

ENGINEERING SYSTEMS CONFERENCE TALK—March 29, 2004

Complexity and Contradiction: Engineering Systems Approach

By Thomas P. Hughes, University of Pennsylvania and MIT

Robert Venturi, arguably the leading late 20th century architectural theorist and practitioner, in his manifesto published in 1966 greatly influenced an entire generation of young architects to think differently about their profession and design. He rejected the reductionist high-modern approach of the interwar years with its emphasis upon the values of science and technology. I believe his powerful argument resonates well with the approach taken to projects and problems by a generation of engineers who today are using an engineering systems approach.

The overall thrust of Venturi's argument is that during the 20th century America passed from an adolescent cultural stage characterized by a need for objectivity, clarity, and control to a mature one characterized by complexity, richness, and ambiguity. This mature culture called for an architecture that expressed these characteristics. Analogously, engineers taking an engineering systems approach now embrace a mature approach encompassing complexity, richness, and ambiguity. The elegant simplicity of a science-based approach does not suffice today because of the greatly increased rate of change, complexity, and scale of structures, machines, and systems. The engineering systems approach, like Venturi's architecture of complexity and contradiction, involves accommodating rather than excluding, accepting redundancy rather than simplification. In short the engineering systems approach embraces real

world “messy complexity.” [Robert Venturi, *Complexity and Contradiction* (1966)]: p.16)

The engineering systems approach takes into account that there is not one best solution for complex problems and that all problems cannot be completely solved. Often problems that can be solved are not the ones that society most needs solved. Excluding societal constraints from problems so they can be solved often reduces the societal relevance of the solution. We should recall that Herbert Simon used the term “satisficing,” a combination of “satisfying” and “sufficing” to refer to satisfactory solutions instead of optimal ones for design problems. As Henry Petroski points out in his recent book *Small Things Considered: Where There is no Perfect Design* (N.Y.: 2003) Simon realizes that “the decision maker has a choice between optimal decisions for an imaginary simplified world or decisions that are ‘good enough,’ that satisfy, for a world approximating the complex real one more closely.” (p.8).

Telford’s Engineering Systems Approach

The practitioners of the engineering systems approach have distinguished predecessors. From them we can gather insights into the approach. In mid-nineteenth century Samuel Smiles the author of the widely read *Lives of the Engineers* (1861) wrote engagingly about Thomas Telford (1757-1834) who designed bridges, canals, and highways that according to Smiles opened inland England and Scotland for economic and social development. Acutely aware of the political ramifications and social impact of his practice, Telford took an engineering systems approach. In 1802 he began surveys for the British government of Scotland, especially the Highlands, in which he identified the

bridges and roads needed to stimulate economic and social development of the country and prevent further emigration. The government responded with legislation facilitating the financing of numerous internal improvements over several decades, many of which were designed and constructed under the aegis of Telford.

The moral and social influences resulting included the training of thousands of workers in the arts of construction. Telford spoke of the road building projects as a “working academy.” He believed that the roads and bridges advanced the country at least a century. Sloth and idleness gave way to energy and activity; cottages took the place of mud “biggins” with a hole in the roof; literacy increased enormously; and ploughs, once unemployed, and other tools and utensils brought rapid improvements in agriculture.

Realizing that his large-scale projects had to be politically as well as technologically enabled, Telford established his residence near London’s Houses of Parliament and organized the Society of Civil Engineers to inform and lobby its members. In short, he, like those at MIT cultivating the engineering systems approach, understood the interaction of engineering, politics, economics, and social change.

Edison’s Engineering Systems Approach

The way in which Thomas Edison solved problems offers another example of an engineering systems approach. An account of his presiding over the invention and development of America’s first central-station electric supply, can be used to introduce engineering students to engineering systems and to remind all of

us of its essentials. First, let me stress that contrary to popular myth Edison was not simply a tinkerer who stumbled upon solutions using a hunt and try method—far from it.

In the case of the development of central-station electricity, a project that extended from 1878 to 1882, Edison displayed his and his associate's systems, as well as engineering systems, approach. Please note the contrast. Before we consider in some detail his engineering systems approach, we should note that he was also a master and advocate of a systems approach to engineering problems. Please consider his eloquent definition of a system:

It was not only necessary that the lamps should give light and the dynamos generate current, but the lamps must be adapted to the current of the dynamos, and the dynamos must be constructed to give the character of current required by the lamps, and likewise all parts of the system must be constructed with reference to all other parts, since, in one sense, all the parts form one machine, and the connections between the parts being electrical instead of mechanical. Like any other machine the failure of one part to cooperate properly with the other part disorganizes the whole and renders it inoperative for the purpose intended.

The problem then that I undertook to solve was stated generally, the production of the multifarious apparatus, methods, and devices, each adapted for use with every other, and all forming a comprehensive system.

Turning to his engineering systems approach, we find that he was not only a gifted engineer, but also a holistic master of tacit craftsmanship and adept in science, manufacturing, organization, politics, and economics. In approaching the central station project, he decided that his goal was to supply electric light at a price comparable to existing and widespread gas lighting (economics). Applying Ohms and Joule's laws he found that to do this he needed an incandescent lamp filament of high resistance (science). This challenge called upon his and his craftsmen's hands-on experimental techniques to obtain a filament of about 100 ohms resistance. Before the distribution lines for his New York Pearl Street central station could be laid, he had to persuade the city's open-handed political masters to give permission for laying them underground along city streets (politics). Realizing that existing manufacturing firms could, or would, not produce the artifactual components of his system, he and his associates established a set of interrelated manufacturing companies. They also organized a utility company to preside over the operating system. We cannot expect an undergraduate engineering student to master such an array of capabilities, but we can ask her or him to grasp the nature of the engineering systems approach as used by Edison.

Stone & Webster's Approach

Two early graduates of MIT's course in electrical engineering, Charles Stone (1867-1941) and Edwin Webster (1867-1950) provide, like Edison, an early example of the engineering systems approach. A memorable anecdote tells of their holistic style. Having established a small consulting firm shortly after graduating from MIT in 1888, they were asked by the financier J.P. Morgan to appraise troubled light and power utilities that had fallen into his hands because

of the financial panic of 1893. Stone and Webster did a sterling job and partook of a steep learning curve. They found that the companies that they appraised had often fallen on hard times because of a messy complex mix of financial, engineering, and managerial problems.

The partners' firm Stone & Webster then began to offer engineering, managerial, and financial advice to utility companies. Their approach was fresh and original. Stone and Webster, who sat at side-by-side desks and signed letters in common, offered their clients construction designs, financing for the construction, and life-cycle management for what the firm had constructed and financed. They believed that these three functions were so closely interconnected that each had to be done taking into consideration the other two. In short, their approach, like the engineering systems approach, involved engineering, financial, and management expertise and imagination. Incidentally Stone & Webster employed 300 college graduates in 1912 and close to 100 came from MIT and 50 from Harvard University. Charles Stone and Edwin Webster designed the firm's symbol, a triskelion that had three arms enclosed in a triangle. The engineering system division might well adapt and adopt this symbol by adding more arms within the triangle.

Coupling a Historical and an Engineering Systems Approach

Historians are inclined, like practitioners of the engineering systems approach, to accept the existence of a real and messy world. Some of us tell stories about technologically-enabled large infrastructures involving machines, systems, form-giving architecture, and the *ilities* so masterfully defined by Joel Moses.

We do not predict but we can provide in tandem with engineers analogy-based scenarios that will give them a feeling for the future with which they must cope.

Conclusion

I could give many more examples of the early master practitioners of the engineering systems approach and dilate upon history and analogies, but I should turn to my gifted colleague Professor David Mindell to explore the recent history of engineering systems and to Dean Daniel Roos to give a history of engineering systems in which he has played a crucial role.