

Complexity in building design

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At the present moment, the complexity of building design seems best exemplified by the super structures towering over modern Dubai. But how did we get from the iconic stone buildings of ancient times to these glass and steel monoliths that stand up to 160 floors high? As the tools available to designers have become ever more sophisticated and the environmental performance standards ever more stringent, there seems to be an inevitable drive toward complexity in the design of buildings. Technological advances have also added additional stages to the construction process and in an industry where time is money; this can produce innumerable challenges for a design team. Yet as we'll see, the new tools are actually optimizing the efficiency of the design process.

1 Historical Context

Of course, historically, the construction of traditional, or vernacular, buildings was not simple either. But typically much of the risk associated with the process could be mitigated by the repetitive nature of these buildings, and the incremental way in which innovations in technology or process were incorporated.

At a larger scale, the construction of the pyramids at Giza, the Parthenon, the Coliseum, the Sun Temple at Konark, the cathedral at Chartres, the Taj Mahal would all have been spectacularly complex processes, even by modern standards. However, even with these examples, each building represented the ultimate refinement of an architectural style, technology, and construction process perfected over many generations. Risk was managed by ensuring that the next building would essentially be the same as the last one with only minor innovations in technology and construction methodology (**Figure 1**). This was an evolutionary process akin to the biological evolution of species – incremental changes over a long period of time resulting in continuous refinement and environmental adaptation.



Amiens



Reims



Chartres

Figure 1: Variations on a Theme – the Gothic Cathedral

2 Innovation in the modern Era

By contrast, the rate of change in many aspects of building design and construction has been very dramatic in the last 100 years. This rapid change can be seen, for example, in the evolution of office buildings in New York City typified by the following icons:

- 1902 – Flatiron Building
- 1913 – Woolworth Building
- 1924 – 33 Liberty Street
- 1930 – Chrysler Building
- 1931 – McGraw Hill Building
- 1952 – United Nations Secretariat
- 1963 – MetLife Building
- 1977 – Citigroup Center
- 1989 – Worldwide Plaza
- 2000 – Condé Nast Building
- 2007 – New York Times Building

This period of development saw the introduction of many new technologies including electrification, air-conditioning, composite construction, curtain walls, fire protection systems, active structural damping, automatic control systems, computer networks and high-performance glazing to name but a few. It is indeed remarkable that all these game-changing innovations were successfully integrated into the design and construction process over a relatively compressed time period with few notable failures. All of the above named buildings continue to be beneficially occupied, although only the most recent provide the full range of amenities expected in a modern office (**Figure 2**).

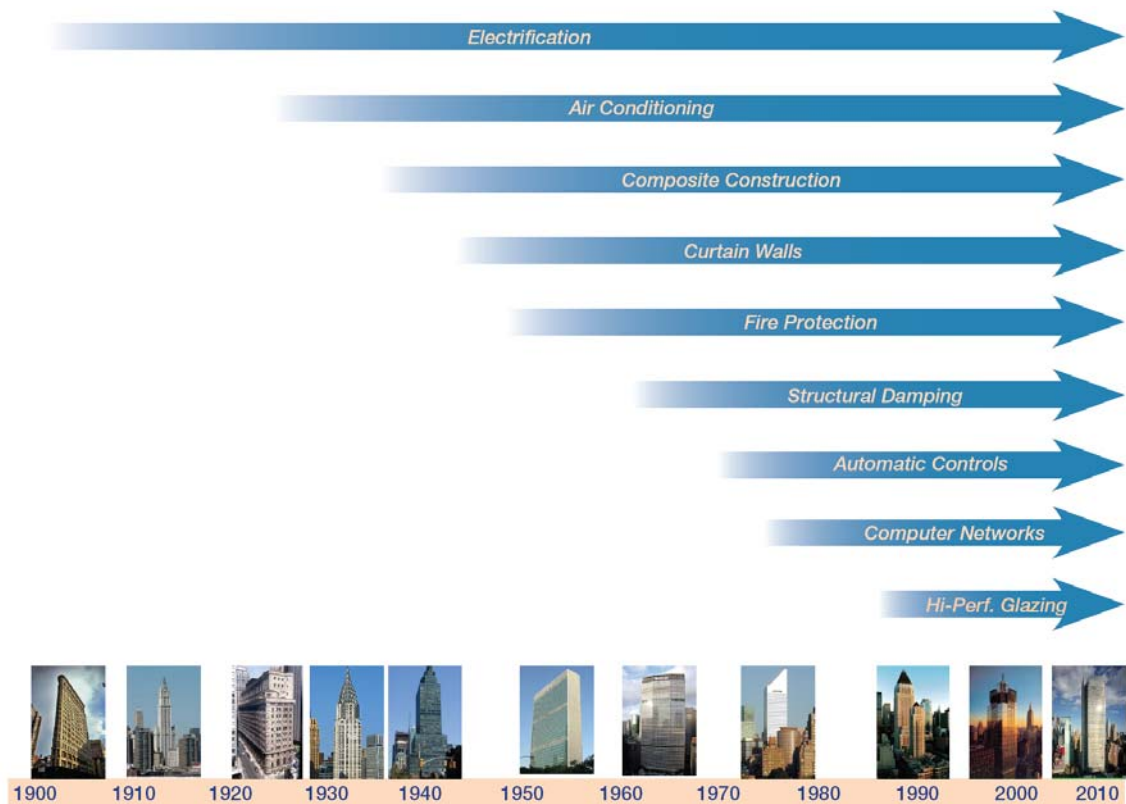


Figure 2: Evolution of Building Technologies

3 The Legacy

However, the results of the past century's building activities have not been without their problems.

Hazards were unknowingly brought into the built environment in the form of asbestos, lead-based paint and off-gassing, man-made materials. Rivers and waterways were used for heat rejection causing damage to aquatic environments. Poor water treatment spread Legionnaires' disease. Poor safety practices led to many construction-related injuries and deaths. Reduced daylight and inadequate ventilation adversely impacted the wellbeing and productivity of occupants in many buildings. Energy consumption in buildings grew rapidly and now represents 40% of all CO₂ emissions in the US. (The proportion is similar in much of the developed world).

Whenever problems like these were identified, they were generally tackled in a systematic manner and solutions were found in terms of both technology and regulation. But the fact remains that we are left with a building stock that still embodies many of the deficiencies that were the unforeseen consequences of rapid innovation in times past.

With the proliferation of design issues to be addressed, the professionals involved in design became highly specialized. Today, a typical project involves a multitude of distinct disciplines whose requirements need to be properly addressed and integrated into the building process in order to achieve a successful and legally compliant result.

Construction has never before been this complicated! However, many parts of the construction industry have found ways to successfully manage this complexity.

4 Sources of Complexity in Modern Construction

An evaluation of contemporary construction suggests that there are four main sources of complexity:

- Sophisticated building components
- Sophisticated systems
- Multi-disciplinary integration
- The desire for endless novelty in the built form

Different sectors in the construction industry deal with these four drivers in different ways.

For example, the high-volume residential market has standardized the components that go into homes to the extent that there is little or no attendant risk. Innovations can be trialed at a small scale and those that are successful can be rapidly deployed across the home-building industry. The larger home builders are actively involved in the development of codes and standards and the industry has largely embraced the need for ever-improving standards. (Cynics would suggest that this speeds up obsolescence). The purchasers of homes are not, for the most part, looking for novelty. Concern about resale values has allowed builders to stay within a fairly standard range of dwelling types over time.

Large parts of the commercial and retail markets are similarly standardized. Industrial sheds, big-box retail buildings, strip malls and lower-grade office buildings are highly commoditized and, when considered necessary, a superficial air of novelty is provided by manipulating the skin of the building. Beneath the multitude of exterior treatments, any one building of a given type is barely distinguishable from another. Again, standardization helps to reduce risk.

At the other end of the spectrum are the high-quality office buildings in commercial city centers, large transportation hubs and, even more so, the buildings built by high-profile private institutions for their own use. These buildings need to tell a story about the sponsoring organization and they therefore lead with novel architecture. This novelty is rarely just skin deep and innovation often pervades the interiors, both visually and in a performative sense.

Buildings like this represent, perhaps, no more than 10% of all the building activity that takes place at any given time, but they create much of the excitement in architectural circles. They also offer the greatest challenges in terms of managing complexity and risk. Utzon’s Sydney Opera House, Rogers’ Lloyds, Gehry’s Guggenheim(s), Piano’s Kansai, and countless others of this ilk, have always been the scariest projects from a risk standpoint – the path from concept to completion being far from clear at the outset and highly dependent on innovations not yet realized. However, they are also the projects that draw out the highest levels of creativity from the multitude of professionals involved in their realization (**Figure 3**).



- Ventilated façade
- Raised floor
- Displacement ventilation
- Heat recovery
- Thermal storage
- Prefabrication
- Precast column
- Cathodic protection

Figure 3: Innovations in the Lloyds Building, London 1980

4.1 Sophisticated components

While steel, concrete, wood, and glass have been used as base materials in construction for centuries, the fabrication of components from these materials has gone through countless transformations (**Figure 4**). In architecturally complex buildings today, these materials are often required to assume three-dimensional geometries that cannot be adequately described with two-dimensional plans and sections. In addition, they need to meet structural and environmental performance criteria.



Raleigh Durham Airport Terminal



Meier Church



Fresco Chapel



Kansas City Performing Arts Center

Figure 4: Traditional Materials in Modern Applications

Modern computational techniques allow the seamless transfer of three-dimensional geometric information to analysis programs allowing designers to iteratively refine the geometry of components while ensuring that performance requirements are met. The data generated by the designers can then be used in a numerically-controlled fabrication process to manufacture the components with great precision from pre-determined quantities of materials. This methodology existed, conceptually, at least two decades ago, but it has now reached a level of maturity where it is available for use on most projects (**Figure 5**).



Figure 5: Yitzak Rabin Center Roof

From designers's computer
to manufacturer's production line

4.2 Sophisticated Systems

With regard to building systems, there has been an explosion of technological innovation in the last 30 years, driven by the availability of cheap computer power and by the pressing need to conserve resources. Almost any system can now be automatically controlled: from security cameras to window blinds and from electric lighting to air-conditioning.

The great challenge here is to ensure that all of these complex components and systems actually perform as intended once the building has been completed. The testing and commissioning of building systems has become a very significant activity on most projects, taking up as much as 10% of the scheduled construction time. Often the time allocated for commissioning comes under pressure from building owners keen to take possession and contractors keen to hand over. But there is growing awareness that a well designed but poorly commissioned building represents a waste of the investment in sophisticated technology, not to mention the ongoing waste of energy and other resources through inefficient operation.

4.3 Multi-disciplinary integration

On a recent project for a university client, there were eighteen distinct disciplines from eight different firms involved in the design. This is by no means unusual and it is the logical outcome of our ever-increasing technical understanding of the built environment. With greater understanding come more specialization and often more detailed and complex regulation.

Keeping this multitude of designers, each with a distinct area of concern, coordinated and working towards a common goal has been a growing project management challenge. It is estimated that, on complex projects, 15 to 30% of the effort put in by designers is wasted due to inefficiencies in communication leading to re-work.

Web-based tools now exist that provide common project communication platforms accessible by all members of the design team. This ensures that everyone has access to the latest information and that changes made by any one party can be effectively communicated to all others. As this technology develops, **it is conceivable that a single digital model could become the repository for all graphical, technical and organizational data for a project.** The same model could be modified for use by contractors during construction and by facilities management staff for operations and life-cycle maintenance.

This approach will most probably be ubiquitous by 2025. Interestingly, the hurdles to widespread adoption are more likely to be legal, rather than technological, as contract lawyers struggle to ascribe liability in a process where all parties are engaged in the creation of a common seamless product (**Figure 6**).



Figure 6: A 3-D model of the Princeton Chemistry Building

4.4 Novelty

When Utzon came up with his conceptual design for the Sydney Opera House in 1957, there was no clear path towards designing the structure until Arup devised a simplifying geometry that could be used to mathematically define the component parts. Even then, the design process was painstaking and mostly manual, rudimentary computers only coming in towards the end of the design phase in the early 1970s.

When Gehry designed the Bilbao Guggenheim in 1994, he could propose any shape he wanted for individual elements and there was no need for a simplifying geometry. Any shape could be computationally defined and then transferred to structural analysis programs for validation.

The relative ease of this computational process has essentially removed the need for geometric discipline in architecture. Virtually any form can be built provided it can be made to stand up. The only constraints on this are aesthetic (where the designer wants to express a particular rhythm) and economic (where the repeatability of elements can yield significant cost savings in fabrication).

5 Built Environment Modelling

In dealing with complexity, increased computing capability has helped us streamline project communication, simplify form definition, and facilitate engineering analysis. The question is whether the human experience in these complex buildings will be pleasant and the environment productive. While there are many intangible factors involved that still defy numerical evaluation, many elements that contribute to well-being can indeed be modeled with a high degree of accuracy.

Using software such as MassMotion, which has been calibrated against live situations, we can test the virtual movement of people through complex transportation interchanges, or the escape of people from a burning building. The design can then be modified to eliminate pinch-points and log-jams. This provides a great deal of confidence in the performance of the final design and also eliminates unnecessary conservatism in the sizing of pathways (**Figure 7**).

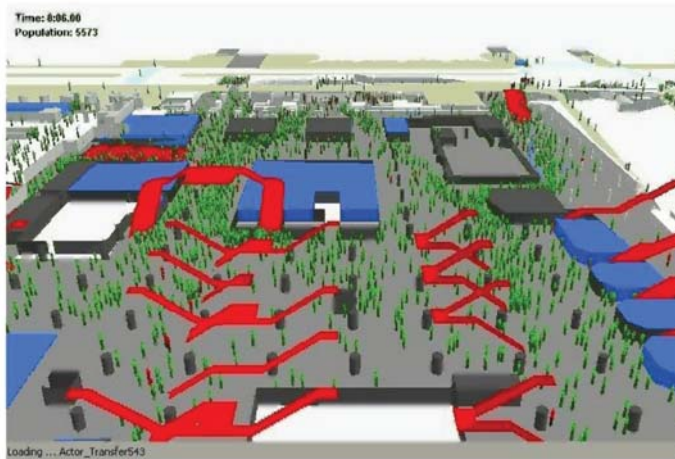


Figure 7: Mass Motion

Similarly, the design of heating, cooling and ventilation systems for complex spaces can be analyzed and refined using Computational Fluid Dynamics software. Temperature, humidity and air velocity distributions can be modeled for a variety of operating conditions to ensure that thermal comfort conditions are optimized. Again, we can ensure cost efficiency by avoiding the over-sizing of systems (**Figure 8**).

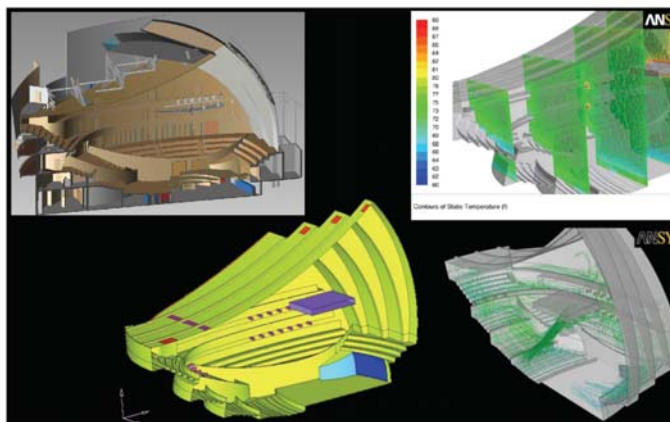


Figure 8: CFD Modeling

The modeling of daylight and electric lighting in buildings has reached such a high level of accuracy that design data obtained from the software very closely matches conditions achieved in reality. This modeling technique is also useful when designing roof mounted photovoltaic installations (**Figure 9**).

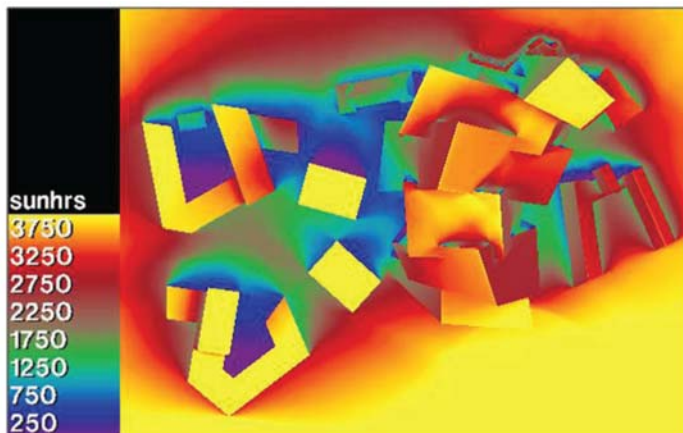


Figure 9: Daylight Exposure Calculation

Techniques for visualizing interior space and auralizing sound are revolutionizing the practice of acoustics. It is now possible to refine the design of a performance space in an acoustic laboratory, and listen to a simulation of the final space, before any construction takes place (**Figure 10**). These and many other computational tools are now routinely applied to the design of buildings.

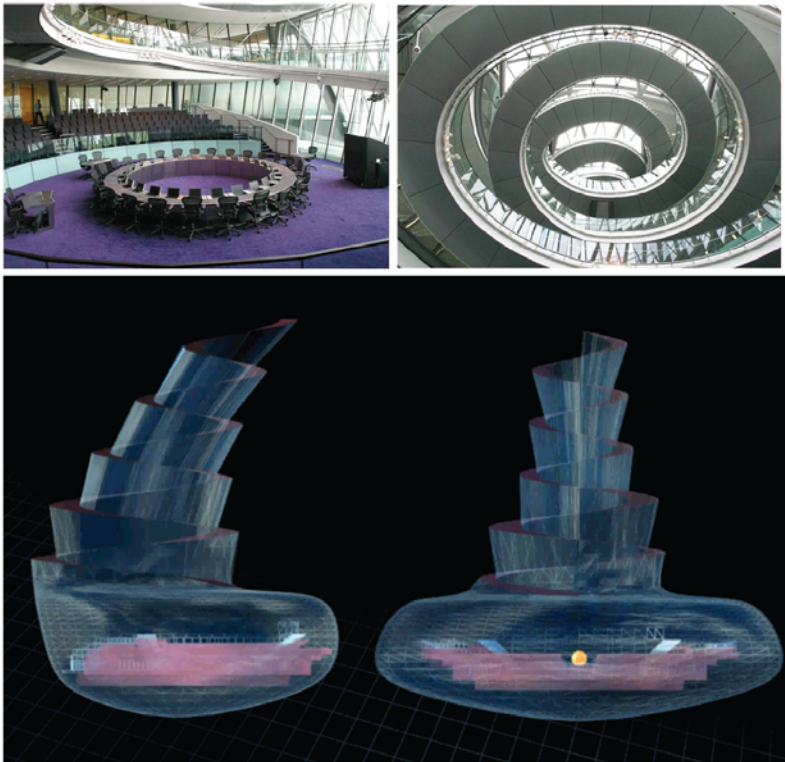


Figure 10: Acoustic Visualization

6 Conclusion

While it is clear that the design and construction of buildings has become increasingly complicated over time, it is equally evident that developments in computational modeling have kept pace and will continue to do so. This gives both designers and builders a toolkit to construct a virtual building, test key aspects of its performance, and optimize the design, well before any physical construction has to take place (or be undone). The Built Environment Modeling (BEM) tools described above can reduce the risk involved in innovation, by providing a greater level of certainty with regard to the expected outcome.

Thus, the design and construction of buildings may be more complicated than ever before, but they are also becoming more intelligent processes. While we can only speculate about how much more complex – and creative – buildings will become going forward, the possibilities appear to be endless and exciting.