Mechatronics and Flexible Specialization for Architecture, Engineering and Construction: harnessing the new paradigm in manufacturing to change the way we design and construct buildings

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ABSTRACT

The construction of buildings has long been considered a holdout from the industrial revolution. In the early part of the 20th century, many felt it was only a matter of time before the example of Ford's mass-production assembly line would be adopted by the Architecture, Engineering and Construction (AEC) industry. Most attempts to bring about this change have ended in failure or the kind of economic eddy occupied today by the mobile home industry. Conventional wisdom has reversed its assessment to hold that the industrialized fabrication of buildings is not feasible. A closer examination shows that this history of failure is the history of a mismatch between inflexible systems of production and a market that demands a high level of variation in the product.

As mechatronic capabilities have spawned a "second industrial divide," marked by integrated manufacturing, flexible specialization, mass customization and manufacturing agility, the means for resolving this mismatch appears to be at hand. In a step towards imagining the form and impact of this new kind of industrialization on the AEC process, a set of principles for the technological shift are derived from an analysis of trends in innovative structural steel fabrication, and current CNC and CIM processes. These principles are applied to create a model of a flexible, automated system for the production of the "Smart Roof," a factory-produced roof designed to accommodate a large variety of building configurations. Four free-form and feature-based fabrication processes are proposed. An *ad hoc* integrated software environment, that projects objects "upstream" from the fabrication process control system to create user-interface program extensions for architects and engineers, is proposed as an alternative to the concept of universal software interoperability through a neutral datafile format, as envisioned by standardization efforts such as ISO 10303.

♦ Mechatronics and Flexible Specialization for Architecture, Engineering and Construction: harnessing the new paradigm in manufacturing to change the way we design and construct buildings

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The subject of this talk is a set of technologies that exist today only as a shadow of their future selves; so, as a way of making this subject matter concrete, I have constructed a prototype process design for the production of whole roofs using a flexible, integrated system for design and manufacturing. Envisioning this system is a theoretical exercise and a way of exploring what the new industrial paradigm, based on mechatronically controlled manufacturing technologies, may mean for Architecture/ Engineering/ and Construction (the AEC industry). The project is premised on the idea that newly designed fabrication processes will be the pivot upon which designers turn their thinking towards these new technologies. ♦ On this slide you see a sample of the morphologic range of capability we would want such a system to handle, ranging from the simple ♦ and conventional to a level ♦ of complexity that responds to the uniqueness presented by each site and building program. ♦

Such a system must recognize the ♦ key characteristics of buildings that set them apart from other manufactured objects:

- Uniqueness ♦
- Scale ♦
- Refinement ♦
- *Ad hoc* team of independent entities

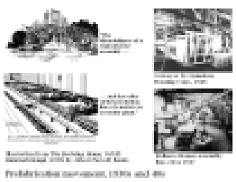
Further, it should follow five key principles ♦ of design that respond to these requirements:

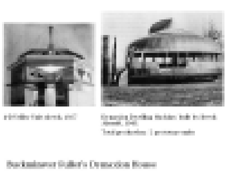
- Repetition with modification
- Enable complexity through computation
- Process continuity
- Embedded dimensional framework
- Multiple integrated user interfaces

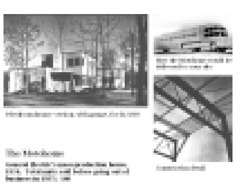
Before getting into the details of fabrication, I want to step back and look at the historical precedent and the rationale for this effort.

Joseph Paxton's Crystal Palace, 1851

♦ Since the mid-19th century, admirers of the industrial revolution have sought to bring to architecture the technical advances associated with the industrial age. Joseph Paxton's Crystal Palace of the 1851 Great Exhibition in London, a third of a mile long, was erected in four months from precast iron structural elements and modular glazing. It marks the symbolic dawn of an age in architecture that never happened. Within three decades, steel replaced iron as a mass structural material. Since casting steel was relatively impractical compared to fabrication from rolled sections, the thread of mass-produced cast metal structural elements was broken. Only in the last decade has computer-numerical control (or CNC) steel fabrication equipment rekindled the notion of mass-produced steel elements—this time around, as a flexible technology with even more advanced capability than imagined by Paxton.

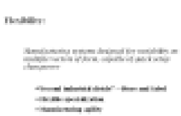




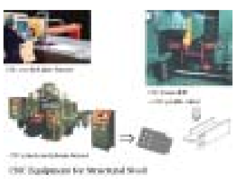


In the early part of the 20th century, during the 1920s and through the 40s, a group of architects, builders and engineers in the United States became enamored with Ford's mass-production assembly line. A host of proposals for new systems for housing—exemplified most memorably by Buckminster Fuller's Dymaxion House, originally called the "4-D Utility Unit" in 1927—and a large number of actual production enterprises, such as the ill-fated Motohome, funded by General Electric in 1934—emerged to form what has been called the "prefabrication movement." Of these hundreds of creative proposals and attempts, only mobile homes, and their close cousin the "manufactured home"—like this 2-wide unit from Fleetwood Homes—remain today a significant segment of the construction market. Even the success of manufactured housing must be qualified, however, because it uses manufacturing techniques that differ little from construction in the field. Manufactured housing exists today because it is cheap—not the result of high productivity, but, rather, because of the low wages paid to factory hands. Time prevents a more extensive review of the historical evidence, but the forgoing gives at least a sense of why I have concluded that, in general, attempts to industrialize building in the U.S. during most of the 20th century failed, and did so because of a mismatch between the inflexibility of mass-production systems and a market that demands as much variety, craft and uniqueness as it is possible to deliver.

With the emerging new industrial technology, we may no longer be required to accept the mass-production tradeoff: a monotonous standardization of product as the price to be paid for higher productivity. The new model for manufacturing is enabled by mechatronics technology, which is defined here, following the lead of U.C. Berkeley engineering professor David Auslander, to be *the application of automated intelligent decision-making to the operation of machines.* The term "mechatronics" combines the concepts of computer-numerical control software with electronic control and feedback technologies that go well beyond the brushless motor control system to which it was originally applied in the late 1960s. The intelligence of mechatronic equipment allows us to design manufacturing processes that unite mass-production with the social and production values of craft labor. Further, because it relies on software, such a system can be integrated with the design process, at least insofar as design is pursued through the use of computers. This may be why, after experiencing the use of rapid prototyping and CNC in the execution of some of his projects, the architect Renzo Piano declared, “I think in twenty years we will be much closer to craftsmanship—craftsmanship by computer.”



The AEC industry has skirted the mass-production phenomenon and remained largely a craft industry. So the prospect of fusing the craft tradition with mainstream industrial manufacturing is of particular significance. MIT economists Piore and Sabel term this turning point in the industrial revolution “the second industrial divide.” “Flexible specialization,” in their analysis, is the essential characteristic of the new model for manufacturing. “Manufacturing agility” and “mass-customization,” popular concepts of the last decade, represent the two major axes of flexibility. Flexibility, in its barest definition, means the ability to rapidly set up a new job on the same equipment used for a different one. There is more to this concept, however, than merely speeding up the changeover operations on conventional equipment. The full promise of flexibility cannot be achieved using the equipment and processes of either mass or craft production; it requires the invention of new fabrication processes designed with flexibility in mind. For the AEC industry this is a vital challenge and opportunity, because it means that embracing the new paradigm in manufacturing requires us to reinvent the way we fabricate buildings, and, in so doing, to renew our thinking about architecture itself.



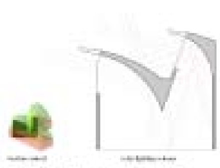
AEC manufacturing techniques of the last decade, particularly in the structural steel industry, have begun to embrace mechatronics and flexibility. CNC equipment from Peddinghaus, ESAB, and others, and major fabricators, among them Herrick Steel and Gayle Manufacturing in California, have begun to pioneer operations along the lines of the new model for manufacturing adopted some time ago by electronics goods manufacturers, and other sectors of industry. Integration between design and fabrication, and throughout the shop floor itself, is a long way off; but there is a beginning.

On the design side itself, one major project that has gained tremendous attention stands out as an example of aligning design with second industrial divide techniques. That is the Guggenheim Bilbao museum, designed by Frank Gehry, a Los Angeles architect, and engineered by Skidmore, Owings and Merrill. The wireframe diagram you are looking at is an animation of the core of the structural working drawings. Each line is a member, and each intersection is a node. The engineer's drawings consisted of a simple set of design elements that required a single page of details, from which the manufacturer created hundreds of sheets of shop drawings for this complex building. The frame was conceived as a series of warped horizontal trusses. There were basically two types of nodes, one of which was a corner; but within each type the intersection angles and other parameters were infinitely variable. Conceptually, this approach is what I call "repetition with modification," the key principle in the design of the flexible fabrication process.

The variable roof technology I am working on is a complete system that integrates design and manufacturing and is intended to help us examine the potential and the limitations of these new trends. The design of technique is premised upon an explicit comparison between the old

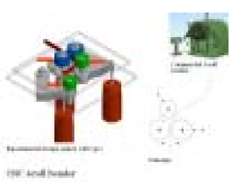
and new paradigms for manufacturing ♦:

- a flexible system capable of mass-customization, rather than a mass-production system that shuns customization ♦;
- using processes based on repetition with modification, rather than processes based on repetition only ♦;
- extensible to most conceivable situations using the system's inherent variability, rather than through modular design or a set of models ♦;
- Our productivity goal seeks primarily to increase value, rather than being limited to increased efficiency.



Increased value means, as illustrated at the beginning of this talk, an enhanced ability to tackle new formal geometries, and, ♦ as shown in this slide, to enable the complexities that result from a designer's responses to the site and to the building orientation, including strategies for daylighting and the use and control of solar heat gain. This kind of strategy illustrates the second principle of process design: "enable complexity through computation."

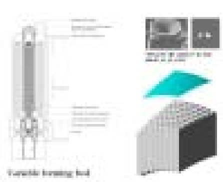
A factory fabricated roof would be manufactured in



full-span sections no more than 70 feet long, and a maximum 14 feet by 13 feet in section. The manufacturing system uses four basic processes. All contain elements of untested innovation. The first two solve the problem of structural framing, and the second two solve the problem of cladding doubly-curved surfaces. In this scheme, we are required to build trusses, each of which may be one of a kind, to provide external and internal surfaces that may be quite divergent. The truss is conventionally designed with top and bottom chords and a web, all continuous pieces of steel bent to the proper configuration. What is obviously unconventional about this truss is that it can conform to an infinite variety of contours, and it does so as a continuously fabricated piece that carries with it its own embedded dimensional system—illustrating two more principles of process design. The chords are to be formed on a CNC 4-roll bender, conceived as a variation on the 3-roll bender that has been used for many years to shape arced steel members. The 4-roll bender has the capability to reverse the direction of curvature, and closed-loop control would allow the imposition of continuously varying curvature.

The design for an experimental, small-scale device shown here illustrates how the ♦ fourth roller is dropped out of the way to clear the workpiece as curvature is imposed by the other bending roller ♦. Blue rollers ♦ are pinch rollers that advance the workpiece.

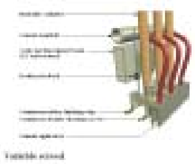
♦ The web is a continuous steel bar. A small experimental device with a single bender was built and tested to demonstrate the principle of meeting non-parallel top and bottom chords with varying curvature. The single-bender solution causes the workpiece to swing wildly back and forth, a problem solved by the double-bender concept illustrated here. At each step the benders release the workpiece and the stock is advanced ♦ the length of a web leg, adjusted for bend allowance. ♦ The benders then grasp the workpiece at the nodes using the proper angular orientation, and ♦ simultaneously perform two bends.

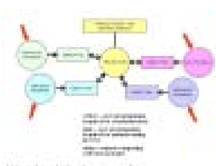


♦ The sheathing for the roof is a thin cementitious shell applied to the structure in two phases. First, a series of reinforcing substrate panels formed from expanded metal mesh are attached. These also act as forms in a process that is similar to the plastering of a ferrocement boat hull.

The panels are shaped on a variable forming bed, a device similar to variable dies proposed by Hardt of MIT, Wright of U.C. Berkeley, and others. The forming bed is composed of a series of individually actuated pins with spherical heads.

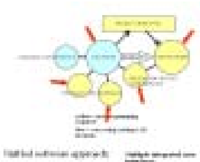
♦ After tiling the roof surface into panels (here illustrated for the simple case of a developed surface), the field of pins is set so that the centers ♦ of the spherical ends align to a surface ♦ that has been mathematically offset from the desired ♦ panel shape. ♦ After the mesh substrate has been attached to the structure, a cementitious shell is continuously cast on the substrate using a moving 3-axis beam, as illustrated in this concept drawing. The beam supports a vibrating variable screed and a set of cement applicators, adjusted using a series of hydraulic cylinders.





♦ Software to integrate design, engineering and manufacturing is the final element of this process design. After considering the current conundrum concerning lack of software interoperability, I have concluded that the standardization approach advocated by many, including the American Institute of Steel Construction (AISC), may not be practical in the short term for the AEC industry.

The universal standards approach, as implemented by ISO Standard 10303 (or STEP), provides a neutral datafile format, with translation, in order to be neutral to all choices of software. As shown on the diagram, it assumes that the ♦ manufacturing process control package would be a stand-alone program that must interoperate with a large number ♦ of specialized, competitive, and possibly overlapping programs. The ideal of a universal interoperability of software is a worthy one, but, at the least, it is an extremely complex and extensive project that will require many years and the work of hundreds, perhaps thousands, of programmers to implement.



♦ My approach is consistent with the notion that a new fabrication process of this type must be promulgated to designers anyway—and what better way to do it than to provide software tools. I call this a unified software approach, because, unlike the model assumed by standardization efforts, it provides a unified proprietary interface for all users on the AEC team. As shown in the diagram, the software is built on a CAD ♦ program core, to which is added a major module ♦ for manufacturing control, and a series ♦ of program extension modules for each of the required user interfaces, illustrating the fifth principle of process design: multiple integrated user interfaces.

The ideas described here are of necessity speculative, and time will tell whether they have enduring validity. If, in the future, mechatronic, flexible manufacturing processes take a dominant role in the design and construction of buildings, we will see profound changes in the sophistication of buildings, the partitions of expertise among the AEC team, and the nature of the design process itself.