Over the centuries, architects have expressed their designs as one-dimensional strings of text, two-dimensional drawings, three-dimensional scale models, and—most recently—digital databases stored in computers. Successive advances in information technology have enabled the description and execution of increasingly ambitious projects. Today, innovative applications of computer-aided design and manufacturing technology are allowing architects to transcend long-standing limits on complexity and, thus, to respond more sensitively and effectively to varied human needs and construction contexts.

The tradition of expressing designs as text strings goes back at least to the Biblical instructions to Noah to “Make thee an ark of gopher wood; rooms shalt thou make in the ark, and shalt pitch it within and without with pitch.” (Genesis 6:14). It continues today in cake recipes, and in the instruction leaflets that come with unassembled products. Such text strings are typically process descriptions of designs: They explicitly specify sequences of operations that will produce desired results but may leave the details of those results implicit. The operations must be executed to see how the details work out.

Conversely, architectural drawings and scale models are state descriptions: They explicitly specify potential states of the world (the geometry and materials of proposed buildings) but leave the processes for producing those states implicit. Thus, component fabricators and construction contractors must translate plans, sections, and elevations into sequences of construction operations that will generate buildings that comply with them. As designs develop, state descriptions of options play crucial technical and social roles. They can be presented to clients and consultants, subjected to engineering and cost analysis, and critically discussed to determine whether they satisfy established goals and constraints.

In current design practice, computer-aided design systems maintain databases that describe the geometry and materials of buildings in digital format. Designers generate these databases by inputting strings of commands—either in textual format or as sequences of operations with a graphical input device such as a mouse or stylus. They select, instantiate, and combine elements from vocabularies of points, straight and curved lines, surface types, and solid shapes, and they assign material and other properties to shapes. The design content of such a database may be defined as the length of the shortest input string that will create it.

On the output side, computer-aided design systems generate strings of commands that drive various production devices—displays, plotters, prototyping devices that rapidly produce physical scale models, digitally controlled fabrication devices that produce full-scale construction components, and positioning and assembly devices that put components together. The construction content of a computer-aided design database, relative to some production device, is the length of the sequence of instructions it produces for that device. In other words, a computer-aided design system takes one kind of process description of a design as input, compiles it into a state description for convenient analysis and evaluation, and then translates it into various other kinds of process descriptions for production.

In the simplest case, as when a plotter executes a stream of instructions specifying pen strokes, there is a straightforward algorithm for converting the state description of a design into a process description, and the process is executed sequentially on a single device. In slightly more complicated cases, as with cutting and milling machines, the conversion algorithm must take careful account of material properties, the physical feasibility of tool paths, minimization of waste, and so on. In the case of constructing complete buildings, multiple fabrication and assembly processes using different devices and materials are possible, and many of these may be executed in parallel. But in all cases, the complete production process can be described as some finite set of operations, each of which takes time and costs money.

Why bother with these translations among digitally encoded state and process descriptions? Essentially, the goal is to take effective advantage of the capabilities of high-speed, digitally controlled production devices. Since computer-aided design systems first emerged in the early 1960s, the associated production devices have become increasingly numerous, versatile, and efficient. The benefits from their use have justified increasingly lengthy and expensive input processes. These benefits are often enhanced by reuse of design content for different purposes at different stages in design processes—for example, to produce shaded perspective renderings, laser-cut or deposition-printed scale models.
engineering and cost analyses, and construction documents—and by transfer of reusable content to subsequent projects.

The concept of a design’s complexity helps to understand how the combined capabilities of computer-aided design databases and digitally controlled production devices open up new design and construction possibilities. This complexity may be defined, for our purposes, as the ratio of design content to construction content, that is, the ratio of a computer-aided design system’s input to its output. [Students of information theory will recognize that this is a ratio of algorithmic information contents, as conceived of by Kolmogorov (1) and Chaitin (2, 3) in the late 1960s.] With designs of very low complexity—consisting, perhaps, of repeating elements arranged in regular rows and grids—short strings of input commands suffice to specify large quantities of construction work (4). Where entire buildings repeat, as with the ill-fated World Trade Center towers, a very small increase in design content suffices to double the construction content. (The system operator need only describe one tower, then give a copy and translate command.) Conversely, a large apartment building consisting of many identical units has low complexity, but the complexity increases rapidly if the designer begins to customize units to individual needs and desires. With very complex designs, such as random arrangements of arbitrary shapes, there are no possible input economies; these designs can only be specified in explicit, point-by-point fashion.

In the preindustrial era, the construction of large and complex buildings was a slow, laborious, manual process that sometimes, as in the case of medieval cathedrals, extended over decades or even centuries. With the industrial revolution, architects discovered that they could efficiently produce large-scale structures, such as urban skyscrapers, sprawling factories, and massive housing projects, by reducing their complexity. They did so by extensively using standardized, economically mass-produced construction components in simple, repeating patterns. The emergence of high-speed computer-aided production devices made such simplification much less necessary. Versatile, programmable devices will always be less efficient than devices that are optimized for repetitive execution of standard tasks, but the difference is decreasing practical significance for budgets and schedules. Today, computer-aided design and manufacturing technology enables the acceptably rapid, inexpensive construction of buildings that are both large and complex.

This new capacity to construct complexity economically is of enormous social and cultural consequence. In the hands of a great minimalist architect like Ludwig Mies van der Rohe, Tadao Ando, or Fumihiko Maki, a building of low complexity may be a masterfully elegant response to a complicated urban context and extensive set of functional requirements, in much the same sense that a powerful mathematical theorem is more about particularization than generalization. More often, then, such a building is an oversimplified and inadequate response to the varied and subtle requirements it attempts to satisfy.

The functional and human differences between buildings of low and high complexity are vividly illustrated by two MIT laboratory buildings, of similar size and function, which were designed by distinguished architects of their day.

The Bush Building (better known as Building 13) is a building of very large scale but very low complexity. It was designed by Skidmore, Owings, and Merrill in the early 1960s on an extremely tight schedule and budget, and was completed and occupied in 1965. The architectural vocabulary is limited to a small number of rectangular, box shapes, and the overall composition is modular and highly repetitive in plan, section, and elevation. The construction documents were produced by hand, but relied on repetitive details, and the strategic use of photoreproduction technology to reduce the time and cost of the design and documentation process. The construction strategy depended on industrial-era techniques of repetition and mass-production to achieve economies of scale. The result is a building that displays considerable formal sophistication in the handling of proportions and repetitive visual rhythms, but imposes a one-size-fits-all discipline on the diverse occupants and activities it houses; provides few of the delights of variety, subtlety, and wit; and responds to the surrounding campus environment in a very crude and blunt way. It has not stood the test of time very well.

Just down the street, the Stata Center will be completed, to a design by Frank Gehry, early in 2004. This building is both large and complex. The ability to provide a higher ratio of design content to construction content through use of advanced computer-aided design and manufacturing technology—particularly for the steelwork and sheet metal cladding—has allowed the architect to be far more sensitive and responsive to the future occupants’ needs (5). He has been able to break down the massive bulk of the building and gracefully integrate it into the campus pedestrian environment, respond in subtle and varied ways to microclimatic considerations and the forms of surrounding buildings, effectively accommodate the requirements of diverse and specialized activities, and create an environment of incident and surprise rather than monotonous repetition.

Meeting the challenges of efficient construction on a very large scale, as necessitated by the rapid growth of cities and by demands for postwar reconstruction, was the greatest triumph of 20th-century architecture. But the frequent oversimplification that this entailed was its greatest failing. Today, through the growing use of computer-aided design and manufacturing technology in place of machinery for repetitive production and assembly, the sacrifice of humanizing variety and complexity in the interests of efficiency is no longer required.

References and Notes

Use of digital modeling and computer-aided manufacturing technology allowed greater complexity in Frank Gehry’s Stata Center at MIT (completed in 2004) and made possible more sensitive response to varied conditions and needs.
BEYOND THE IVORY TOWER: Constructing Complexity in the Digital Age
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