ENGINEERING SYSTEMS SYMPOSIUM

ENGINEERING SYSTEMS AT MIT—THE DEVELOPMENT OF THE ENGINEERING SYSTEMS DIVISION

Daniel Roos

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The Engineering Systems Division (ESD) builds upon academic programs and research centers established at MIT during the past three decades. Although these programs and centers were begun independently, they had common characteristics, which greatly influenced the formation of ESD. This paper examines the evolution of those programs, explores the rationale for the creation of the Division, and describes the structure, goals and objectives of the Division. The discussion focuses on three different periods of about a decade each, corresponding to three phases of engineering system development at MIT: Early 1970s-1985, when Dean of Engineering Alfred Keil introduced the first engineering system programs and broadened the activities of the MIT Engineering School; 1985-1995, when concerns about US competitiveness motivated MIT to initiate new programs in manufacturing; and 1995 to the present, when ESD was proposed and established. The three periods leading up to the launch of ESD provided valuable insight and lessons about engineering systems. Those lessons that influenced our understanding of engineering systems, and the design of ESD are described (a time line of the startup of the initiatives discussed in the paper appears in Appendix A). The purpose of this paper is not to suggest that MIT has followed the best approach, which other universities should adopt. Rather, it is to describe how one university dealt with the changing nature of engineering, the impact that those changes had on the MIT School of Engineering (SoE), and the nature of the programs within the SoE focusing on engineering systems.

Approval of ESD was a time consuming and complex process. Some appreciation of the difficulty in creating ESD can be gained from the fact that the ideas behind it had been explored by several committees over a period of twenty years, and all previous proposals had been turned down. Finally, in 1996, the Eagar Committee, appointed by Dean Joel Moses, recommended creation of a new Division of Engineering Systems. The Division would be charged with overseeing the existing engineering system programs, with developing Engineering Systems as a new field of study, and with institutionalizing the field at MIT.

Even after the Eagar Committee report, it was two more years before ESD was approved in 1998. Part of the delay was attributable to doubts expressed by traditional SoE faculty, who questioned the legitimacy of Engineering Systems because of its broad perspective and the inclusion of management and the social sciences. The Sloan School of Management was concerned that the SoE not develop what it considered second-rate management programs. In spite of these concerns, ESD was approved because of the success of the pre-existing programs it built on, and the recognition that MIT needed to address large-scale, complex engineering systems in the 21st century.

When the Division was approved, twenty faculty from the Engineering and Management Schools joined ESD. The initial focus of those faculty was on understanding the characteristics and properties of large-scale, complex systems, and developing appropriate engineering systems methodologies to better understand system behavior. Over time, the faculty realized that understanding engineering systems also requires a different mode of thinking about problem solving. This approach incorporates holism vs. reductionism, an enterprise, life cycle perspective, inclusion of stakeholders, consideration of design characteristics such as flexibility, safety and security, sustainability, adaptability, and agility in addition to the traditional design criteria, and incorporation of context considerations as an integral part of the design process.

PHASE 1: EARLY 1970s-1985—TECHNOLOGY AND THE CIVIL SECTOR

In the early 1970s, newly appointed Dean of Engineering Alfred Keil made a bold proposal to reorganize the SoE at MIT. Keil hoped to build upon and broaden MIT's worldwide reputation in engineering science to become a leader in what Keil described as "modern engineering." Keil wanted "to resynthesize the engineering science base which had developed rapidly during the 50s and 60s, and to establish such new disciplines as operations research, systems analysis, and applied micro-economics which are essential to the analysis and syntheses of socio-economic systems." Keil proposed "to start a systematic approach to technology in the context of socio-technical systems (transportation, energy, communications, etc.) through integrated team efforts of faculty, followed by systematic curriculum development for this area."

Keil's vision reflected changing perspectives on technology. When the Vietnam War ended there was great interest within the nation and at MIT in converting from military technology applications to the application of technology in the civil sector. This focus on using technology to solve major societal problems was fueled by the huge loss of engineering jobs in the early 1970s due to the end of the Apollo program, as well as reductions in NASA and DOD programs. The US government began funding new technology-based civil programs in sectors such as transportation and housing. Industry responded by developing new civil sector technology units.

At the same time that technology was being utilized to address societal problems, concerns were developing about the negative impacts of technology on society. In 1962 Rachel Carson published the groundbreaking book *Silent Spring*, cautioning about polluting the environment. In 1965 Ralph Nader published *Unsafe at Any Speed*, which documented the Corvair safety problems and General Motors attempts to cover them up. In response, the federal government established new agencies such as the Environmental Protection Agency, and introduced regulations such as the Clean Air Act to safeguard the public against the harmful effects of technology.

Keil reflected these two different perspectives on technology and society by establishing three new socio-technical initiatives in the SoE; these would become a part of ESD a few decades later. Each focused on both the benefits of technological developments as well as the negative impacts. The first was The Center for Policy Alternatives (CPA), established in 1971 under the direction of Dr. J. Herbert Holloman. Holloman had previously served in senior positions at General Electric, as the Assistant Secretary for Technology at the Department of Commerce, and as President of the University of Oklahoma. Holloman brought in many new research staff who made substantial contributions, but unfortunately CPA had minimal interaction with faculty from the academic departments.

Keil's second initiative was the Center for Transportation Studies (CTS) founded in 1973 as a "bottom up," faculty-led initiative. SoE transportation faculty in the Civil and Environmental Engineering, Mechanical Engineering, Ocean Engineering, and Aeronautics and Astronautics departments proposed the creation of this interdisciplinary center which also included faculty from Economics, Political Science, Urban Studies and the Sloan School of Management.

Prior to CTS, the transportation emphasis in the SoE was on the design and construction of transportation vehicles and infrastructure. CTS broadened that perspective, addressing issues such as, Should a highway be built and if so, where should it be located to cause minimum disruption to the surrounding urban environment? New quantitative social science and systems analysis approaches were developed including network equilibrium models, econometric models to predict transportation demand, and supply functions to model different cost and performance characteristics. The analysis shifted from a focus on individual transport modes to a multi-modal analysis (e.g., a freight transportation analysis would consider the rail, truck, container and air alternatives).

CTS provided the interdisciplinary institutional mechanism, so that transportation problems could be examined as a socio-technical system. There was still a need for highway engineers to design and construct highways, but that technical analysis became part of a larger transportation systems framework, which represented a different mode of thinking about transportation engineering problems. That different mode of systemic thinking about transportation influenced the development of ESD.

The third initiative was the Technology and Policy Program (TPP), which offered a new Masters degree. Keil obtained funding from the Sloan Foundation to begin TPP in 1975, and appointed Richard de Neufville as the first Director, a post he held for over 25 years. The theme of TPP was "engineers with a difference" and the goal was dual literacy in both technology and policy. Only students with an undergraduate engineering degree were admitted to the program. TPP had more course requirements than other Masters programs at MIT. This was done to counter the perception by many at MIT that TPP was a "soft" degree in a school that emphasized quantitative rigor. Although TPP focused on policy, only one-third of the graduates pursued careers in the public sector. One-third of the graduates were employed by industry and the other third went on for advanced degrees.

At the same time that Keil was launching these new initiatives, he was also proposing a major reorganization of the departmental structure in the SoE. Keil encountered significant opposition from the SoE department heads as well as the SoE faculty so the plan was abandoned, and Keil's desire to broaden the School of Engineering was never fully achieved. Although he had created CTS, CPA and TPP, these were small-scale programs that had a comparably minor impact on the SoE as a whole.

Following Keil's departure as Dean in 1978, Holloman had a major health problem and left MIT. CPA later encountered financial difficulties, and as a result, an Institute Committee chaired by John D.C. Little was formed to determine its future. The Committee found that CPA had numerous problems and recommended it be closed. However, the committee recommended that "a new, MIT-wide centerpiece for policy, teaching, and research related to engineering and science be formed within the School of Engineering." Dean of Engineering Gerald Wilson was not convinced a new center would be more effective than CPA, so he established a second committee to explore how this new center would operate.

The Little Committee had recommended that Daniel Roos, who was the CTS Director, should direct the new center. Wilson therefore asked Roos in 1984 to chair the Engineering School Committee and subsequently to direct the new Center for Technology, Policy and Industrial Development (CTPID). CTPID differed from CPA in several respects. First, it involved faculty in all its projects and was more closely linked to the departments. CTPID assumed responsibility for TPP to better integrate policy activities in education and research, and to provide more research opportunities for TPP students. Including "Industrial Development" in the center name emphasized that although the Center focused on policy, the role of the private sector as well as the public sector would be considered. CTPID's flagship program, the International Motor Vehicle Program (IMVP) described in the next section, illustrates the importance of this dual focus.

PHASE TWO: 1985-1994—US COMPETITIVENESS IN MANUFACTURING

During the 1980s, concerns about US competitiveness emerged as Japanese industry became dominant in many industrial sectors. US industrial leaders felt American engineering schools were not adequately preparing students in critical fields such as manufacturing. There was pressure both from within MIT and externally from industry for MIT to develop programs that were responsive to that challenge. The timing was excellent for the introduction of new manufacturing programs from the perspectives of both Sloan and the SoE. The Sloan faculty, under Dean Lester Thurow, developed a strategic plan in the late 1980s that emphasized Sloan's relationship with the SoE was a strategic advantage. Until then, Sloan had limited interactions with the SoE. The

SoE had achieved worldwide recognition after World War II by focusing on engineering science. However, some engineering faculty were concerned that the shift to engineering science had gone too far and that areas in engineering at the macro scale, such as design, manufacturing, product development, and the environment should now be emphasized.

MIT's response to the challenge of improving US competitiveness was multifaceted, with three new initiatives. The MIT Commission on Industrial Productivity examined global competitiveness, the IMVP focused on competitiveness in the motor vehicle sector, and the Leaders for Manufacturing Program (LFM) was launched as a major new MIT manufacturing initiative.

The Commission on Industrial Productivity was appointed by MIT President Paul Gray in 1987 to better understand the reasons for the decline in US competitiveness, and to recommend what could be done to improve it. This was the first commission MIT had convened on a major national issue since the end of World War II. The Commission Chairman was Michael Dertouzos, head of the MIT Laboratory for Computer Science; the Vice-Chairman was Robert Solow, recipient of the Nobel Prize in Economics. The selection of these two prominent faculty members signaled the importance MIT associated with the Commission. The results of the Commission's study were published in the book *Made in America*, which became a best seller for the MIT Press. Following the publication of *Made in America*, the Industrial Performance Center (IPC) was established in 1991. Richard Lester, the IPC Director had served as Executive Director of the Commission and several IPC faculty members were authors of *Made in America*. IPC has undertaken similar competitiveness studies around the world and is very active in the Industry Studies Program sponsored by the Alfred P. Sloan Foundation.

The second major competitiveness initiative was LFM. Launched in 1988 as a three-way partnership between the SoE, Sloan and industry, LFM built on work to develop a new manufacturing initiative that had been ongoing at MIT over a period of five years. There were several setbacks along the way, including rejection of major manufacturing proposals from MIT by the National Science Foundation (NSF) and IBM.

LFM was based on the following founding principles:

1. The Partnership Concept—The industrial sponsors of the programs provided more than funding. They assumed ownership and actively participated in all parts of the program. LFM was also an intra-MIT partnership between the SoE and Sloan. Each LFM student had two faculty advisors, one from the SoE and one from Sloan, and received two degrees, an MBA from Sloan and a Master of Science degree from an engineering department.
2. Financial Support—LFM provided students with full fellowships and a six-and-one-half-month, fully supported internship. In addition, funding was needed for a research program and curriculum development. Nearly $50 million was raised from industry, a portion of which was endowment funds to provide for long-term needs and commitments. LFM was the largest industry-sponsored program that MIT had ever initiated. The significant funding enabled SoE and Sloan to hire new faculty for LFM as well as obtain commitments from existing MIT faculty to participate in the program.
3. Enterprise-Wide Manufacturing—LFM adopted the slogan "Big-M manufacturing" to emphasize an enterprise-wide approach encompassing the entire production process, not just what happens on the manufacturing assembly line.

Because of LFM's focus on improving US competitiveness, industrial sponsorship was limited to US companies. That restriction was dropped a decade later when LFM achieved its initial objective, and its sponsors realized that participation from non-US companies would be beneficial.

A third major MIT competitiveness initiative was the IMVP, established in 1985 and focusing on the automotive sector. It had a different design than the typical university research project. In addition to undertaking a research program utilizing academics from around the world, each year the IMVP held an off-the-record Policy Forum, which brought together fifty senior individuals representing the perspectives of motor vehicle industry stakeholders including government, organized labor, the financial community, automotive manufactures and suppliers from all major auto-producing regions of the world. Forum participants discussed and debated the IMVP research findings and their policy implications. MIT's role was as an objective, neutral party. The Policy Forums enabled adversaries in industry and government to discuss key issues on a "level playing field" based on research results rather than unsubstantiated claims and war stories. The Forums increased international understanding, and in many cases, influenced policy formulation and corporate strategy. The IMVP research results and Policy Forums discussions were reported in the book, *The Machine That Changed the World*, which was published in 10 languages, sold more than 600,000 copies, and has had a major impact on US industry.

The IMVP performed benchmarking studies of product development, manufacturing and supply chain management that revealed how several Japanese companies (primarily Toyota) had achieved superior performance in all aspects of the production process. They utilized a lean production system, which was fundamentally different from the mass production system utilized by the Western auto companies. Lean production represented a different mode of thinking about the production process based on an enterprise-wide approach. Integrated product development teams were utilized in contrast to the vertical "stovepipe" structure in Western companies. Manufacturing was performed by teams of educated workers that focused on perfect first time quality, immediate correction of problems and continuous improvement, compared with the mass production approach using unskilled workers. Assemblers and suppliers had a shared destiny and a trust relationship based on mutual reciprocal obligation, rather than the adversarial relationships that frequently occurred in the West. A supplier tier structure was used to simplify organizational interfaces, and supplier groups were established to insure communication between key members of the team.

The IMVP provided many lessons in MIT's evolution toward engineering systems: the importance of using an enterprise-wide approach, consideration of system characteristics such as quality, flexibility and adaptability, the need for a stakeholder perspective, and the importance of structuring relationships within the organization and the extended organization. Lean production represented a framework and different mode of thinking about the production system, which was one example of an engineering system.

PHASE 3: 1995-2004—INCREASED ENGINEERING SYSTEMS ACTIVITIES IN SOE

As US industry became more competitive in manufacturing, MIT competitiveness initiatives broadened to other aspects of the production system and value chain. The principal focus was on system design and product development, because of their cost and performance implications. Although some aspects of product development and system design were included in LFM "Big M" manufacturing, there was not sufficient time in the academic program to explore product development in depth.

As a result, three new programs were started: a Master of Science in System Design and Management (SDM), a Master of Engineering in Logistics (MLOG), and the Center for Innovation in Product Development (CIPD). Before launching SDM, Professors Tom Magnanti and Ed Crawley, the initial SDM Co-Directors, surveyed approximately thirty companies to solicit their views on the proposed new program. They received an interesting message. The companies wanted an alternative to the MBA: a technically based, system-oriented degree that would include management components. Companies also indicated it would be extremely difficult to allow their best and brightest to be away from the company for a full year at MIT. These interviews greatly

impacted the design of SDM. To achieve the right balance of technical and management components, SDM was developed as a joint program between the SoE and Sloan, with a single SM awarded jointly by the two schools. SDM was also MIT's first distance learning program; students could take many courses while they continued to work at their company. Residency at MIT occurred over short, intense time periods rather than one continuous time period. Although SDM has been well received by its graduates, it has been a very expensive undertaking, because of the distance-learning component. As a result, SDM is currently undergoing an extensive review.

At the same time, there was a growing sense in industry that companies could not reach "the next level" by focusing on their own operations. Companies needed to look at how they interacted with suppliers and customers, and how they conducted their distribution operations, cooperating along the supply chain for improved performance. In response, the CTS faculty launched the Master of Engineering in Logistics (MLOG) Program in 1998. MLOG is a nine-month program, giving the students analytical tools, systems thinking and managerial concepts, preparing them to take leadership roles in industry. The research background for MLOG was already in place due to several programs in logistics and freight transportation conducted at the Center since the mid 1980s. Industrial support came mainly from companies interested in logistics, rather than passenger transportation. Research and teaching in these areas increased to such an extent that in 2002 CTS changed its name to the Center for Transportation and Logistics (CTL).

With the success of the MLOG program, industrial ties were deepened. CTL and MLOG emphasis deepened in "supply chain management"—looking at how entire networks of suppliers, manufacturers, assemblers, distributors and retailers interact with transportation, warehousing, and information technology providers to get each product to the consumers who want it at the right time and place and at the lowest possible cost.

CIPD was founded in 1996 as a National Science Foundation Engineering Research Center. As the name suggests the major focus was on product development. It had strong support and funding from several companies that had actively promoted formation of the Center. Unfortunately, NSF did not renew funding for the Center, so CIPD now operates with industry funding.

Since the engineering systems academic programs and research centers started at different times, focused on different problems and were largely independent of one another, there was no overall strategy for engineering systems in the SoE. However, at a 1987 SoE retreat, large-scale systems, was identified as an important emerging area of concern. A Large Scale Systems Committee was formed, co-chaired by Dean Joel Moses and CTPID Director Daniel Roos. In its deliberations, the Committee, considered two types of engineering systems, closed systems and open systems. "Closed systems" were systems where technical considerations predominate, whereas in "open systems" contextual considerations (i.e., social, political, institutional factors) are as important or more important than the technical factors.

During the formation of ESD, the ESD faculty agreed that the distinction between open and closed systems was not helpful. Instead, thinking of a spectrum of systems where the technical and non-technical factors have different degrees of importance was deemed more effective. Systems that were previously analyzed as closed systems increasingly are subjected to open system influences. Consider, for example, automotive systems. The automobile, which was perceived as a technologically mature product, is now influenced by new technology (i.e., light-weight materials, smart electronic components, alternative propulsion systems). The globalization of the automobile industry has shifted locations of both design and manufacturing facilities from a national to an international context. Concerns such as quality, human resources management, and time to market have motivated fundamental changes in automotive product development, manufacturing, and supply-chain design. New approaches such as just-in-time inventory control, integrated product development teams, and lean production techniques have reshaped companies' automobile production processes, while social concerns such as air pollution,

materials recycling, global climate change, and safety have also had a major impact on auto design and production. Cross-functional integrated design teams have improved the product development process and significantly reduced time to market.

Furthermore, design and manufacturing are only part of the automotive system. Government policies determine the role of automobiles in providing personal mobility, influencing automotive safety, and impacting the environment and urban development. Developing these public policies requires not only technical expertise but also an understanding of institutions, human behavioral responses, and other non-technical considerations.

During discussions at the Large Scale Systems Committee, several MIT faculty members recognized that they were often involved in several different engineering systems academic and research programs. These faculty wanted an intellectual home so they could more effectively collaborate with one another. Therefore, in 1991, Dean Joel Moses created the Technology, Management and Policy (TMP) program to bring together faculty with common engineering systems interests. The major TMP initiative of the faculty group was to create the TMP PhD program, which provided a mechanism for students to go beyond the professional practice masters degrees, especially TPP.

Institutional support for systems thinking continued to coalesce when LFM and SDM were combined under a common administrative framework. The combination made sense since both programs shared many common sponsors and focused on different but closely related parts of the production system.

ESTABLISHING ESD

As the millennium approached, the engineering systems education programs (i.e., LFM, SDM, TPP, MLOG) collectively had an enrollment of approximately 400 graduate students, more than most MIT SoE departments. Although different faculty groups established these masters programs at different times, they shared many common characteristics:

- Practice Orientation—Whereas most MIT masters programs were research based, these programs focused on professional practice.
- Experienced Students—Most students in the programs had at least 5 years of professional experience since receiving their undergraduate degree.
- Cohort-based—Students took classes together and participated in a range of other activities as a group. They learned from one another as well as from the faculty.
- Leadership and Team Building—The programs emphasized leadership and team-based, rather than individual, activities.
- Close Relationship with Industry (and Government)—The industrial partners participated in the design of the programs. Both LFM and TPP have industry and government internships as part of the program.
- Interdisciplinary—Faculty were involved from engineering, management and the social sciences
- Experiences Outside the Classroom—Students participated in field trips, plant visits, special seminars from building exercises and foreign trips as part of the programs.

In spite of their success, the academic programs did not have the ability to hire, promote and tenure faculty or to admit students directly. The programs depended on the academic departments to appoint engineering systems faculty and admit students. MIT had instituted a policy of no faculty growth, so departments viewed their first priority as hiring faculty in

departmental technical specialties. As a result, few engineering systems faculty were hired and there were insufficient faculty to participate in and lead engineering systems programs. Most engineering systems faculty members had initially been hired by departments as technical specialists, but over time their interests shifted to engineering systems.

MIT had formed several committees to explore creating a new department for engineering systems activities. The committee proposals, which were prepared over a twenty-year period, were turned down because of significant opposition from the existing engineering departments. By 1995, Dean of Engineering Joel Moses decided the time was right to reexamine these issues. Formation of the Committee on Large Scale Systems was an important first step. Dean Moses recognized that more needed to be accomplished in the SoE. Therefore, he appointed a Committee, chaired by Professor T. W. Eagar, then Department Head of Materials Science and Engineering, to explore “Hiring and Promotion of Faculty Interested in ‘Big E’ Engineering,” that is, Engineering Systems and the broader aspects of engineering. The Committee identified several shortcomings in the current SoE structure. “Big E faculty are spread between various centers and educational programs. They lack a common home to collectively develop their intellectual agenda. As a result, there is not a critically sized group of faculty that can collectively plan and implement future Big E activities within the school. This is reflected by the need to establish an ad hoc faculty review committee when non-traditional faculty members are considered for promotion or tenure. The school is faced with a dual challenge. First, how can the departments become more involved in Big E activities? Second, how can the faculty within those departments work together school wide to develop a Big E intellectual agenda that provides a framework and related methodology to work on large-scale systems problems?”

The Committee submitted its report to the new Dean of Engineering Robert A. Brown in August 1996 (Brown succeeded Joel Moses, who was then Provost), concluding that MIT should make a commitment to developing strength in engineering systems in order to lead engineering education and research well into the next century. Moreover, the Committee found that MIT required a balance between the disciplinary aspects of engineering science and the integrative aspects of engineering systems. A survey of SoE department heads and center directors found the School had only about half the needed number of faculty engaged in integrative activities in engineering systems, and they were too dispersed among departments to form a critical mass. MIT needed more faculty members in engineering systems and they needed an intellectual home for educational and research activities. The Committee recommended the creation of a Division of Engineering Systems within the SoE.

There were mixed reactions to the Eagar Committee report and some opposition to the formation of ESD from both Sloan and the SoE departments. In an era of no faculty growth, some viewed ESD as competitive, rather than complementary. Some Engineering faculty felt many issues addressed by ESD (e.g., policy) were not consistent with the technology mission of the SoE, while others thought that engineering systems lacked quantitative depth and rigor. Some at Sloan were concerned that ESD could become a competing industrial engineering department.

Approval of a new academic unit is not an easy process. It took two years after the Eagar Committee report was submitted before ESD was approved. In contrast, Biological Engineering, which was science- rather than system-based, was proposed a year after ESD, yet it was approved one year earlier. The Engineering Systems Council, consisting of the directors of the 11 academic programs and research centers dealing with engineering systems, met weekly and prepared white papers on engineering systems and ESD. After presentations to the Engineering Council, the Sloan Policy Committee, the Academic Council, and the Institute Faculty Meeting, these groups supported the Division. In December 1998, the Executive Committee of the MIT Corporation approved the formation of ESD.

One might wonder why the Eagar Committee proposal for a new Division was approved, whereas the proposals of all the previous committees were unsuccessful. There were two main reasons: First, the existing engineering systems programs had compiled an impressive track record over

the past two decades. SoE department heads noted that the programs were attracting excellent students and those students were pursuing successful, meaningful careers. ESD represented a logical next step for the SoE.

Second, the problems addressed by Engineering Systems were increasing in importance. This perspective was reflected in President Charles Vest's comments in the President's Report for academic year 1999/2000. "Human kind's advances will depend increasingly on new integrative approaches to complex systems, problems and structures. Design syntheses and synergy across traditional disciplinary boundaries will be essential elements of both education and research." Vest's remarks reflect how the world has changed. Critical contemporary societal issues involve large-scale, complex systems that are impacted by technology (i.e., energy, communications, transportation, health care, etc.). A recent article in *Business Week*[1] describes the implications of system complexity. "A huge chunk of the electricity grid fails. The Internet clogs up, and PC's crash. The space shuttle falls to the earth. Complex high-tech systems appear to be failing, and our society feels increasingly threatened. What is going on? Behind these calamities lies a common flaw: The systems are too complex to manage."

ESD STRUCTURE

In many respects, ESD is similar to an academic department. It can appoint, promote and tenure faculty, admit students, implement educational programs, and grant degrees. There are, however, important differences between ESD and a typical department. The Division has "porous boundaries" to facilitate interdisciplinary interactions and all ESD faculty share their academic appointments with another academic unit. The interrelationships between ESD, SoE, and the other schools at MIT are shown in Figure 1. ESD can be viewed as a horizontal unit that interacts with the vertical departments. The Division Director is an Associate Dean of Engineering, rather than a department head to emphasize the interdisciplinary aspect of the unit.

The ESD faculty is shown in Figure 2. The Division is quite fortunate to have an outstanding faculty including two Institute Professors, the highest honor MIT can bestow upon a faculty member (only thirteen currently hold the title). All ESD faculty have either dual or joint appointments. This promotes strong interactions with the other departments, which is an ESD priority. Dual faculty commit their time and efforts about equally between a department and ESD. In most cases, this means a formal 50/50 split of responsibility for academic salary, promotion, tenure, teaching duties, and administrative responsibilities. In other cases, faculty may have a traditional joint appointment with ESD. These faculty generally spend less than half time in ESD activities and their faculty line remains with their home department.

The objective of these dual/joint appointments is to enable ESD faculty to pursue activities that benefit both their home department and the Division, thereby adding value to both units. Furthermore, ESD faculty can leverage the work of their departmental colleagues, thus adding further value to the departments, the Division, the Schools, and the Institute. As part of its initial formation, ESD was quite fortunate to be allocated four faculty slots to hire new faculty. Given the dual nature of ESD appointments, the Division could hire eight new faculty partnering with other academic units.

Initially, ESD faculty appointments could only be made at the senior level so the initial ESD faculty members all had tenure. The rationale was that only senior faculty had the experience necessary to understand complex systems and it would be unfair to subject junior dual faculty to the tenure process involving both ESD and another department. However, Division faculty felt strongly that it was essential to have junior faculty, since any new field of study is typically begun by young people. As a result, four new junior dual faculty have been appointed since the Division was formed.

[1] Bruce Nussbaum, "Technology: Just Make It Simpler," *Business Week,* September 8, 2003.

A major challenge for ESD was the faculty assimilation process. Faculty members came from nine different academic units and had very different methodological interests and application areas. Fortunately, the faculty was able to develop a shared vision of the Division's goals and objectives. ESD provides the institutional mechanism and common framework for faculty with different disciplinary perspectives to work together and in so doing to define Engineering Systems as a new field of study.

ESD FOCUS

In general terms, ESD has two primary foci. The first is to support the existing engineering systems academic programs. This has been achieved primarily through engaging more faculty in directing and teaching in the programs through the new ESD hires. ESD also provides better coordination of the programs, both from an administrative and educational perspective, continuing a process that began when LFM and SDM agreed to operate together. A major step in the coordination process was the co-location of all the academic programs to the same floor in the ESD building. Prior to the relocation of these programs, each was located on a separate floor of the building and MLOG was on the other side of campus. Co-location will simplify administrative coordination and be of great benefit from an intellectual perspective, since students from the various programs will commingle with one another.

Providing support for the existing academic programs represented an evolutionary improvement, and was necessary, but not sufficient, to justify the creation of ESD. ESD has as its second focus a bolder mission to broaden engineering education and practice, and to create a new field of study. If successful, ESD should impact the engineering profession in the same way that MIT impacted engineering with the introduction of engineering science after World War II. This is, of course, a major challenge that will take at least a decade to accomplish. An important step has been approval of a new Engineering Systems Ph.D. in December 2002.

There has been divided opinion among the faculty regarding whether engineering systems is a discipline or a field of study. Some argue that engineering systems should be viewed in a similar manner to management, which relies on several disciplines (i.e., economics and finance, organizational theory and human resource development, and operations management). Other ESD faculty, argue that to be successful, ESD will need to develop an underlying theory of engineering systems based on careful observational techniques, and some quantitative modeling approaches that all graduates understand. Ideally, these two perspectives will not be in conflict and ESD is pursing both paths. Undertaking large-scale system oriented research projects allows us to "learn by doing" and provides insight into new methods and theories while work is also ongoing on engineering systems theory.

ESD STRATEGIC PLAN

A major activity during ESD's first year in 1999 was to develop a strategic plan. As part of that process, the faculty agreed upon a mission statement, goals and objectives of the Division, and principle areas of focus. These are described below.

The ESD mission is to:

> Establish Engineering Systems as a field of study focusing on complex engineered systems and products viewed in a broad human, social and industrial context. Use the new knowledge gained to improve engineering education and practice.

The goals and objectives of the Division are:

> Create an intellectual home for faculty from engineering, management, and the social sciences, committed to integrative, interdisciplinary engineering systems programs.

> Develop concepts, frameworks, and methodologies that codify knowledge and define Engineering Systems as a field of study.

> Educate engineering students to be tomorrow's leaders, via innovative academic and research programs. These leaders will plan, design and develop systems that are technically excellent, socially responsive and are implemented on time and budget.

> Introduce Engineering Systems into the mainstream of engineering education, by working with the MIT engineering departments, the Institute as a whole, and other engineering schools worldwide.

> Initiate research on engineering systems of national and international importance, working in partnership with government and industry.

A fundamental challenge for ESD is to develop the intellectual agenda for the Division. This task is complicated since "systems" means different things to different people. There are contrasting perspectives on systems not only in engineering but also in the physical and social sciences. Therefore, ESD faculty felt it was important to define characteristics of the engineering systems that the Division would address. They decided that ESD would focus on large-scale systems that are technically enabled (i.e., technology plays an important role in the system construct), where system analysis and design are done at the enterprise level (within and between organizations) and the societal level (considering contextual factors such as social, political, institutional and economic factors). As such, the design process examines the interaction of system components rather than examining individual components (which are primarily the domain of the engineering scientist). Because of system scale and complexity, emergent properties are very likely to occur and the design process requires the inclusion of many system characteristics and impacts that were not adequately considered in previous design approaches (i.e., quality, safety, security, sustainability and flexibility, etc.).

Some of these system characteristics and impacts were treated previously as externalities that did not affect the design. However, these externalities are part of the context in which the engineering system operates and should be considered as design variables. Thus, engineering system design should involve the design of the organization that has to manufacture the system or product; the regulations and public policies governing its use and disposition; the marketing; and the relationship with suppliers, distributors and other participants in the value chain. From this perspective, the design process includes the physical attributes that are the domain of traditional engineering; the process attributes that are the domain of both engineers and managers; and the context and societal attributes that traditionally have been the domain of managers, governments, and social scientists.

Conceptualizing engineering systems goes beyond system characteristics. As scale, scope and complexity increase, engineers need a different mode of thinking and problem solving to compliment the traditional engineering science approach. Thus Engineering Systems encompasses both the characteristics of large-scale, technically enabled systems, and the mode of thinking, or problem solving approach, needed to properly develop and operate such systems. These will be the focus of the Engineering Systems Symposium in March 2004.

SUMMARY

ESD has a dual mission: to broaden engineering education, and to define and develop Engineering Systems as a new field of study. It builds upon successful research centers and practice-oriented educational programs that were established before the formation of ESD. Based on the success of these units, SoE identified large-scale engineering systems as a priority area. An SoE Committee was formed, which recommended ESD and the Division was created in December 1998.

In retrospect, the following factors were most important in establishing ESD:

> Initiating Faculty—A core group of faculty who had worked together for many years were the principle proponents of ESD. These faculty came primarily from the Civil and Environmental Engineering (CEE) Department and had played leadership roles in directing many of ESD's educational and research programs. They recognized that, although much had been achieved with the existing departmental structure, MIT needed a new interdisciplinary unit in the SoE to go "the next step" in the development of engineering systems.

> Committed Faculty—The group of initiating faculty did not provide enough disciplinary breadth. ESD needed an interdisciplinary faculty that extended far beyond the CEE proponents. Fortunately, faculty from numerous departments in engineering, management and the social sciences were enthusiastic about joining ESD. Although the faculty had many different disciplinary perspectives, they shared a common vision of Engineering Systems.

> Intellectual Challenge—A primary goal of ESD is to establish Engineering Systems as a new field of study. Only a portion of that field has been developed, so ESD must now pursue further development.

> Successful, Implemented Programs—The engineering system educational programs and research centers implemented over a twenty-year period helped establish credibility and legitimacy to further engineering systems activities at MIT.

> SoE/Sloan Connection—Most of the educational and research initiatives involved faculty from both SoE and Sloan. Unlike some universities where the business school is removed from the rest of the university, Sloan has strong ties to the Institute in general, and SoE in particular.

> Dean's Initiatives—Strong support from the Dean of Engineering's office was instrumental in starting many of the programs. Dean Alfred Keil established CPA, CTS and TPP. Dean Gerry Wilson established CTPID and LFM (with Sloan Dean Lester Thurow). Dean Joel Moses established both TMP and SDM, and co-chaired the Committee on Large Scale Systems. Dean Robert Brown established ESD. Dean of Engineering Tom Magnanti was a co-founder of both LFM and SDM (before he became Dean). As Dean, he has provided ESD with faculty positions, space, and financial resources, all of which are crucial in launching a new enterprise.

> Industry Involvement—Most ESD initiatives have a strong industry presence. In addition to providing important financial support, industry is considered an equal partner in structuring and overseeing many of the programs in general and LFM in particular.

> Financial Support—Adequate funding is important, as LFM demonstrated. New faculty can be hired, thereby avoiding opposition from the academic departments. Funding is also important to support curriculum development of the new academic programs, and student fellowships.

Thus, many elements needed to come together. If viewed in a manner consistent with its own founding principles, ESD is itself the result of an integrative process that took decades to unfold. Over the course of the period spanned by this paper, social context came into play as national technology priorities swung in the post-Vietnam era from military concerns to solving complex social problems, and then in the 1980s, to addressing economic competitiveness brought on by new challenges to American industrial strength. In responding to these and other contextual shifts, MIT grappled with limits in its own culture and organizational design. This design had fostered great success in highly specialized scientific engineering disciplines, but now in some ways worked against the holistic modes of thought and interdisciplinary exchange required to encompass the diversity of factors and unexpected, emergent properties associated with large-scale, complex systems. Through much of the 1990s, the socio-technical and institutional elements were brought into alignment within MIT, and with the launch of ESD, it is anticipated that a sustainable institutional framework to support the new synthesis articulated by Dean Alfred Keil in the early 1970s has been firmly established.

APPENDIX A

TIMELINE

1962	Silent Spring—Rachel Carson
1965	Unsafe at Any Speed—Ralph Nader
1971	Alfred Keil Appointed Dean
1972	Center for Policy Alternatives (CPA) founded
1973	Center for Transportation Studies (CTS) founded
1975	Technology and Policy Program (TPP) founded
1984	Ad Hoc Committee on Technology and Society Studies at MIT, chaired by John D.C. Little
1985	School of Engineering Committee on Technology and Policy, chaired by Daniel Roos
1985	Center for Technology Policy and Industrial Development (CTPID) founded
1987	Commission on Industrial Productivity
1988	International Motor Vehicle Program (IMVP) founded
1988	Leaders for Manufacturing (LFM) founded
1989	Made in America
1989	Committee on Large Scale Systems
1990	The Machine that Changed the World
1991	Industrial Performance Center (IPC) founded
1991	Technology, Management and Policy (TMP) founded
1991	Technology, Management and Policy (TMP) founded
1996	Hiring and Promotion of Faculty Interested in ‘Big E’ Engineering committee, chaired by Tom Eagar
1996	Center for Innovation in Product Development (CIPD) founded
1996	System Design and Manufacturing (SDM) founded
1998	Masters of Engineering in Logistics (MLOG) founded
1998	LFM and SDM combined
1998	ESD founded

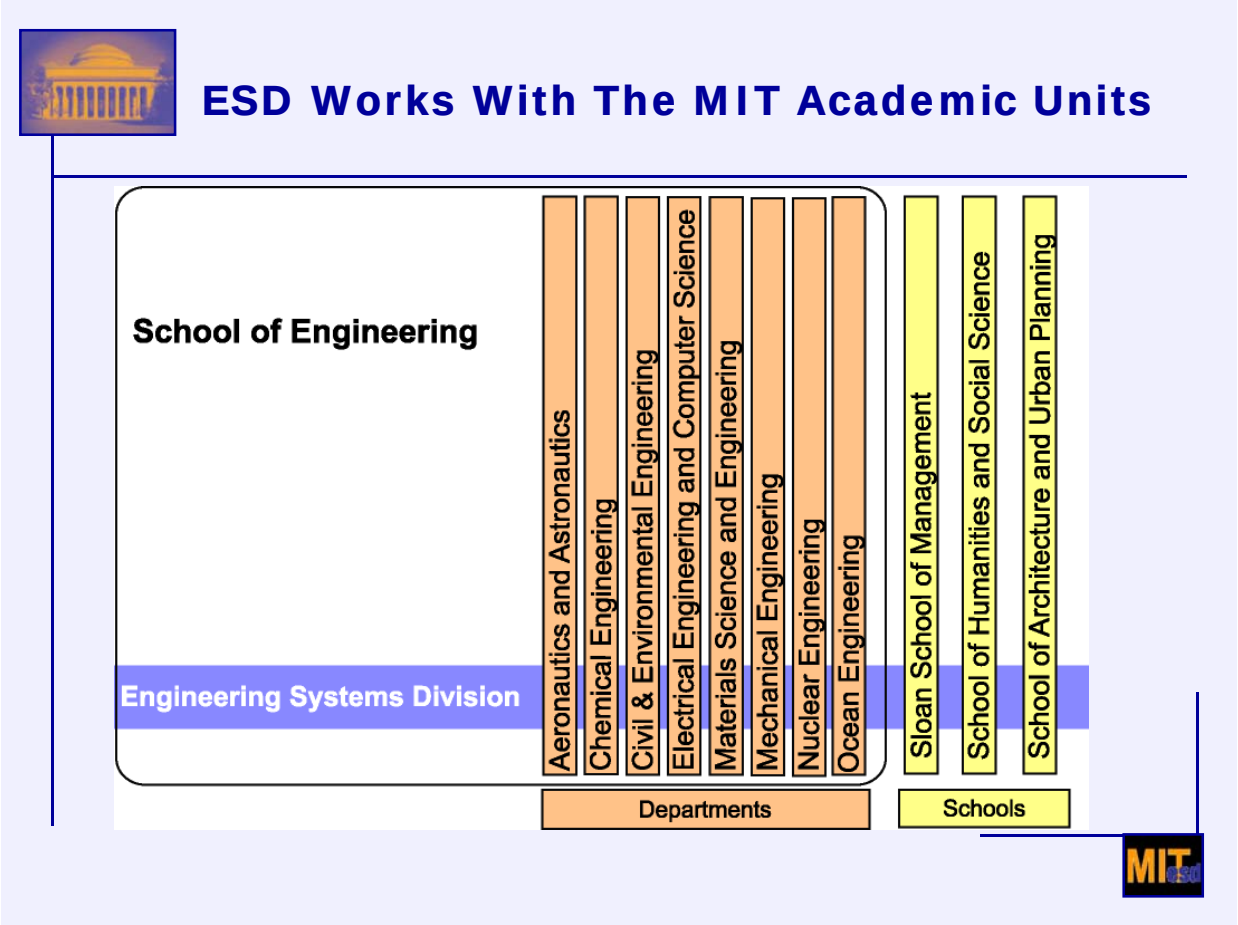

Figure 1: ESD Organizational Structure

Faculty Member	Affiliated Unit	Appointment
Thomas Allen	Sloan School of Management	Joint
George Apostolakis	Nuclear Engineering	Joint
Cynthia Barnhart	Civil and Environmental Engineering	Dual
Joel Clark	Materials Science and Engineering	Dual
Edward Crawley	Aeronautics and Astronautics	Joint
Richard de Neufville	Civil and Environmental Engineering	Dual
Olivier de Weck	Aeronautics and Astronautics	Dual
Thomas Eagar	Materials Science and Engineering	Dual
Steven Eppinger	Sloan School of Management	Joint
Daniel Frey	Mechanical Engineering	Dual
Stephen Graves	Sloan School of Management	Joint
David Hardt	Mechanical Engineering	Joint
Daniel Hastings	Aeronautics and Astronautics	Dual
Randolph Kirchain	Materials Science and Engineering	Dual
Thomas Kochan	Sloan School of Management	Joint
Paul Lagace	Aeronautics and Astronautics	Joint
Richard Larson	Civil and Environmental Engineering	Dual
Nancy Leveson	Aeronautics and Astronautics	Dual
Seth Lloyd	Mechanical Engineering	Joint
Stuart Madnick	Sloan School of Management	Joint
Christopher Magee	Mechanical Engineering	Dual
David Marks	Civil and Environmental Engineering	Dual
David Mindell	Science, Technology and Society	Dual
Fred Moavenzadeh	Civil and Environmental Engineering	Dual
Joel Moses	Electrical Engineering and Computer Science	Institute
Earll Murman	Aeronautics and Astronautics	Joint
Dava Newman	Aeronautics and Astronautics	Joint
Deborah Nightingale	Aeronautics and Astronautics	Joint
James Orlin	Sloan School of Management	Joint
Kenneth Oye	Political Science	Joint
Daniel Roos	Civil and Environmental Engineering	Dual
Warren Seering	Mechanical Engineering	Joint
Yossi Sheffi	Civil and Environmental Engineering	Dual
David Simchi-Levi	Civil and Environmental Engineering	Dual
David Staelin	Electrical Engineering and Computer Science	Joint
Joseph Sussman	Civil and Environmental Engineering	Dual
David Wallace	Mechanical Engineering	Joint
Annalisa Weigel	Aeronautics and Astronautics	Dual
Sheila Widnall	Aeronautics and Astronautics	Institute
John Williams	Civil and Environmental Engineering	Dual

Figure 2: ESD Faculty

REFERENCES

Carson, Rachel. *Silent Spring.* Boston: Houghton Mifflin, 1962.

Dertouzous, Michael L., Richard K. Lester, and Robert M. Solow. *Made in America: Regaining the Productive Edge***.** Cambridge, Mass: The MIT Press, 1987.

Eagar, Thomas. *Hiring and Promotion of Faculty Interested in Big E Engineering.* Cambridge, Mass: MIT Report, 1996.

Horn, Dean. *Multiple Genius—The Amazing and Great Accomplishments of MIT's Alfred Keil*. Cambridge, Mass: MIT Sea Grant Program Publications, 2001.

Little, John D. C. *Ad Hoc Committee on Technology, Policy and Society Studies at MIT*. Cambridge, Mass: MIT Report, 1984.

Nader, Ralph. *Unsafe At Any Speed: The Designed In Dangers of the American Automobile.* New York: Grossman,1965.

Roos, Daniel. *School of Engineering Committee on Technology and Policy*. Cambridge, Mass: MIT Report, 1985.

Roos, Daniel. *Engineering Systems Division Strategic Plan*. Cambridge, Mass: MIT Report, 1991.

Vest, Charles, M. *MIT Presidents Report, 1999/2000.* Cambridge, Mass: MIT Report, 2000.

Womack, James P., Daniel T. Jones, Daniel Roos. *The Machine That Changed the World.* New York: Rawson Associates, 1990.