HISTORICAL CASE STUDIES IN SYSTEM THINKING.[1] A PEDAGOGICAL TOOL FOR TEACHING CONSTRUCTION THOUGHT TO ARCHITECTS AND STRUCTURAL ENGINEERS

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System thought implies multi-dimensional matrix thinking rather than linear thinking processes. It originated to help solve the problems of nineteenth-century technologists and still permeates construction today. By tracing the stages of its development we can discover some of its characteristics and these can provide us with tools to help architects and engineers think conceptually in construction design and process.

TRANSLATION AS A TECHNOLOGICAL METHOD

In the early years of the 19th century, the Franco-American-British mechanical engineer Marc Brunel was asked to design a bridge across the Neva at St. Petersburg. He decided to propose a tunnel instead that would be unaffected by driving ice floes in the spring melt. In 1818 while he was pondering how to dig through the river silt, his attention was caught by a mollusk called pipeworm or *teredo navalis* in Chatham Dockyard. These shellfish drill through ship timbers causing damage and major maintenance problems.[2] Like many other innovators before and since, Brunel turned the fortuitous observation into the solution of a question that had been plaguing him in a totally different field. He crossed intellectual boundaries between timber technology and tunneling, between animal behavior and machine construction. He examined how the pipeworm drilled and transformed what he found into two designs for a mechanical tunneling shield which he patented the same year and subsequently used for digging the famed Thames Tunnel 1824-1843.[3]

Brunel's thinking process allowed him to translate information from a zoomorphic into a mechanical format. Historians of technology have written great deal about the transformation of reciprocating to rotary motion in steam engines but very little on the concept of translation. Information is *transformed* when it is altered or remolded within the borders of a field and reapplied to the same object in a different way. Information is *translated* by applying it across a boundary, moving it from one field or object to another. Design can involve either transformation or translation. Although Brunel left us no information on how he developed the idea for his tunneling shield, translation procedures like the one he must have followed are characteristic of associative or "matrix" technological thinking, which are non-linear thought processes. The translation process that led to the invention of the tunneling shield appears to have been typical rather than unique in Brunel's work, since it figures prominently in many of his other projects, for instance in his use of iron to reinforce mortar or earth.

Following a long European tradition of placing iron bars in masonry walls, Marc Brunel used iron post-tensioning rods to reinforce the brick and mortar cylinder of his open caisson for sinking the first shaft of the Thames Tunnel in 1824.[4] He also used brick to clad the walls of his tunnel and may have translated the traditional solution from his caisson to help him solve a problem in the cladding. Brunel was concerned about the strength of the mortar he used and set up a series of experiments to test it, and he tried to enhance its tensile strength by imbedding various materials including iron in a mix of two parts cement and one part sand. The result reminds us of various modern materials ranging from reinforced concrete to fiber concrete, but that is our view in hindsight. His translation process did not go that far because he was merely trying to reinforce brickwork. But he did discover that the cement adhered to the iron as well as to the brick and bonded everything solidly together and built a testing machine to pull the iron rods he used out and had an assistant tabulate the results.[5] Although he did not take the final step in the invention of reinforced concrete in this instance, his discovery enabled others to build on his work later and to take the translation one step further.[6]

However, when he was forced to replace his original Thames tunneling shield with an improved one in 1835-1836 he did take the translation process a step further, but in a different direction by using iron bands to reinforce the soft tunnel workface. He imbedded them deep in the earth in front of the shield to stabilize the soil. He surely knew that the iron would not bond with the clay, sand and gravel mix as it did with cement. But he still tried the idea, refusing to accept that it was conceptually illogical. Brunel was a technologist and used to the idea that logic changes with the parameters of a problem in unforeseen ways. He translated the reinforcing technique from one situation and material to another, and it worked. The technique is still in use and known as "soil nailing."[6]

The process of translation can be used in structural work too. Abraham Darby III's 1779 "Ironbridge" over the Severn at Coalbrookdale in England was the first successful large-scale iron structure in the Western world. Darby prefabricated and assembled it in ten half-spandrels to form five parallel arches, and it resembled a timber bridge made of stick members. It was a logical step to use wood connection techniques in a new stick-shaped material, but the shortcomings of connection techniques that put shear, bending and tension stresses on a material that cannot accommodate them well, soon became apparent. The Coalport Bridge was begun a few years later than the Ironbridge and lies a few miles downstream. It was designed in much the same way as the earlier bridge but a few of its wood-type connectors had changed to the bolted flanges and lugs more typical of machine construction. Thomas Wilson's Wear Bridge at Sunderland 1795, John Rennie's Thames Bridge at Southwark 1819 and Telford's Mythe Bridge at Tewkesbury 1826 all used a more advanced form of translation. They had more "modern" connections and their builders organized them in a new way: as systems.

THE DEVELOPMENT OF THE SYSTEM CONCEPT

Instead of designing them traditionally by first determining the bridge form and then subdividing it hierarchically into parts for prefabrication, the early nineteenth-century bridge builders began to use a non-hierarchical design process, standardizing the members and connections as they went and arranging them into an assembly. Whereas Darby had made a multitude of parts for the Ironbridge to conform to the preconceived structural idea and form, each different and each with individually solved connections, Wilson used Thomas Paine's idea to build the Sunderland Bridge from identical components which he assembled into voussoir-shaped elements and connected together to make the arch.[8] Instead of a linear mode of thought in which a form is subdivided into parts, a new parallel design process determined the final form as much as the form influenced the parts. The form and the elements were designed in parallel using a "kit-of-parts."

This change progressed with the nineteenth century influenced by the economies to be had in the casting of multiple iron elements from the complex molds and by the fact that the elements were assembled rather than manufactured on site. System thinking became the dominant form of technological thought in iron construction. The Sayn Foundry in Bendorf, a German town on the Rhine near the Dutch border, represents a transitional stage in this development. The building still stands and is an excellent example of the complex and high-quality technological and border-crossing thinking that went into designing early iron structures. It was built in 1830 by a Prussian engineer and iron founder named Karl Ludwig Althans.[9] The foundry is a cruciform basilica in plan with the furnace replacing the altar and the nave serving as casting floor. The structural detailing is typical of the stage in the development of system thinking in which it was built. The frame elements were interconnected like a jigsaw puzzle. Each piece was tailored to fit the next and no overriding connection system or typology regulated how it was assembled. We find wedging, mortising and bolting used opportunistically throughout the structure. However, it went a little further than the original Ironbridge in using repetitive, standardized parts.

Quite aside from its fascinating iconographic issues, the building displays a complex border-crossing inventiveness in exploring the possibilities of system development in construction. The columns are 6.5-m-long, 18-mm-thick cannon barrels, an advertisement for the foundry itself, and the swiveling derrick cranes they carry turn on ball-bearings made of cannonballs. The lower chords of the fishbelly trusses supporting the gantry that lifted molten iron from the furnace to the casting floor, are over-sized, laminated-steel wagon springs. These gun-barrel-columns, cannonball-ballbearings and wagonspring-truss chords, all invented years before their usefulness was recognized by patents, suggest that Althans was a border-crosser who solved his technological problems associatively. This is the same form of translation that inspired Marc Brunel to observe the behavior of the pipeworm and invent the tunneling shield or turn iron reinforcement in masonry into "soil nailing." Althans was clearly another master of matrix thinking.

The foundry's cross-section combines a three-dimensional frame and several configurations of trussed arch that spread the live- and deadload paths to all members in an ambiguous way. This gave the cross-section a structural redundancy that helped the building survive so long. It was difficult at the time to cast high-quality iron elements, and Althans was surely aware of the dangers of over-optimization. Compared to the conceptual clarity that contemporary engineering theoreticians like von Gerstner, Eytelwein or Navier were striving for in their simplified modeling of structural behavior, Althans's structural ambiguity and redundancy may well have been a form of theoretical translation and a clear-headed way of introducing a factor of safety into the structure. The severe dynamic loads introduced by the building's cranes explain the need for a high level of structural redundancy and the complex stiffening mechanism which provided the designer with further scope for translation, this time from formal design to structure. The intricate Gothic tracery in the front windows not only conform to the ecclesiastical formal design, it also forms a lattice stiffening truss or, with its glass infill, a shear membrane against lateral movement.

The continuous clerestory window bands along the nave have the same tracery configuration and also function as effective longitudinal stiffening trusses. They are attached to the tops of nave columns, and as these carried the large liveloads of the traveling and derrick cranes, the tracery stabilized them in a very efficient manner. They are remarkably similar to the wooden-lattice bridge trusses with multiple, prefabricated members that Ithiel Town patented in the United States in 1820 and which German builders had begun to copy at that time.

Town used an iterative approach to structural integrity through structural redundancy, but it had other advantages that were specific to North American building culture. Town's lattice bridge can demonstrate how builders in different cultures developed their own brand of construction thinking and how such differences were based on economic and cultural criteria.[10] Eighteenth-and early nineteenth-century American builders had little skilled labor at their disposal. They therefore simplified their wooden bridges with a lavish use of standardized iron connectors for easy assembly by amateur carpenters, while their European counterparts still had highly skilled labor to make labor-intensive and time-consuming intricate timber connections. Since American connections were so simple and cheap there was no need to limit their number. On the contrary, American builders preferred many connections as a strategy to increase structural redundancy. If a connection were poorly assembled, or if it disintegrated through lack of maintenance, the surrounding ones held it and damage became apparent long before the bridge collapsed. It is an American cultural trait to make structures safe through a *quantitative* proliferation of parts rather than by guaranteeing the *quality* of individual connections.[11]

American builders had no trouble accepting the idea that a new kind of quality can come from an increase in quantity. They intuitively understood that new structural characteristics can emerge from repetitive construction. This understanding would later influence the replacement of quality by quantity in consumer society and it appeared logical to Americans. No labor may have been saved by trading quality for quantity, but there were major savings in skilled labor, maintenance and the prevention of collapse through construction errors. This was advantageous to a society that was expanding and always overextending its professional capacity. America did have immigrants but it lacked professionals to supervise sites and check structures.

KEW PALM HOUSE AND THE PATTERN OF TECHNOLOGICAL METHOD

In comparison to the generation of iron buildings like the Sayn Foundry that preceded it Richard Turner's Palm House at Kew Gardens made a notable advance in the simplification and standardization of connections. It used mostly wrought instead of cast iron, and its frame is post-tensioned by an ingenious system of "tubular purlins." These tubes served as spacers between the webs of the structural arcs, and wedged tension rods running through them held the structure together. The arcs were rolled deck-or bulb-beams, precursors of our modern I-beams. Two half barrel-vaults stiffened the frame laterally and two domed apses held it longitudinally. Turner adopted the stiffening vaults and domes from previous schemes for the building, and similar ones had been used in several previous free-standing hothouses, notably in Paxton's 1839 Chatsworth conservatory.

Iron constructors knew by then that iron buildings had entirely different problems than stone or wooden structures. A fixed beam-column connection for instance, would stiffen a structure but could not accommodate thermal expansion at the same time. Turner was one of the first to adopt what is now standard strategy in technological design thought. He separated problems and solved each aspect independently. His "tubular purlins" were only post-tensioning devices. Secondary purlins ran parallel to them and carried the glazing bars out at the edges of the arcs. The only connection between the two purlins were intermediate supports for the thinner ones at several points in each bay. A third, even thinner bar connected and stabilized the glazing bars. At first blush the triplication of the purlin seems needlessly complicated. However it did separate the different construction problems into three distinct layers and helped stabilize the frame in two ways. Each connection was at best semi-rigid and could deform slightly when it was loaded. Even the welded supports between the primary and secondary purlins were somewhat flexible and acted as rocking beams. Each of the many flexible connections helped stabilize the frame by deforming and absorbing a little energy each time lateral forces acted on the building. In the same way, each connection also absorbed a little of the building's thermal expansion, thereby avoiding stress concentrations that would have made single, stiff connections fail.

Turner's clear hierarchy of structural members and their relationships advanced system thought in building. He demonstrated that it was possible to fulfill contradictory detail criteria by decoupling the problems, solving them serially and then reuniting the solutions to form a component subset. Like Paine and Wilson in the Sunderland bridge, Turner expanded the concept of system to include an intermediate level, the subassembly. This would have far-reaching consequences in construction, because the repetition of identical or similar components could be designed to produce a different technological result than using a single, larger component. In retrospect, Town's lattice bridges with their many, identical components repeated over and over again, manifest the same approach to incremental problem solving through iteration and to the system dictum that "the whole is more than the sum of the parts." Turner's innovation required a sophisticated level of reasoning on the part of a builder that was beyond most engineers and contractors at the time. But it did provide a rationale beyond the economics of reusing casting molds for the many modular, repetitive systems that were beginning to appear at the time.[12]

In order to isolate and solve his technological problems incrementally, Turner probably had to think of his building as a complete shape and then dissect it into parts for prefabrication in the old fashioned way. Most of the prefabricated buildings that preceded the Crystal Palace were still designed in this fashion. British and French factories shipped prefabricated houses around Cape Horn to California's Gold Rush communities in 1849 and 1850 and British entrepreneurs exported modular buildings to Australia in their Gold Rush two years later. In spite of the early advances in bridge design, most bridges, lighthouses, and machinery, the Sayn Foundry, and the Kew Palm House were all still being designed as closed systems, or ones in which the form and the structure are two aspects of a single design process.

Closed systems are simple to understand, but they cannot easily adapt to different uses. Open systems are more flexible. They result from two levels of design: the design of the structural system first and then the design of the building form. Such structural systems can be put together in many ways to make different buildings. But this also makes them more complex to design because the system has to accommodate many configurations that may not all have the same characteristics. Their connections have to satisfy criteria that are only completely known when the formal design is complete. Ideally open-system connections are therefore designed to be stiff in themselves so that they do not need secondary stabilizing mechanisms. Thomas Wilson's Sunderland Bridge was an early form of open system in principle.

Two factors supported the development of the open system: component manufacture and system hierarchy. Turner had begun to develop a system hierarchy, and Charles Fox carried his idea further in the Crystal Palace which became a prominent example of open system design. Although the original form and idea were Paxton's, Fox carried it out, and he displayed a peculiar brand of three-dimensional hierarchy in system thinking. Even today most structural designers think primarily in two dimensions. They design a building in plan and cross-section and create two-dimensional structural frames that they stack one behind the other to form a three-dimensional building. Both Althans and Turner's buildings are in principle extrusions of two-dimensional frames. Paxton's sketch for the Crystal Palace is also a cross-section and the design he developed from it was an extrusion of that cross-section too. But Fox's gridded, three-dimensional module is different. Its east-west cross-section is identical to its north-south cross-section. Fox designed the module identically in the x-and the y-axes so that it could be added to equally in both directions making it structurally "non-directional." The trusses on all four sides of the module were the same. However, he had to carry the roof and a wooden floor on those trusses, and both of these sub-systems were "directional" because the gutters and joists spanned in one direction only. In the case of the roof, Fox had the one set of trusses carry spread loads, while the other carried the underspanned gutters, that lay 2.4 m apart, as point loads.

The floor presented a more complex problem: joists are more closely spaced than roof gutters. The trusses bearing the joist ends would carry far more than those which lay parallel to them, which only had to carry the load of a single joist. Fox had to devise a system to spread the load equally over the trusses spanning in both directions. He used the same technique he had developed to post-tension the gutter, but rotated the wrought-iron tension rods 90°. The rods underspanned two beams that spanned from girder to girder at their third points. He notched the joists into these beams, attaching them by means of primitive strap-hangers at the third-points of the other pair of cast-iron girders. This enabled him to distribute the floor loading equitably to all four edges of each module. The question is not whether or not this was a good solution, but that the rotation was a simple transformation of an underspanning technology that required a shift in geometry and a complex ability to think three-dimensionally. Fox was able to do both well. Another example was the "glazing wagon" he built to rationalize covering the hectares of flat roofs. As far as we presently know, this cart introduced a first real split between modularized construction and erection method.

When roof glazing began, a team of workmen set up scaffolding in each module separately. They were served by a boy whose job it was to go up and down the ladder carrying glass panes, glazing bars and putty to the laborers. It was a tedious process. There were a total of 1,245 grid modules or an area of 66,623 m^2 to glaze, not counting the lead-covered areas adjacent to the transept and the vault itself. Fox realized that the roof was a critical bottleneck. There already were between two and three thousand workmen on site and he would have had to increase manpower beyond practical limits to finish the job. So he chose to enhance productivity by rationalizing the movement of men and materials.

Fox designed a covered, wheeled cart using the gutters as tracks. Each cart carried two workmen who placed glazing bars, strings of putty and panes economically and rhythmically directly in front of them. One sat on each side of the ridge and they pushed themselves backward as they worked. A boy sat behind them and passed materials forward. They moved from module to module along the gutters without leaving their seats. Each workman placed an average of 108 panes a day, traversing four modules, and covering over twenty-eight meters.[13]

The keys to Fox's ingenious solution were the intermediate material depot on the mobile worksite and the disassociation of the linear glazing process from the modular planning of the building. Fox reversed the translation process he had done before and made a three-dimensional construction module into a linear process. He also inverted the assembly-line principle and moved his workers past their work. This was a logical step to take when assembling something that was fixed to the ground.

Building types from the American balloon-frame and English terrace housing to towers, sheds, and halls were hybrids of open and closed systems. Many of them had characteristics that were as subtle and fascinating as Fox's. Finally, thirty years after the Crystal Palace, the open system concept came into its own in Gustave Eiffel's tower at the 1889 Paris Exhibition. Like Turner before him, Eiffel segregated issues to solve detail problems. But where Turner reunited the detail solutions in a specific component design for a unique building, Eiffel recombined them to form an open system that he could use to build any iron structure. Eiffel defined connectors and members that linked them. Like Ithiel Town, Eiffel kept member cross-sections and connectors constant but he used a more complex catalog of parts and varied his component length to produce similar, rather than congruent elements. The generator of his construction system that emerged fully matured in the Garabit Bridge of 1884 and his tower in 1889, was a simple catalog of only nine basic connection gussets and he combined them to build complex objects without the many customized components his predecessors had needed. Eiffel's connectors form the constants of his system geometry, while the configuration and length of his linear members are the variables, and it is this distinction between system constants and variables that made his structures so valuable to system thought. We do not know whether he conceptualized what he did in quite this way—he never wrote about it—but he clearly had some form of logically ordered thinking process that helped him develop a simple and yet sophisticated catalog of wrought-iron parts and connection rules. The Eiffel Tower has been well-publicized ever since it broke ground, but less as an example of system thinking than as a monumental *tour de force* and a building process.

Along with others, like Charles Strobel, who standardized rolled steel cross-sections and their connections for the Carnegie group in 1881, Eiffel's kit-of-parts approach to construction influenced and simplified steel bridge and high-rise construction. The idea was even adopted in 1904 by "Meccano," an open-ended British engineering construction toy for boys—called "Erector Set" in the United States. Meccano firmly imbedded the concept of open-ended, standardized assembly kits and sophisticated hierarchical system thinking in the minds of generations of future engineers and manufacturers.[14]

CONCLUSION

Marc Brunel and Ludwig Althans demonstrated the subtle complexities of matrix thinking and border-crossing translation. Richard Turner decoupled aspects of a technical problem to reunite them in a different way, and Charles Fox decoupled assembly from construction and thereby recognized building as a process. Thomas Wilson, Ithiel Town, and Eiffel developed the kit-of-parts approach to assembly. These examples and many others like them can help us distinguish the critical concepts that led to system thinking as practiced in building. They allow us to relate the specific to the type and to distinguish between *what* and *how* a builder thought which is what can help us develop design method. Each of these conceptual building blocks presents us with a node in the decision-making process which we can reexamine in light of today's construction world and use in the education of architects and structural engineers.

NOTES

1. For a complete discussion of this topic with many more examples see: Tom F. Peters, *Building the Nineteenth Century*. MIT Press, 1996
2. Until the middle of the nineteenth century the Institution of Civil Engineers repeatedly discussed this problem.
3. British pat, 4204 Jan. 20, 1818
4. "The Thames Tunnel is open to the public every day" handbill issued in Feb. 1840, and Richard Beamish, *Memoir of the Life of Sir Marc Isambard Brunel*. London 1862, p. 284
5. Beamish, op. cit. p.286-287
6. Charles W. Pasley, Observations on limes, calcareous cements, mortars, stucco and concrete, and on puzzolanas, natural and artificial., 2nd. ed. London, 1847, part 1, p. 164; Marc Brunel in Min. Proc. ICE, vol. 1, 1838,

p. 16; George F. White, "Observations on Artificial Hydraulic, or Portland Cement; with an account of the testing of the Brick Beam erected at the Great Exhibition, Hyde Park." Min. Proc. ICE, vol. 11, 1851-1852, (18.05.1852), pp. 480-481, 492-495 and footnote p.493

7. Alec W. Skempton and Michael M. Chrimes, "Thames Tunnel: geology, site investigation and geotechnical problems." *Géotechnique* 44 no. 2 (1994): 191-216
8. see for instance Charles Taylor, A Supplement to Nicholson's Operative Mechanic, and British Machinist. London, 1829, plate 4 or Edaward Cresy, *An Encyclopaedia of Civil Engineering, Historical, Theoretical, and practical.* London, 1847, p. 497
9. Paul-Georg Custodis, *Die Sayner Hütte in Bendorf.* Cologne: reprint from *Rheinische Kunststätten.* (1980) no. 241.
10. Gregory Dreicer is currently writing on Town and border-crossing influences in nineteenth-century bridge building.
11. Tom F. Peters, "An American Culture of Construction." *Perspecta 25,* pp. 142-161, 1989 New York: Rizzoli.
12. For a full discussion of this example see: Tom F. Peters: *Building the Nineteenth Century.* op. cit.
13. Cecil D. Elliott, Technics and Architecture. Cambridge MA, 1992. caption on p. 132, ciing the *Illustrated London News,* Dec. 7, 1850.
14. Svante Lundkvist first discussed the importance of this toy for engineering education in 1991 in a talk at a meeting of the Society for the History of Technology in Madison, WI.