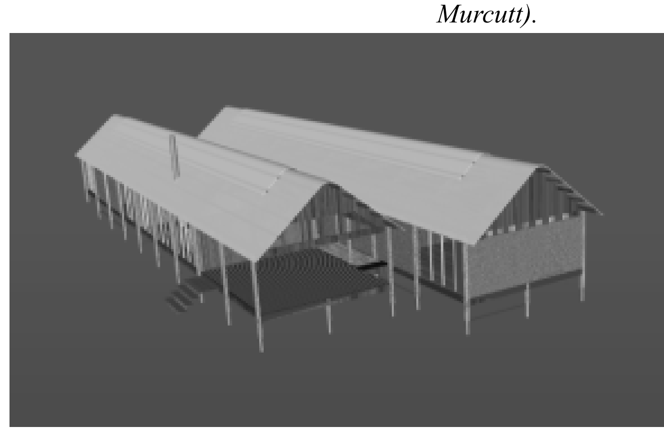

Figure 3g. Marie Short house (Glenn Murcutt).

As expected from novice modelers, the files vary substantially in their respective quantities of objects, suggesting different modeling approaches among files, and even inconsistencies within files. Files produced by more experienced individuals are likely to show more consistency.

The main observation from this small sample is that measured quantities of various file elements are not especially revealing on their own, but may be useful indicators of where one should look to determine particular file characteristics. These include inconsistencies of technique, or extensive use (or lack) of various organizational or production methods.

In the current study students create designated CAD models according to specific criteria. Comparisons are made of the utilization of certain modeling techniques, including:

- Blocks vs. non-grouped objects vs. xrefs
- Layers
- Multiple file usage, including xrefs
- Color styles

We have focused initially on block descriptions and layer usage, the two most common organizational tools of the novice user. Measurements are taken of:

- Model file size;
- Number of objects (this includes graphical objects such as arcs and polylines, nongraphical objects such as layers and linetypes, and block definitions);
- Numbers of block definitions and block instances (user defined only);
- Model file size and number of objects after one iteration of block/element explosion; these values give a measure of the extent to which blocks and other complex elements are utilized.

The ratios of these values provide a crude metric of relative complexity, particularly as a means of indicating where a student may have used these organizational tools to a great or lesser extent (Table 1). Future work will involve refinement of these metrics.

	Clingan-court	Rietveld-Schröder	Magney house			Marie Short house	
Student	A Fig. 3a	B Fig. 3b	C Fig. 3c	D Fig. 3d	E Fig. 3e	F Fig. 3f	G Fig. 3g
file size (KB)	5087	3715	1161	2113	994	332	2876
no. objs	1967	3071	874	695	1164	5808	2797
no. layers	26	42	18	7	23	55	108
no. block defs	43	0	13	1	9	23	20
no. block instances	290	0	120	7	29	1367	272
objs/block instance	6.78	N/A	7.28	99.29	40.14	4.25	10.28
instances/block def	6.74	N/A	9.23	7.00	3.22	59.43	13.60
objs/layer	75.65	73.12	48.56	99.29	50.61	105.60	25.90
size/obj	2.59	1.21	1.33	3.04	0.85	0.06	1.03
EXPLODED							
file size (KB)	26346	5569	7547	3199	1801	6151	7462
no. objs	4662	9812	1999	2294	2301	129298	9556
objs/block instance	16.08	N/A	16.66	327.71	79.34	94.59	35.13
objs/layer	179.31	233.62	111.06	327.71	100.04	2350.87	88.48
size/obj	5.65	0.57	3.78	1.39	0.78	0.05	0.78
COMPARISONS							
exploded size/orig objs	13.39	1.81	8.64	4.60	1.55	1.06	2.67
orig size/explode size	0.19	0.67	0.15	0.66	0.55	0.05	0.39
orig size/exploded objs	0.42	0.31	0.44	0.30	0.51	0.04	0.29

Table 1. CAD model data.

How can one combine these various measures to give an accurate assessment of CAD complexity? Is this even necessary? In terms of student assessment, a simple weighting of the criteria could suffice. This may, however, reflect the student's usage of a particular feature rather than the actual complexity of the model.

6 Formal Model Evaluation and Future Work

We are currently in the process of automating the extraction process in order to produce statistical summaries of model file data and organization. These can then be utilized in formal assessment of student models.

In a future stage of work we will evaluate the formal model to determine whether it provides a useful measure of CAD complexity. By examining the CAD model analysis, we will determine whether any normalization of the data is possible, whether there are any trends or anomalies to be found, and whether the results coincide with our expectations drawn from experience. The evaluation of this experiment also allows us to determine the feasibility of continuing the project on a larger scale by utilizing a larger sample set of CAD models and testing more of the complexity criteria from our formal model.

The results should provide insights regarding the use of formal measures of complexity to improve the usage of CAD technology in the selection and assessment of student projects, as well as in practice.

7 Conclusions

The CAD subsystems described above provide a basis for measurement of five different aspects of complexity. Within each there are more variables to measure.

Complexity, like intelligence, or the weather, includes both interdependent components and others that act independently. Unlike intelligence, CAD complexity itself is not an objective; the goals are to optimize and manage complexity. Unlike the weather, complexity can be controlled. Measurement of CAD complexity is fundamental to both optimization and control.

The implications of these observations extend beyond the educational context. Ultimately, CAD is about communication, and that changes everywhere technology progresses. CAD usage is evolving beyond single task "throw away" functions of project-based design and construction, towards interoperability and longer-term applications, such as large-scale system simulations and facility management. Interoperability requires greater consistency in the use of CAD as well as the design of CAD software. Long-term applications demand both consistency and durability of CAD models. As these factors grow in importance, so does the need to further develop and refine principles and concepts of CAD organization, based on objective measurement.

Acknowledgements

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Appendix

We provide here a more detailed analysis of the models described in Section 5. Some analysis of the data and images of the models follow the table.

A comparison of files A and B illustrates the issue of design complexity vs. CAD complexity. Both models were created by students who appear relatively capable with CAD technology, as evidenced by their final presentations. The file sizes are of the same order, with a ratio of about 1.4:1. However, Model A (Clingancourt student residence) represents a design with a considerable amount of repetition, while Model B represents one (Rietveld-Schröder house) with relatively little. This is borne out by the relative use of blocks in the two files (none at all in file B[*]). A one iteration explosion of file elements increases file A fivefold, but file B only 50%.

Variations in students' modeling techniques can be seen in files C, D and E, which represent the same building. File C makes significant use of blocks, the others, less so.

There may not be a direct correspondence between file size and number of objects, as evidenced in files D and F:

- File D is very large for the number of objects it contains. The object/file size ratio is approximately 1:3. The author has created only one effective block definition, this being the triangular element repeated along the high edge of the roof. The high file size is largely due to the louvers, each of which is an individual 3D solid.
- File F, in contrast, contains a large number of objects given its size, with a size/object ratio of approximately 17:1. An examination of the file indicates that extensive use is made of blocks in the drawing of the roof structure, skylights and louvers, explaining the relatively small file size. However, some block definitions are comparatively small and specialized and there are a number of them, e.g. the roof panels. The large number of objects can be explained by the combination of simple blocks and line work. This file can be considered a good example of tectonic modeling, i.e. an assembly of the actual construction components of the design.

File G is a large file with an object to file size ratio of approximately 1:1 despite having a large number of block instances. A possible explanation is the author's extensive use of individual 3D solids in addition to blocks.

[*] The omission of blocks could reflect upon the student's CAD modeling skills or his understanding of the design itself as lacking repetitive elements.