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Evolution of Design Integration with Digital Fabrication: Post-Covid Update

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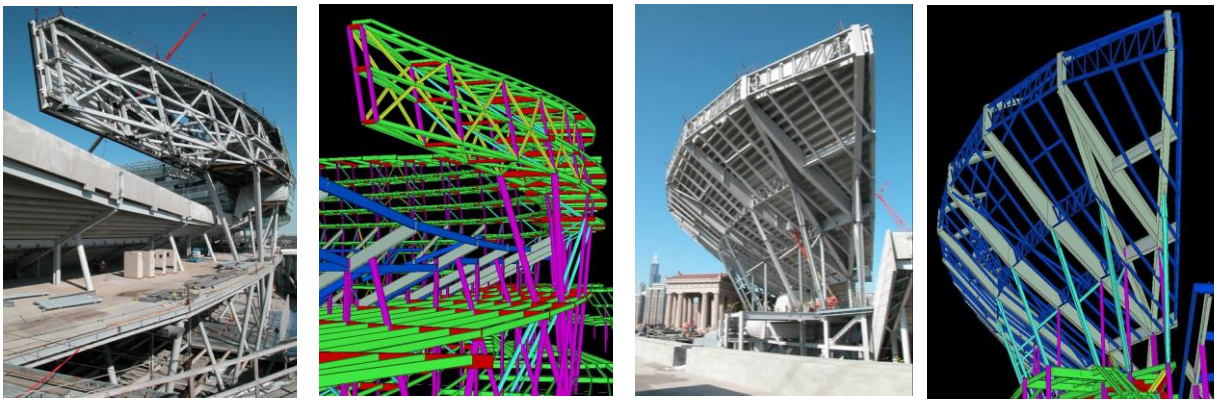

Figure 1: Soldier Field, Chicago, IL 1999-2003 – Steel Design/Fabrication/Erection & BIM Models

Abstract

The best way to envision the potential change and disruption in our profession and industry is to look at the transformation in almost every other industry that has implemented 3D design integration technology over the past several decades. Our building industry has lagged other industries that are more vertically integrated, but the horizontal nature of our professional relationships will become flatter with Building Information Modelling (BIM) technology that is both interoperable and global. It is difficult to predict the shape of change that will occur over the next decade, but it will be large and disruptive. One way to explore this subject is to look at how far we have come in this evolution to envisage where we may be headed in the future.

This paper looks at the experience of the author's engineering practice over the past several decades, tracing the evolution of design integration with digital fabrication technologies. This digital history begins with the design of Solder Field football stadium in Chicago in 1999. One of the most significant achievements from a structural engineering perspective was the implementation of BIM for the steel frame. [Figure 1] The use of a BIM as a Contract Document for the steelwork allowed for a streamlining of the bidding and approval process, as well improving accuracy of the fabrication and erection of the steel frame, made possible using a single model from design through construction. The delivery of a steel model also allowed for 3D coordination with precast seating risers, as well as the building skin. This was one of the first time this was used at a large scale by Thornton Tomasetti, and now, looking back at the evolution of our use of BIM, this project laid the foundation for many other systems and innovations to follow. Some of these innovations are supporting cloud computing, robotic fabrication, sustainability, and artificial intelligence (AI), with AI having the largest potential to disrupt our industry.

Keywords: Detailing and Construction, Advanced Manufacturing, Design Integration, Sustainability, Artificial Intelligence

1. Introduction

There have been many innovations in computational design with the evolution of more powerful computer systems, as well as the wider adoption of 3D software throughout our industry. These parallel innovations in software will also be presented, including the development of embedded analysis within the design tools utilized by engineers and architects. This leads to a brief look into the future with cloud computing, robotic fabrication, parametric modeling, and artificial intelligence (AI), with the goal of continued integration of the design process through construction and operation of our buildings.

2. A Brief History of Computational Design

This brief history describes the evolution of the tools have we used to design and build structures. One could start with buildings at 2500BC, but perhaps more appropriate to engineering, the story of computational design starts with shipbuilding, also being constructed over this period. Because the tools ship builders used included a Spline, a tool that had a significant impact on the invention of CAD systems. [Figure 2]

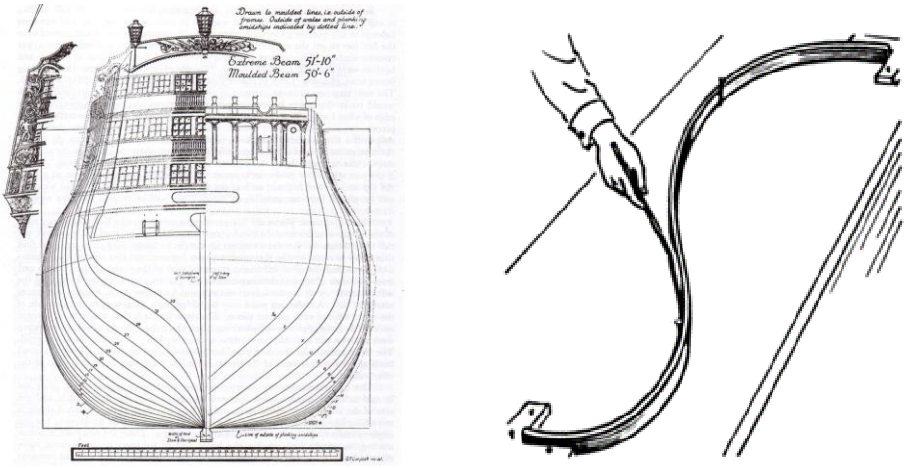

Figure 2: Ship Building and the Spline Tool

3. Where have we been?

The timeline for building engineering in this paper begins in the mid-19th century, with Chicago claiming the world's first tall building. It had a modern steel frame, fireproofing, and elevators – all innovations from this period, but all the drawings and calculations were completed by hand, as they had been for centuries. Things got interesting in the engineering world as we entered the 20th century with the invention of automobiles and airplanes. Incredible innovation occurred over the first half of the century in architecture, automotive and aerospace, while continuing to use hand drawings and calculations.

The next six decades from 1950 to 2010 is where there was tremendous innovation in computer-aided design for these fields, parallel with the development of semiconductors. The origins of CAD systems in the 1950's begins in France, with Paul de Casteljau at *Citroen* and Pierre Bezier at *Renault* developing algorithms for the shipbuilder's Spline, and digitizing these in early computer programs. [Figure 3]

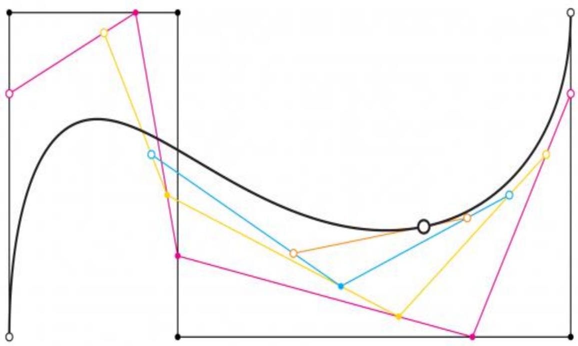

Figure 3: Casteljau's Algorithm for a Spline

The French continued with three-dimensional analysis programs for fighter planes at *Dassault* in 1968. Chuck Eastman at Carnegie Mellon sees all of this and predicts our BIM future in 1974 with his seminal *GLIDE* program. [1] [Figure 4] CAD evolved in 2D and 3D with 1992 being a remarkable year for this evolution, with Frank Gehry's Fish in Barcelona, the first BIM architectural structure, albeit with aerospace software from *CATIA*, and the Petronas Towers using 3D CAD. Soldier Field in Chicago is how this author entered the BIM world at the beginning of the 21st Century. *Tekla's XSteel* was used for this landmark project. It is also how the author got involved with BIM at AISC, the American Institute of Steel Construction. This 60 year cycle concludes in 2010 with extraordinary 3D tools like *Revit*, *Generative Components* and *Grasshopper* being utilized by architects and engineers. The development of CAD and BIM software over these 60 years paralleled the improvement in hardware following Moore's Law, which was merely an observation and projection of historical trend of the doubling of components on an integrated circuit every two years.

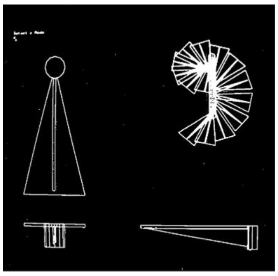

Figure 4: Charles Eastman **GLIDE**

Chuck Eastman, now leading Georgia Tech's Digital Building Lab, had a similar observation about our industry; perhaps we could call it Chuck's Law – that our AEC Industry follows the Aerospace Industry by two decades. Yes, our AEC Industry was drawing by hand for two decades following Boeing's use of CAD with the 747, and Frank Gehry's Fish notwithstanding, we primarily used 2D CAD contract documents for 2 decades after *Boeing* used BIM for their 777. [2] The Boeing 787 launched in 2013, and it is still premature to predict what our industry may adopt from it in the coming decade.

We now turn our attention to the structural engineering profession and Thornton Tomasetti (TT), where they designed a number of pavilions for New York's World's Fair in 1964. *Kodak's* complex pavilion shows that not much has changed from centuries of engineering ships and buildings. Still using hand calculations and drawings.

By the 1980's Thornton Tomasetti was using 3D structural analysis software, following in Dassault's footsteps two decades earlier. By 1992, Thornton Tomasetti was using both 3D CAD and 3D structural analysis systems for designing The Petronas Towers, the world's tallest building with Cesar Pelli. These systems are not yet integrated with BIM, but this is all part of the evolution of computational design. [Figure 5]

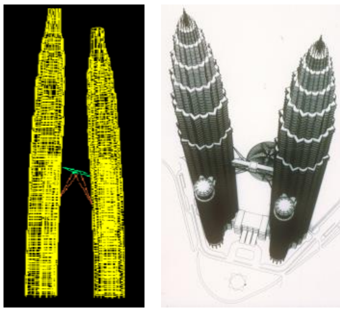

Figure 5: Petronas Towers

Soldier Field in Chicago is Thornton Tomasetti's first use of BIM software in the design and delivery of a project. [Figure 6] Tekla's XSteel software was used to model all the steelwork in a BIM Model, and it became the Contract Document for Steelwork in the bidding, shop drawing and construction phases of the project. It allowed the team to speed up delivery of steelwork in a very tight construction schedule. The steel industry had a head start with interoperability with the CIMSteel Standards developed in the UK, and Chuck Eastman later worked with AISC in implementing IFC's for steelwork. [3] There were many challenges, including the use of 2D AutoCAD for most of the contract documents and shop drawings. Even the precast concrete industry utilized 2D CAD, though Chuck later consulted with PCI to develop their IFC's. But the advantages of the direct flow of steel design information to digital fabrication and ease of steel erection outweighed the challenges. With robots that cut and punch steel, even complex structures neatly fit together in the field. An added benefit was that the cladding was fabricated by Permasteelisa, who was experienced enclosing Frank Gehry's buildings. Permasteelisa used TT's Tekla model to carefully tailor the exterior enclosure to fit our structural frame.

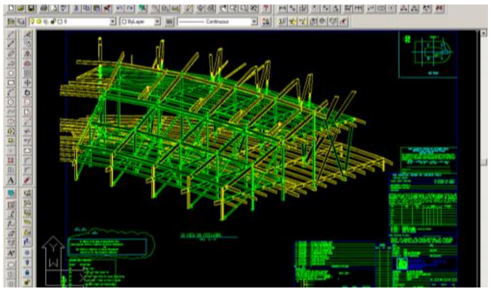

Figure 6: BIM as Contract Document

4. How did we get here?

CORE Studio is Thornton Tomasetti's in-house R&D team challenged to develop tools and workflows to support the evolution of Computational Design.

BIM software such as *Tekla* and *Catia* were utilized following Soldier Field. Barkley Center in New York's Atlantic Yards was another sport related project that allowed further development of modeling and collaboration tools. Our advanced computational modeling team evolved into our CORE Studio by 2014, developing tools to achieve our goals. CORE studio operates like a startup, oscillating between making tools and using them with project teams. There are many tools and many projects, but here are two examples of projects and their tools:

- **30 Hudson Yards** where TT was the Structural Engineer, but we also delivered the structural steelwork in *Tekla*, while improving workflows between our analysis software, *Tekla* and the rest of the design and construction team.

- **The Shed at Hudson Yards** combined our structural and façade engineering teams, rapid design iteration and environmental analysis. [Figure 7]

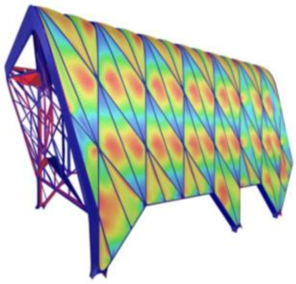

Figure 7: The Shed at Hudson Yards, NY

5. Where are we going?

Here are four paths among many from our recent work that show promise: Artificial Intelligence (AI), Interoperability, Parametric Modeling and Cloud Computing:

- **ASTERISK** is our large effort in Artificial Intelligence capturing what we have learned over the past decades to leverage that knowledge in engineering future structures.

- CORE Studio has also spun off software via **TTWiiN**, TT's technology accelerator, such as **KONSTRU**, our Interoperability and Collaboration software.

- **SWARM** was spun off as well via **TTWiiN**, a user-friendly interface for *Grasshopper* design optimization. Swarm is really an app store for the design community. It connects designers who need easy to use parametric tools with the super users who are building them. [Figure 8]

- **SWARM** merged with **ShapeDiver**, a startup hosting *Grasshopper* scripts in the Cloud focused on the product design industry. This is a very interesting collaboration, as there is much our AEC Industry could learn from product design, as vice versa.

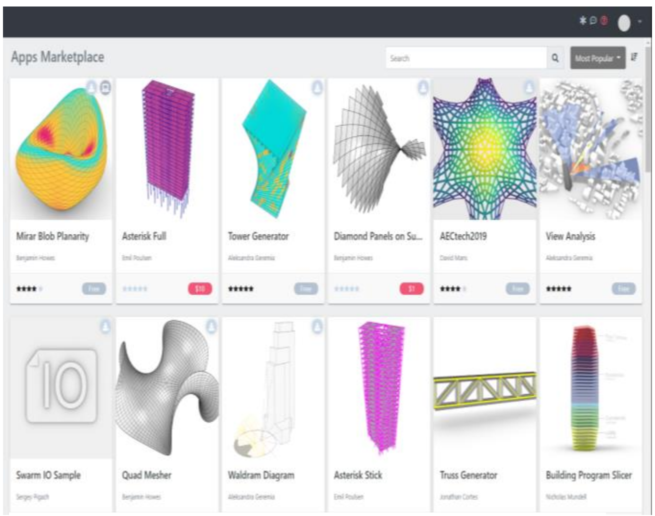

Figure 8: SWARM is Grasshopper App Marketplace

- **ShapeDiver** is really *Grasshopper* Tools in the Cloud with a parametric interface connecting designers and suppliers in product design as well as the AEC Industry.

- **OnScale** is very high-powered Cloud Engineering tool, scalable to solve very large, complex analysis problems. **OnScale** was acquired by **ANSYS** in 2022.

5. Conclusion:

Returning to the *Boeing 787* to look at where our industry might be going considering the two-decade lag per Chuck's Law. Shortly after the 787 launched in 2013, the author was a visiting professor at University of Washington's Architecture School. Realizing that these architecture students would be in their mid-careers in 2 decades, perhaps it would be illuminating to go over to Boeing's Everett, WA plant and study their potential future. Daniel Friedman and this author led a seminar on "Learning from the *Dreamliner*" in Spring 2014. While there are many things we learned from the *Dreamliner* in that seminar, here are a few that could spark some discussion in our industry:

- A single model was used for all suppliers and sub-contractors for design and production.
- Large "Chunks" of the Boeing 787 are design-built collaboratively with sub-contractors.
- Extensive use of prefabrication of "Chunks" offsite – with just in time delivery.
- Material advances and analysis to improve performance.
- Digital Twins: A single model contains the entire BIM model and analysis models, as well as performance data.
- The Digital Twin model is delivered to the airline with their Boeing 787 – specific to that plane's customization.
- Digital Twins are used throughout Boeing 787 operations for maintenance, upgrades, system optimization, troubleshooting, etc.

6. Post-Covid Update:

This paper was initially prepared for the IASS Symposium at the University of Surrey in August 2020. Covid-19 intervened and disrupted everyone on our planet. Now four years on, there appear to be two technologies disrupting our industry: virtual communication tools and artificial intelligence (AI).

The rapid adoption of remote communication tools for virtual meetings have had a large impact on our industry as well the education systems that support our professions. These changes were already underway, with adoption accelerating due to lockdowns. These systems helped reduce the disruptions caused by Covid.

AI applications were also under development for our industry prior to 2020 [4]. AI did not have widespread industry recognition until ChatGPT was released to the public during Covid, followed quickly by releases by its competitors. AI is now the hot new technology in many industries including ours. We are at an infliction point where generative AI will rapidly accelerate well beyond the initial impact we are seeing today, to becoming a transformative force driving advancements in design, engineering and construction practices while complementing human expertise.

Acknowledgements

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