The Center for Technology, Policy, and Industrial Development

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Acknowledgements

The primary purpose of this report is to trace the development of the field of Engineering Systems on the occasion of the twentieth anniversary of the founding of the Center for Technology, Policy, and Industrial Development (CTPID) – an interdisciplinary research center at the Massachusetts Institute of Technology – that significantly contributed to this emerging field.

To do this, the report maps the intellectual trends that evolved since World War II, the emergence of large-scale systems, and the growing reliance on and pervasiveness of technological innovation. Technology's intrusion into the social and the natural systems is explored here and the report examines the changes in the public's attitude toward technology, primarily due to its unintended consequences. Before World War II, technology was seen as a benign instrument; then with the war technology began to be viewed as a useful instrument; and most recently a concern with technology's consequences is prevalent and there is a move toward reevaluating technology development. Throughout this evolution, MIT recognized these trends and changes and put in place programs and centers to respond to them – one of which was CTPID.

With intellectual trends continuing to evolve and attitudes toward technology continuing to change, a further evolution became necessary – from CTPID and similar programs – to the Engineering Systems Division (ESD). This is the most recent response and ESD is still in its formative stage. In a university environment it takes a great deal of time to form a body of knowledge. I believe great progress has been made, but there is still a long way to go. My hope is

that the conclusions I suggest in Chapter V of this report will be considered and implemented to serve the future generations of ESD students.

I would like to acknowledge and appreciate the tremendous effort Susan Cass and Timea Pal put into developing, preparing, and writing this report. In order to gather information on CTPID and ESD, they interviewed many individuals, formally and informally, who helped them gain an understanding of the underlying history of CTPID and ESD, but more importantly, the motivations behind these endeavors. Reports and other written materials gathered from CTPID's programs and the many committees considering structuring science, technology, and policy studies at MIT were heavily relied upon. Valuable input was gained from individuals who reviewed early drafts of the report and from Su Chung, CTPID's Administrative Officer.

Chapter I

Introduction

> *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.*
>
> *We have begun to prepare for this by increasing our understanding of, and partnership with, business, industry, and governments in new endeavors of learning, research, and problem solving. This will be an important element of the Research University of the Future. It is an exciting moment for us.*
>
> Charles Vest, 2000

The 20th anniversary of the founding of the Center for Technology, Policy, and Industrial Development (CTPID) presents an opportunity to look back over those years and consider the center's accomplishments. This report is an attempt to do that, but not as a historical account of the center. Our goal is to highlight the intellectual contributions of CTPID, its impact on MIT and the larger academic, governmental, and industrial communities. With more than 90 sponsors during its history (see Appendix B) and more than 27 programs over the years (see Appendix C), CTPID's effect has been significant. Here we do not seek to document the people involved or the specifics of each program – rather to focus on the overall impacts of their contributions and those of CTPID as a whole. This report relies heavily on information gathered from individual programs' reports, newsletter articles, web sites, interviews, and publications. There is a wealth of knowledge about center programs produced by each program and these have served as a key source for the report. In effect, this document can be seen as a report with many authors. For convenience, we begin with a brief outline of organization, highlighting the focus of analysis, from Chapter II to the conclusion in Chapter V.

Chapter II: The Groundwork for the Establishment of CTPID explores the post-World War II context in its relevance to the eventual establishment of CTPID. Throughout this period, engineering education and research became increasingly shaped by the broad socio-economic and political context as well as by scientific and technological progress. This led institutions of engineering education to be more responsive to these changing social situations. A need for a multi-systemic, problem-solving approach to large-scale, technical systems that brings government, academia, and industry together emerged during this time as well.

Engineering education and research evolved as a result of the changing needs in society and the development of new capabilities in science and engineering. Over time, the emphasis shifted from narrowly defined agendas to broad-based analyses designed to reduce the scope of unintended consequences and to enhance the ability to anticipate counterintuitive behaviors of complex systems. It became evident that engineers needed to improve their responses to increasing social, environmental, and competitiveness parameters and to improve ways of matching technology to society, that is, bringing about a closer alignment of technological capabilities, on the one hand, with socio-economic factors on the other. This chapter highlights the basic elements that have shaped the eventual focus for CTPID.

Chapter III: CTPID's Focus, Approach, and Impact examines the research and educational efforts that evolved in order to accomplish a desired policy orientation and to address the contemporary societal problems that led to the establishment of CTPID. The importance of a policy focus and the need to consider the impact of technology was emphasized as early as 1931 by Albert Einstein at the California Institute of Technology when he said, "Concern for man himself and his fate must always constitute the chief objective of all technological endeavors ... Never forget this in the midst of your diagrams and equations." Since Einstein made that statement, technology has become more and more pervasive and has penetrated into every aspect of everyday life. To note the obvious, for example, people now use all types of electronic devices to do work from wherever they may be: cell phones, blackberries, and lap top computers. This has created the need for a technologically literate society, but it has also created confusion on the part of regulatory agencies. Even this limited example shows the tremendous complexity of technology. If society as a whole does not try to understand and develop policies to cope with these intricacies, then the propensities for conflict and social alienation will inevitably increase. This chapter addresses the need for the development of an organizational structure to enable the focus on such salient challenges.

Chapter IV: Engineering Systems describes the forging of this new approach in the field of engineering. The importance of the emerging field of Engineering Systems was underscored by MIT's President, Charles Vest, when he said, "Technologies are moving from applications and processes that most of humanity can understand and envision to ones that are difficult both to understand and to project" (Vest, 2004). This chapter addresses the generation of a new knowledge base to address the issues and challenges posed by engineering systems and the progression toward building an Engineering Systems Division at MIT.

The report closes with *Chapter V: Conclusion* and a review of what we have learned to date. The founders of CTPID and other like-minded research centers of the time, perceived the need to develop a new domain of expertise that could address the type of large-scale systems education that the traditional, department-based research centers could not tackle. ESD was established to meet this need. It continues to evolve and develop in order to provide the leadership in the area – for the nation and the world as a whole. It is an essential part of the "programmatic" initiatives of the School of Engineering – "The big four O's" as defined by Dean Thomas Magnanti: Nano (nanotechnology and miniaturization), Bio (bioengineering), Info (information engineering) and Macro (engineering systems) (Magnanti, 2003).

Chapter II

The Groundwork for the Establishment of CTPID

The Second World War played a crucial role in shaping engineering education and research during the decades that followed. The experience of the global military conflict by the United States set in motion three trends that are particularly relevant to the establishment of the Center for Technology, Policy, and Industrial Development (CTPID) in 1985. It hastened demand for and reliance on large-scale, complex, technological projects to address military and societal needs. It gave rise to a growing awareness of the social embeddedness of technology. And it led to a reconsideration of the world economy's architecture that later generated mounting concern with the economic leadership of the United States. After World War II engineering education and research became increasingly shaped in response to interactions between the broader socio-economic and political context on one hand, and scientific and technological progress on the other.

Narrowly defined agendas in engineering education and research became inadequate to address the complexities and uncertainties of large-scale engineering projects. A broader analytical framework was needed to reduce the scope of unintended consequences and foresee the counterintuitive behavior of these systems. In parallel, a growing awareness of the significance of science and technology as a policy instrument and the importance of policy in the development of science and technology was evolving. Finally, the concept that there exists a causal link between the role that science and scientists play in society and the progress of the nation began to take hold after World War II.

In response to these defining forces, three modes of thought were gradually emerging in engineering research that found a home in CTPID, transforming it into a centerpiece of large-scale system research with special attention to public policy and industrial competitiveness issues. These were: interdisciplinary work, a holistic view, and a problem-solving, collaborative approach.

The first three sections of this chapter provide a presentation of the major contextual changes that took place in the post-war time period. The last section addresses the ways in which these trends defined reforms in engineering education in recent decades, with particular attention to the transformations relevant to the establishment of CTPID.

This is not an exhaustive, historical overview of the socio, economic, and political contexts in the post-World War II period. This chapter aims to focus on the context that led to the formation of CTPID and we have concentrated on what we believe are significant developments that preceded and led to the formation of the center.

The Emergence of a Large-Scale Systems View

The first trend set in motion by World War II, relevant to the foundation of CTPID, is the increasing complexity and scale of technological projects. While the concept of large-scale systems is still somewhat vague and ambiguous, there is growing consensus that the term refers to technologically enabled projects incorporating a large number of components that interact in dynamic and complex ways with each other, as well as with the social and natural environments. This definition fits with what began to emerge post-war.

After the experience of World War II, the United States realized it could not stay isolated from global conflicts, for which a strong military is needed. The essential contributions of engineers and scientists to the development of weapons and the means to deliver these and other defense instruments convinced the Department of Defense (DoD) that the future of the military rests on technology. The belief that military supremacy lays primarily in science and technology was pioneered by Vannevar Bush who at that time was Director of the Office of Scientific Research and Development. The DoD then convinced the Congress to allocate funds to research and development. To develop the future generation of researchers, DoD promoted the concept of sponsored research. Rather than having research and development laboratories affiliated with the DoD, they promoted the notion of sponsored research in higher education systems. This sponsored research on new technologies and the growing concern with national defense initiated a focus on large-scale systems.

The significant investments in scientific research that followed the war allowed for a series of discoveries that have found applications in space exploration, transportation, housing, health, and later on in energy. This scientific and technological progress made possible the emergence of waves of large-scale projects during the following decades.

In the 1950s, engineering absorbed and articulated the lessons learned from the war experience and a group of “systems sciences” began emerging. The systems thinking at the time reflected a top-down, hierarchical view. The Manhattan Project and space programs set a paradigm for the design and implementation of large-scale projects that were based on a clear understanding of the underlying principles governing the whole system. The goals and specific objectives were clearly defined, the designs developed based on exact specifications that got implemented with great precision. The aim was to reduce the uncertainty characteristic to systems to calculation (Bar-Yam, 2004; Mindell, 2004).

The launch of Sputnik further intensified the focus on large-scale systems, as the U.S. government became convinced that the advancement of basic research in science and technology for large-scale space exploration projects was exploitable for national security, economic growth, and sustained societal benefit. The DoD thus increased funding for defense and space projects. With the moon landings, the classical systems method and systems engineering gained widespread recognition. The Apollo Space Program, for example, was run on the systems management model and achieved excellent results.

During the 1960s, systems analysis was applied to national defense and the Vietnam War, ignoring completely the complexity of real life by attempting to reduce the defense system to simplified models using quantitative instruments. This marked a downfall of systems thinking as it became applied to a problem for which it was not suited (Mindell, 2004). The Vietnam War presented an irony. Why was one of the most technologically advanced nations on earth unable to subdue a technologically inferior enemy? This question made people start to realize that technology does not solve everything and question the technological determinism of national defense (Smith, 1990).

Where technology could solve problems was in the civilian sector and the 1960s saw increasing governmental efforts to support technological innovation and progress mainly in transportation and housing. The reorientation toward projects in the civilian sector led to the application of the systems paradigm used in defense and space agencies to a series of urban issues. An example is the grant that MIT received to develop high speed ground transport travel from Boston to Washington, D.C. by developing magnetically levitated technologies. This led to the foundation of the Magnet Lab.

Several events generated this turning point in systems approaches from military technology applications to a focus on societal problems. These include: the Vietnam War, the abandonment of Apollo, the oil shocks, the Mansfield Amendment, *Limits of Growth*, the cancellation of the supersonic transport, and the invention of the microprocessor – all occurring within five years of the moon landing. The developments during and immediately after the Vietnam War led to the understanding that the problems of the world will not be solved by new inventions and devices alone, but rather by large systems properly conceived, implemented and managed (Mindell, 2004). Awareness was growing that as the technological projects were becoming more and more complex, their applications increasingly extensive, their impact on the natural and social environments was becoming significant and pervasive (Jackson, 2005). The restrictive nature of the earlier systems paradigm that strove to quantify and calculate needed to change to incorporate the "messy complexity" of these new systems with a strong, socio-technic interface. In comparison with military projects, civilian applications of systems thinking required more negotiation, compromise, and consultation than the more authoritarian technically-focused projects of the military (Mindell, 2004). Engineers thus became increasingly aware of the need to take into account politics and the social world rather than just exclude them as external variables.

Today we interact with numerous systems set around technology or technological artifacts with significant socio-technical interfaces, such as the national transportation system. Progress made in the realm of information and communication technologies greatly contributed to the increasing size and complexity of engineering projects. Developments made in recent decades have intensified connections and interactions among different engineering projects, and have facilitated their pervasiveness into society.

Twentieth century America matured from a cultural stage characterized by a need for objectivity, clarity, and control to one characterized by complexity, richness, and ambiguity (Venturi, 1966). This shift was reflected in engineering education and research, as the realization was growing that there is no best solution for complex engineering problems, and not all problems can be completely solved (Hughes, 2004).

Society, Policy, and Technology – The Social Embeddedness of Technology

Technological and scientific innovations had an isolated character prior to World War II when intellectual curiosity represented the main drive for technological progress and technology was not in the mainstream of society. As the scale and complexity of engineering projects increased, the intersections between the technical, natural, and social systems grew. This tendency would be strongly reflected in CTPID's research focus.

The experience of World War II forged a partnership between science, industry, and the military under the coordination of Vannevar Bush. The war brought technology and politics together given the important role that scientists like Albert Einstein had in developing atomic bomb. Einstein was long active in the cause of world peace; however, in 1939, at the request of a group of scientists, he wrote to President Franklin Delano Roosevelt to stress the urgency of investigating the possible use of atomic energy in bombs. The Manhattan Project further pushed technology into the political arena by initiating the nuclear race.

Societal needs started to become more important in driving technical progress after World War II and this became more obvious as the government started to encourage applying the technological progress developed during the war in the civilian sector. Karl Compton, President of MIT from 1930–1948, was quoted as saying, "One of the lessons of history is that the improvement of man's physical and environmental well-being does much to contribute to the elimination of political and social unrest, and that the reverse promotes revolution. We know also that the constructive applications of science do improve man's environmental well-being if the gains from science are fairly distributed among the people" (Hook, 1946, p. 331).

Oftentimes large and complex systems have had initially surprising societal consequences and the negative impacts of technological projects became an increasing focus. The concern over these unexpected effects started to become a topic of public debate. Before the 1960s, virtually no one seemed to care about the devastation projects like the redevelopment of the West End of Boston had on the community. It was assumed that the projects were required for the collective good (Altshuler and Luberoff, 2003). [See *The West End Project* below for more information.]

But there came a change in the 1960s – citizen activism combined with the spreading awareness of the disruption associated with urban mega-projects. With an interest in civil rights and environmental protection, citizens began to participate more actively in the political processes of urban planning. For instance, the inner belt highway that was proposed as an additional highway system around Boston did not get built after the community's protestations. Most of the money that would have gone for this highway got shifted into public transportation investments. [See *The Inner Belt Expressway: Impacts Considered*, p. 12 for more details].

The West End Project

Before the 1960s, virtually no one seemed to care about the disruption that projects like major highway development programs, airport expansions, neighborhood redevelopment, or urban renewal could cause. It was assumed that the projects were required for the greater good and that the residents of these neighborhoods would in most cases be better off (Altshuler and Luberoff, 2003). An example is the Boston West End project which began in the late 1930s when it was suggested that the entire West End of Boston, a working-class neighborhood of extended families, be cleared and replaced with public housing. Although this suggestion was not taken immediately, the creation of the federal slum clearance program after World War II ultimately led to the decision to redevelop the West End which secured federal and local approval in 1956. The plan included a 2,400 unit complex of elevator apartment buildings and townhouses to be rented for about $45 a room, more than current residents were paying for a 5–6 room apartment. These rental fees constituted luxury housing, not affordable, public housing.

Reasons for redevelopment of the West End were economic. Industry and middle class residents had left Boston for the suburbs. This resulted in an over-supply of tax-exempt institutions and low income areas that yielded little for the municipal coffers.

Putting up high-rent buildings would bring in municipal income. In addition, the developers and the city hoped to further private rebuilding by increasing the morale of private and public investors. With shopping districts, a hospital, Beacon Hill, and the Charles River nearby, some envisioned more profitable uses. The assumption was that high-income residents benefit the city, while low-income ones are a source of public expense.

Despite warnings, residents did not believe the redevelopment would happen. They were not familiar with the complicated process and received poor information from the press and city agencies. Since their cause seemed hopeless to them, citizens often gave up without a fight. By the summer of 1960, only rubble remained where two years earlier more than 7,000 people had lived (Gans, 1962).

In this example, redevelopment proceeded on the assumption that the needs of the site residents were of less importance than the rebuilding of the site. Great pains were taken with planning for buildings, but planning for the West Enders was done almost as an afterthought. Funds allocated to relocation were only about one percent of the cost of clearance and rebuilding. The real cost of relocation, however, was much higher, and was paid in various ways by the people who had to move. The destruction of the neighborhood exacted social and psychological losses. The scattering of families and friends was particularly difficult for the elderly (Gans, 1962).

But there came a change in the 1960s – citizen activism combined with the spreading awareness of the disruption associated with big urban projects. With an interest in civil rights and environmental protection, citizens began to participate and protest. Reform began at the national level with improved relocation assistance.

The American public was eager for dramatic change in the way the nation used its resources. Scientific and technological research could no longer be regarded as value-free inquiry because no aspect of it is removed from the interests and attention of citizens. In response to the increasing public concern with environmental and distributional effects of engineering projects, a new set of institutions and regulations were set in place such as the Environmental Protection Agency and the Clean Air Act.

President Johnson amended the National Science Foundation (NSF) charter in 1968 to expand the agency's mission to include problems directly affecting society. There were several programs intended to stimulate the application of science and technology to "practical needs" at NSF. The largest was Research Applied to National Needs, RANN and in 1969 IRRPOS (Interdisciplinary Research Relevant to Problems of Our Society) which supported interdisciplinary research projects in universities, national laboratories, and the like. The Office

The Inner Belt Expressway: Impacts Considered

In 1948 an Inner Belt Highway was proposed by the Massachusetts Department of Public Works, but due to funding difficulties it did not proceed. It was proposed again in 1962 by the same department to relieve the growing traffic burden on the Central Artery as well as on other connecting corridors. It was to be an eight lane expressway, part of the interstate highway system to go around the center of Boston through several neighborhoods including Boston, Brookline, Cambridge, and Somerville and would be designed to handle 150,000 vehicles per day.

In keeping with the era's growing concern with the social impact of technological projects, residents, civic leaders, and academics organized a coalition to oppose the inner belt. Fred Salvucci, who later served as transportation secretary under Governor Michael Dukakis in the 1970s and 1980s, was one who led the anti-Inner Belt protests. He was joined by Representative Thomas P. (Tip) O'Neill in protesting the destruction of neighborhoods along the route.

Salvucci reflected on the social and political context when he said, "With the National Environmental Policy Act in 1969, I saw that it was now appropriate to look at interstate highways in a different way – through the lenses of environmental impact, urban design, even socioeconomic justice" (Thrush, 2004).

The Boston Transportation Planning Review was born in the 1970s and Gov. Sargent made the following policy statement:

> The plan will be based on not where expressways should be built, but whether expressways should be built. It will integrate road-building with mass transit, and it will study some of these other, imaginative means of moving goods and people: park-and-ride systems, metered traffic on expressways, special bus lanes, and the host of other space age approaches now available to transportation planners.
>
> Four years ago, I was the commissioner of the Massachusetts Department of Public Works, our road-building agency. Then, nearly everyone was sure that highways were the only answer to transportation problems for years to come. We were wrong. Today, we know more clearly what our real needs are: what our environment means to us, what a community means to us, and what is valuable to us as a people. (`www.bostonroads.com/roads/inner-belt`)

The protest succeeded and the inner belt did not get built. Most of that money got shifted into public transportation investments like the Red Line extension and the Orange Line and the refurbishing of the commuter rail. This was good for the neighborhoods that avoided the demolition, but was also very good for the downtown and the economy of the City of Boston.

of Technology Assessment (OTA) was established in 1972, as a means for Congress to secure competent, unbiased information concerning the physical, biological, economic, social, and political effects of technology.

The civil unrest and political turmoil of the 1970s led to a great amount of resistance to further investments in technological and scientific research directed by military interests. A good illustration of this is MIT's divestment of the Draper Lab and development of the Urban Systems Lab. This was intended to direct the technology of Draper Lab from defense to civilian problems.

Finally, the recent emphasis of the National Institutes of Health (NIH) funding and life sciences is a result of the same trend. The end of the Cold War marked a big expansion of this field further requiring increasing awareness regarding the social and environmental impacts of technology development and implementation. The concern with the social impact of technological projects that began early in the Vietnam War continued to grow in importance.

Nevertheless, the idea that technology can solve all problems continues to prevail in the political arena. Richard Nixon, when faced with the oil embargo in 1973, introduced Project Independence, a plan oversold to the public as a solution to the country's dependence on foreign oil. The goal: to make the United States energy independent in 10 years by using technology to develop new sources of power. As we know, this plan did not succeed, but at the time perhaps deflected attention from failure in other areas. This overdependence on technology to solve problems emerged again after September 11th when President George W. Bush declared that technology would provide the answer to our security needs.

As we have shown, the decades following World War II led to an increasing awareness of the social embeddedness of technology. The technological progress in information and communications in recent decades brought about an even deeper and more extensive penetration of engineered systems in society. Moreover, the revolutionary discovery and utilization of the Internet exponentially increased the ease and speed of providing information thus allowing for greater public participation in the development and implementation of engineering projects. Social and political contexts started driving technology and "societal relevance" became a new by-word. The significant changes of the social, political, and cultural contexts in recent decades challenged the understanding of engineering as an isolated and static field, and shifted attention toward issues such as environmental awareness and distributional equity greatly valued by society. The increasing awareness of the societal implications of engineering projects, and of the intensive interactions between the technical, natural, and social systems led to a reconsideration of roles and relationships between government, universities, and industry (Roos, 2004).

The Growing Concern with U.S. Competitiveness in the Global Economy

The third factor shaping engineering education and research post-World War II and leading to the formation of CTPID was the mounting concern with the economic leadership of the United States. The United States emerged from World War II in a very healthy economic condition. The implications of the technological changes achieved through federal funding during and immediately after the war went beyond their military applications and laid the basis for their commercial application. Considerable tacit knowledge was generated in U.S. laboratories and research centers with significant positive externalities in the public as well as private sectors.

The dual use of technology generated military supremacy as well as a take-off of the U.S. economy. Several technological advances were achieved through DoD funding that came to find applications in the civilian realm. The Global Positioning System (GPS), for example, was the result of a military project and considered top secret for years, but is now widely available for commercial use.

The consensus on the way technology moves from military to commercial applications was contested in the late 1950s as it became more obvious that national security and competitiveness overlap in complex rather than straightforward ways. The Kennedy administration's dissatisfaction with the slower pace of economic growth reflected concern about diverting technical talent from the civilian sector with funding for large-scale space projects. The first attempts to foster the commercialization of available technological know-how as a matter of policy began in the 1960s (Smith, 1990).

The U.S. economy thus relied heavily on its leadership in technology and enjoyed unprecedented growth until the OPEC oil crisis in the 1970s. The oil shock in 1973 generated considerable economic upheaval in developed countries and set into motion efforts directed toward further exploration of alternative sources of energy and efficiency in use. The second oil shock during the

1979 Iranian revolution caused a precipitous drop in economic activity leading to a worldwide and prolonged economic recession (Grayson, 1993).

In addition to the changes in the societal context (increased value attached to environmental and distributional issues), the decades after World War II also saw significant changes in the economic context and industrial organization. American industry faced growing international competition ever since the architecture of the post-World War II global economy generated a second wave of globalization. The diminishing share of U.S. industries in the global market and the increasing U.S. trade deficit during the late 1970s and early 1980s generated considerable concern and became one of the most important issues on the nation's policy agenda.

By the 1970s, companies from Europe, Japan, and newly industrialized nations were able to successfully penetrate the U.S. market. The increasingly integrated capital markets helped to move toward a truly global economic order with intensified competitiveness (Smith, 1990). Concerns regarding the declining competitiveness of U.S. companies became especially alarming with the recession in the global economy. The conventional belief in the technological determinism of economic growth brought about a growing concern over the competitive edge of U.S. industry in the global arena on mainly technological grounds. The confidence in U.S. technological and industrial prominence was replaced with increasing anxiety that the U.S. economy would become overshadowed by Asian and European enterprises (Bryner, 1992).

Many business schools realized the importance of an awareness of technology. The concerns regarding the international competitiveness of the United States became impossible to be ignored by engineers as well. U.S. company representatives expressed their desire to see more adequately prepared engineers entering their companies who could compete effectively in the international arena. This trend put considerable pressure on MIT to develop programs that would respond positively to this challenge. In the 1970s and 1980s it became obvious that engineering education needed to be changed to meet the changing technical needs of industry.

Given MIT's long tradition of engagement with industry and government, the economic concerns of the 1980s further strengthened this collaboration to address the needs of large-scale engineering projects in the manufacturing and high-tech industries (Vest, 2004). With the increasing concern of the public with social issues such as the preservation of the environment, social justice, and consumer protection, the systems and products designed and implemented had to meet baseline environmental and health standards in the increasingly competitive environment.

The Evolution of Engineering Education

The contextual changes presented up to this point had an impact not only on national policy making, but on social institutions as well. Given the fact that the primary focus of this report is to present the forces and contextual settings that explain the establishment of CTPID, we will outline below the most relevant changes in the field of engineering education and research.

Engineering education had an experiential character before World War II, but the war experience led to the realization that engineering education had not prepared engineers sufficiently for participation in enterprises like the Radiation Laboratory and the Manhattan Project. Engineering education failed to keep pace with more rapid changes in basic sciences of the early 20th century, especially physics, and the war exposed that flaw. Scientists outperformed engineers in developing new defense instruments. The atomic bomb was developed by physicists and chemists, and radar was developed primarily by physicists. Engineers played a mere secondary role (Penfield, 1998).

Nonetheless, both scientists and engineers played a role in national defense. Some even assert that the World War II victory was achieved "on the talents of scientists and engineers, whose work gave the nation weapons systems, radar, infrared detection, bombers, long-range rockets, and torpedoes" (Jackson, 2005, p. 1635). As a result of such views, engineering education became regarded not merely as a byproduct of prosperity, but integral to creating economic growth and maintaining a strong national defense (Grayson, 1993).

Vannevar Bush, head of the wartime Office of Scientific Research and Development, brought science to bear on World War II and joined science and engineering. At the request of President Roosevelt, he wrote a report putting forth the idea that the American educational system should focus more on basic sciences. He warned that while the United States was already preeminent in applied research and technology, it had a secondary place in the field of pure sciences. He believed that basic research generates new knowledge and provides scientific capital to the whole nation. His recommendations led to the establishment of the National Science Foundation (NSF), the federal agency that became an important source of funding for basic research conducted at American colleges and universities, including MIT.

Gordon Brown, a former student of Vannevar Bush, Head of the Department of Electrical Engineering between 1952–1959, and Dean of Engineering at MIT for the nine subsequent years, embraced the engineering science model, “emphasizing physics-based, laboratory-driven work in education and research” (Mindell, 2004). He had a significant impact on engineering education through his vision of basing this education on fundamental sciences. As department head, Brown initiated revisions of the engineering curriculum at MIT by incorporating more physics and mathematics (Penfield, 1998).

The gradual transition toward engineering science was greatly supported by a large grant from the Ford Foundation between 1959 and 1971. The final report, however, points out that while the grant had an essential role in initiating some interaction between the two, largely unconnected, paths of engineering: one focusing on the basic principles of engineering (engineering science) and the other focusing on applying social sciences to social problems (engineering practice), institutions of engineering education ought to become more flexible to changing social problems. Beyond strengthening education and research in basic and engineering science, engineering education ought to provide the framework for a meaningful involvement of students and faculty in current social problems. This is reflected in the crystallization of the idea that science and technology can no longer be considered separately from human and social consequences, and education and research in the fields of sciences and technology ought to adopt a more integrated view. Widening the horizons of MIT students by integrating the social sciences and humanities thus became a priority of the school.

In other words, the pendulum reached too far in the direction of basic sciences, and the beginning of the 1970s brought about forces to rebalance the situation by reintroducing more design and engineering management (Moses, 2004). The Ford report suggests that engineering students should also obtain an appreciation of management, economics, technical arts such as drafting and production engineering, in addition to science. Perhaps, most importantly in the context of this chapter – The Groundwork for the Establishment of CTPID – engineering students ought to give full appreciation and consideration to relations among human beings and social issues. This was very consistent with the shifts in the societal and national values and priorities and increasing importance of the concept of "societal relevance".

In the spirit of the increasing demand for humane, socially sophisticated professionals concerned with the consequences of science and technology on the quality of life, a report on MIT education was commissioned in 1970, referred to now as the Hoffman Report. The underlying assumption of the report is that when technical and scientific knowledge and societal values are separated, the consequences are often grave. The report recommends students and faculty play a meaningful role in the formulation and implementation of public policy in areas of great concern to society such as environmental pollution, provisions for better health care, as well as urban environment problems including housing and transportation.

With the increasing pervasiveness of large-scale engineering projects in the military as well as in the civilian sphere during the post-war period, it became obvious that there was a lack of resources to research and teach large-scale systems within the Institute. Initially, these systems were analyzed through the tools of operations research, systems engineering, and system analysis. The techniques used to design and build the increasingly large and complex engineering systems have often been ad-hoc, and the policies that govern the use of these systems often emerged after their implementation. There was a lack of proper intellectual framework within which to study, understand, and develop large, complex engineered systems (Vest, 2004).

Teaching engineering of large-scale systems is difficult and because MIT's discipline-based departments believed that they could not do it, this type of teaching moved into established centers and programs such as the Draper Lab. The Draper Lab was able to bridge engineering science and large-scale systems that the government expressed an interest in. Engineers arrived at the realization that technological progress is unpredictable, complexity is not always computable, and that people and politics are part of technology and not external to it. Engineering education thus stopped treating politics and society as completely external variables to be excluded from models. It ceased considering models as sacred and stopped see engineers solely as scientists, but also as inventors, managers, and policymakers (Mindell, 2004).

Parallel to the increasing awareness of the Institute's inability to teach about large-scale, socio-technological projects, concerns with the social and environmental impacts of technology in the civilian sector were becoming more intensified. In reflection of these tendencies, Dean of Engineering Alfred Keil ordered the establishment of three socio-technical initiatives in the School of Engineering – the Center for Policy Alternatives (CPA) in 1971, the Center for Transportation Systems (CTS) in 1973, and the Technology and Policy Program (TPP) in 1975. The underlying reason for the foundation of these centers was to focus on the beneficial, as well as damaging effects of technology in society. By establishing these programs, MIT encouraged faculty and students to play an active role in the determination and implementation of public policy in areas of great social concern.

Conclusion

These changes in the global, national, and institutional contexts led to the evolvement of three different trends that became the characteristic features of CTPID. These are an interdisciplinary approach, multi-stakeholder involvement, and a problem-solving mode.

Interdisciplinary Approach

The interdisciplinary approach evolved early on at MIT and had several stages in its progression. At first, interdisciplinary research was understood as a combination of fundamental sciences such as biology and chemistry forming biochemistry, or geology and physics forming geophysics.

In response to technical projects like radar and gunfire developed during World War II, research conducted in academic research laboratories and centers relied on the use of different sciences and fields of engineering. MIT's war time radiation (radar) laboratory, RadLab, is an example of a new, interdisciplinary research model – continued in 1946 with its civilian successor, the Research Laboratory of Electronics.

The experience of World War II also brought along the recognition of the need to focus on operational aspects of military systems, in addition to their development, and hence brought engineers and planners together. The organization needed to tie different elements of a project together set the stage for the modern practice of systems integration. This management aspect of systems became formalized in the mid 1950s with the ballistic missile project of the

Air Force (Mindell, 2004). The U.S. military thus had an important role in promoting interdisciplinary research and large-scale systems type of approaches.

As technology and systems grew larger and more complex, it became evident that an interdisciplinary approach was needed to design and implement such large-scale, technologically enabled systems (Mindell, 2004). This resulted in the blend with management, and later attention to the social sciences as the concept of social relevance was becoming more popular. The Hoffman Committee advocated for an interdisciplinary approach by overcoming the intellectual fragmentation of MIT and putting greater emphasis on the social sciences.

Jerry Wiesner, the 13th president of MIT, emphasized the need to integrate different disciplines to address these complex societal problems. At his inaugural speech in 1971 he said:

> New cooperative ventures involving the social sciences and humanities should draw disparate disciplines closely together, and in so doing provide opportunities to create exciting new forms of professional education. Thus, we can recast the concept of liberal education in a contemporary mold by integrating science and technology with the study of man and his culture. (Rosenblith, 2003, pp. 353–354)

Engineering programs thus started to incorporate the natural sciences, social sciences, humanities, and communication arts into a strong core of mathematics, engineering sciences, and analysis and tried to bring these intellectual disciplines and fields of knowledge to bear on real problems of society. The aim was to achieve both breadth and specialization.

This commitment to interdisciplinary research was reaffirmed by President Hockfield in her May 6, 2005 inaugural address:

> … With our expertise in interdisciplinary problem-solving, MIT is uniquely equipped, and obliged, to make a critical difference: to do the analysis, to create the innovations, to fuel the economy, and to educate the leaders the world needs now.
> [`web.mit.edu/hockfield/speech-inauguration.html`] (Choucri et al., 2006)

The attempt to broaden the scope of education by integrating social sciences and humanities with natural sciences and engineering prevails today within MIT and outside the Institute. The Report on the Harvard College Curricular

Review released in 2004 suggests expanding the limits of liberal education by crafting curricula that builds on a new set of foundational courses that includes science and engineering courses.

This interdisciplinary approach emphasized within the Institute in the early 1970s demanded new organizational structures to which the Center for Policy Alternatives and the Center for Technology, Policy, and Industrial Development responded.

Multi-Stakeholder Involvement

The interdependence between academia, government, and industry was especially strong during the World War II, with the government relying heavily on academia and industry to develop new defense technologies (Jackson, 2005). At the beginning of the war, MIT President Compton put the services and facilities of the Institute at the disposal of the government. The Radiation Lab was given one-half million square feet of floor space (Maslanka, 1961). MIT served as a vortex of intense activity in the development of new weapons and techniques in a great variety of fields.

During the war, MIT activities became organized around government contracts and all departments became involved in war-related work. Some members of the MIT community questioned the role of military funding in shaping the educational activities within academia and were concerned about MIT being regarded as an institution that is dependent upon the development of war weapons. Leon Trilling, for example, deplored the inflexibility and short sightedness of defense contracts and the focus on performance (Leslie, 1993). In response, MIT attempted to broaden the base of sponsored research by increased industrial participation. The objective of MIT thus became to incorporate research sponsored by external industrial and governmental agencies into the education plan in a way that did not jeopardize the freedom of thought and liberty of action within the Institute. Incorporating research sponsored by government and industry into educational plans represented a challenge because of the desire to keep a balance between education and research.

In the 1960s and 1970s, with the shift of funding from defense to civilian sector, the collaboration between academia, industry, and government gained new meaning and importance. In his inaugural speech Jerry Wiesner said:

> Professional faculties and their students are reaching out to the society – the neighboring community, government, industry – in order to make a conscious contribution, through understanding and action, in the fields of environment, health, urban studies, architecture, educational innovation, international understanding, and in the management of science and technology. (Rosenblith, 2003, pp. 353–354)

In this spirit of increased collaboration between academia and private sector, the Hoffman Report emphasized the importance for industries to provide more financial support to universities and to make their personnel, equipment, and facilities available to faculty and graduate students in exchange for university conducted research. The evolution of the Instrumentation Lab reflects the uneven balance between defense and civilian research and the fluctuation between one and the other over time. [See example, *MIT's Instrumentation Lab*, below.]

MIT's Instrumentation Lab

MIT's Instrumentation Lab dates back to the 1930s. Throughout its history, its focus has been the development and early application of advanced guidance, navigation, and control technologies to meet DoD's and NASA's needs.

The evolution of the Instrumentation Lab reflects the uneven balance between defense and civilian research and the fluctuation between one and the other over time. The defense focus was primary early in its history and strengthened when a panel, chaired by MIT president James Killian, was appointed by President Eisenhower in 1954 to assess American vulnerability to growing Soviet strategic strength. The panel, referred to as the Killian Panel, gave top national priority to developing and deploying both intermediate range and intercontinental ballistic missiles which the MIT Instrumentation Lab became heavily involved in. In the post-Sputnik missile buildup, the Air Force pumped $9 million a year into the Instrumentation Laboratory for ballistic missile guidance R&D.

In 1961, the laboratory won the contract for the Apollo navigation and guidance system. The size of the Apollo contract dramatically shifted the laboratory's balance of military and civilian commitments, from virtually all military in 1961 to about half and half by 1965. By the late 1960s, the lab's overwhelming dependence on defense contracts and the implications for their research and teaching began to be questioned.

Thus began the debate as to whether special laboratories should be converted to civilian applications or divested. Ultimately, the Instrumentation Laboratory was divested. In 1973, it became an independent, not-for-profit research and development corporation named the Charles Stark Draper Laboratory, Inc.

With the increasing complexity and scale of the engineering systems being designed and implemented, there was a need to support research and educational programs on large and complex systems with an interdisciplinary approach that explores the changing relationships among the multiple stakeholders – universities, industry, and government – in all phases of engineering system development (Roos, 2004). This was addressed by the research and educational centers and programs mentioned above – the Center for Policy Alternatives, the Center for Transportation Systems, and the Technology and Policy Program.

But what about funding these multi-stakeholder projects? The federal government traditionally funded basic research and infrastructure building because the costs and risks tend to be high and because of the lack direct commercial application. Applied research, on the other hand, has been traditionally funded by the primary users of the results in pursuing their mission (Bryner, 1992). This began to change in the mid 1980s to early 1990s because of concerns about the United States losing its economic leadership position particularly with regard to Japan and Europe. While America was leading in the development of new knowledge, U.S. industry was too slow in turning research into marketable products. Legislative changes were adopted by the U.S. to foster investment and cooperation in research and development, and facilitate commercialization of results (Bryner, 1992).

Going even beyond legislative changes, the federal government took the initiative to establish cooperative efforts between academia and industry. Engineering research centers, science and technology centers, and industry-university cooperative research programs were established by the National Science Foundation (Bryner, 1992). This led to studies such as the one undertaken by the MIT Commission on Industrial Performance.

Multi-stakeholder collaborations work. The areas where U.S. industries have been most competitive in global markets are sectors of the economy such as aerospace, agriculture, and biotechnology where government, universities, and industry have been working closely together. It harnesses the efforts of a greater number of actors than direct government assistance can do (Bryner, 1992). The prevailing notion became that if nations are to remain competitive in world markets, government, industry, and educational institutions must cooperate in developing and exploiting new technologies.

Problem-Solving Mode

The third defining characteristic of CTPID is a problem-solving approach which has a deep history at MIT. A commitment to hands-on learning forms the core of MIT's motto and mission. William Barton Rogers's founding vision was to provide technical training that students could apply to practical goals, producing better results with greater efficiency. Engineering education and research in the pre-World War II era focused on practical skills – it had an experiential and problem-solving character – and engineering graduates were often lacking the foundations in science and engineering principles as we discussed earlier in this chapter.

The research strategy adopted by MIT immediately after the Second World War was to divert efforts to projects more directly in the public interests, under the sponsorship of government and industry. A new perspective of the engineer emerges in the Lewis Committee Report that underlines the importance of taking into account the societal impact of engineering activities. The success of the new engineers is measured not so much by scholarship, but by strict standards of performance. Engineers are responsible for the safety of people and welfare of groups and society at large.

As changes in national and social values and priorities put engineering, especially civil engineering, in center stage, large-scale, and complex engineering problems related to urban problems, transportation, housing problems, and related areas became the main focus of engineering practice. This shift in focus then generated forces to rebalance engineering education and research more toward engineering practice.

This chapter reviewed the contextual setting and changes in engineering education in the years leading up to the establishment of CPA and CTPID. We introduced three defining characteristics of the center which we treat in detail in the next chapter as they apply to CTPID and its programs.

Chapter III

CTPID's Focus, Approach, and Impact

Issues of technology and policy were a major national concern in the 1970s and 1980s. As a leading research and education institution in engineering and science, MIT's administration decided that the times required a heightened awareness of the interconnections between the science and technology process and public policy. The increasing concerns with social, environmental, and competitiveness issues required engineers to become more involved in the matching of technology to society. These forces resulted in a mushrooming of numerous independent centers and programs without sufficient synergic collaboration between them. Faculty members with interests in this area were decentralized among many departments. A more optimal organizational structure was needed to provide an intellectual home for these initiatives. Such an organizational structure was an MIT-wide endeavor to focus on technology and policy, crosscutting several disciplines to address the social and technical complexities of large-scale engineering systems and projects, to understand the process of invention of new technologies and their diffusion, as well as to understand the roles of governments, industry, and universities in promoting new technologies and addressing their implications on society.

This chapter presents the evolution of research and educational efforts within MIT to accomplish this policy orientation and address the contemporary societal problems that led to the establishment and 20 years of robust activity of the Center for Technology, Policy, and Industrial Development (CTPID). Here we also provide further information about the distinguishing characteristics and evolving nature of CTPID that made it unique and posed to become successful in these quests. We cite research programs to give examples, not in an effort to recognize some programs and not others. Over its 20 year history, CTPID has included more than 27 programs. Of course, some of these are no longer active for one reason or another, and we write of these using the past tense. Unfortunately space does not permit us to discuss each program in detail here; we only use them to help illuminate a point.

Policy and Industrial Development Focus

The quickening pace of technological changes and their growing embeddedness in the social and natural environments gave rise to interactions between technology and society that generated tremendous complexity. These complexities created a series of public policy issues that needed to be addressed. This tendency required a change in the way engineers viewed and thought about technological options.

One of the main global societal concerns at this intersection of policy, technology, and society was environmental degradation. The distributional equity dimensions of large-scale transportation and urban development projects represented another critical issue in the spotlight of policy debates. A good example of this is detailed in *Airline Regulations* on p. 27. As technology became increasingly regarded as the main source of economic growth, and the early 1980s brought increasing unease over U.S. industry losing its competitive edge, global industrial competitiveness became the third set of societal problems that needed to be addressed by adequately conceived policymaking.

As a result of increasing public awareness of the potentially regressing effects of technical change on social and natural environments, MIT faculty and researchers advocated for the Institute to assume a leadership role in public policy research. In concordance with the vision of the Institute at the time of its establishment, MIT has always remained interactive with society in order to promptly respond to problems of national and international concern. The need to address the public concerns regarding equity and environmental issues generated a great deal of policy research and led to the development of outstanding talent at MIT.

Several individual MIT faculty members became active in the policy arena and MIT sought to encourage this sort of involvement. The initial policy-oriented programs that were set up in the 1970s and early 1980s at MIT were located mainly within individual departments and while they were functioning well, they tended to be narrowly focused on the subject matter of the department and dealt with specific, technological subject matters. These programs and initiatives were isolated from each other and lacked weight.

Airline Regulations

Policy makers have fairly consistently been concerned with fairness in setting regulations. The Interstate Commerce Act of 1887 aimed at the prohibition of discriminatory practices among persons and locations. Prior to this Act, the railroad rate structure was characterized by pervasive price discrimination among shippers, localities, and commodities.

As far as aviation, the Civil Aeronautics Board (CAB) requires a uniform fare taper or relationship between fare and distance. Thus people flying between Grand Forks, North Dakota and De Moines, Iowa face essentially the same fare structure as those flying between Boston and Washington, D.C. even though the airlines are able to achieve substantial economies of density on the heavily traveled routes. Since rate differentials based on route density would appear discriminatory, even though they would in fact reflect cost differentials, the CAB has resisted them.

The structure of air rates has also discriminated in favor of rural areas. While there is a certain amount of controversy concerning the existence of cross subsidies between rural and urban interest in the sense that the airlines actually suffer losses on their light density traffic, it is generally agreed that a cross subsidy exits in the sense that rates to rural areas are lower and service is higher than each would be in the absence of regulatory controls. In addition, the Board grants explicit subsidies to local carriers. The rate structure discriminates in favor of the low density areas since the price marginal cost rations they experience are much lower than those associated with high density areas. “In the absence of regulation, it is highly likely that the airlines would either reduce service or raise rates (or both) to low density regions to make their returns on this traffic commensurate with the returns to other traffic, particularly since the demand functions of this traffic are probably quite price and service inelastic” (Friedlaender and Simpson, 1977, pp. 24–25).

Without necessary financial resources flowing through a strong administrative center, a lack of coordination of present policy activities, and resistance to change of the organizational culture, efforts to increase the growth and crystallization of these initiatives were hindered.

One of the attempts to overcome these limitations was the establishment of the Center for Policy Alternatives (CPA) in 1972 to identify and study important social issues in which science, technology, and engineering play a significant role by bringing different disciplines together. CPA focused on addressing the policy implications of complex and large-scale socio-technical problems and engaged in policy analysis for government, industry, labor, and educational institutions. It was particularly interested in assessing and ameliorating the adverse consequences of technology on the natural and social environments. CPA relied on the use of several disciplines to achieve its goals and objectives, among them: engineering, science, public health, law, management, economics, political science, and public health.

Another of the initiatives that was part of MIT's attempt to address contemporary societal issues was the formation of the Technology and Policy Program (TPP) in 1975 that offered a new Masters degree and its theme was "engineers with a difference". TPP's goal was dual literacy in both technology and policy.

Throughout its existence, the CPA collaborated with several institutions, including government, industry, and educational institutions, from the United States and abroad. Several of the issues it addressed were international in scope. Among the funders of CPA's research projects were the U.S. Agency for International Development (USAID), the National Science Foundation (NSF), the Office for Technology Assessment (OTA), and the Environmental Protection Agency (EPA).

In 1983, the Provost appointed an Ad Hoc Committee on Technology, Policy, and Society Studies at MIT chaired by John D.C. Little. The committee was charged with:

- defining policy studies and their proper role at MIT;
- identifying and reviewing existing activities;
- preparing recommendations for strengthening and focusing the field at MIT.

The Little Committee found MIT's current capability in the technology and policy area as follows:

> MIT is already doing a great deal of policy research . . . , but we feel that present efforts in some cases lack focus and critical mass and could be substantially improved. In particular, we would like to insure in MIT's research and educational programs that the people doing policy-related work are aware of the intricacies and foundations of good policy and

> that the research being done draws on MIT's technical and social science expertise. (p. 3)

While the Committee suggests a number of measures to accomplish this goal, the key action proposed is to establish a new center for technology and policy with an MIT-wide focus based in the School of Engineering. The center would include a teaching program in the form of an enhanced Technology and Policy program and a research program that incorporates the Center for Policy Alternatives. The name of the new center which began on July 1, 1985 was the Center for Policy, Technology, and Industrial Development (CTPID).

While both CTPID and CPA set out to focus on similar objectives, CPA consisted of research activities and was considered to have inadequate links both to faculty and the undergraduate and graduate teaching programs. CTPID was to bring education and research together in a more expanded and integrated framework, with greater MIT faculty and student participation. By including the Technology and Policy Program's Master's degree program into the organizational structure of CTPID, the center brought together students, faculty, and research staff in a newly integrated fashion. Moreover, as the concerns with U.S. industrial competitiveness intensified at the turn of the decade, CTPID aimed to expand its focus and work on solving problems that industry was confronted with at the time. Ever since its establishment, CTPID researchers have worked on exploring the role that technology and scientific policy plays in industrial development, particularly how they can foster improvements in industrial productivity and affect overall competitiveness.

CTPID thus evolved from a policy-initiative into a broader center whose aim was to conduct conspicuous and coherent policy-related research and teaching activities and to act as a centerpiece that would cut across several departments at MIT, including social science departments such as Political Science, Economics, Urban Studies, and Management. The new center aimed to achieve a synergy among the prior initiatives and thus substantially improve the policy focus of MIT. Several of the programs that came under the administrative coordination of the organization existed prior to CTPID and opinions tend to differ regarding what the prospective development of these programs would have been if left alone.

CTPID represented the organizational unit through which MIT aimed to gradually assume a more prominent role in technology and policy, addressing intellectually challenging and important issues as they emerged. It was to become a source of technology/policy know-how by understanding the interface between technology, policy, and society, with a mission formulated as follows:

> to more effectively utilize science and technology in policy and decision making, focusing on problems of national and international importance, and to educate future leaders with dual competency in technology and policy; to perform a catalytic integrating role at MIT, building upon its unique science and technology resources, by providing a broad interdisciplinary perspective and increasing the policy impact of MIT departments' traditional educational and research activities. (MIT Report to the President, 1989–1990)

This policy/technology orientation and the methodologies that the center has adopted to accomplish this focus represent an essential intellectual contribution of CTPID.

In order to address the societal resistance to technology based on unreasonable grounds, the center set out to enhance the development and deployment of new technologies by providing relevant and reliable information to policymakers and the public about the impact and responsible use of technological projects. CTPID also aimed to investigate the role of public policy in shaping technological development by identifying the adequate policy framework for technical innovations and inventions to address prevailing societal needs. While the former reflected the supply push view, the latter approach is more consistent with the demand-pull perspective on technical change. Research on technology policy addressed questions such as the policies and programs appropriate to insure technological leadership of the U.S. economy; the role of government in stimulating basic research in both public and private sectors; the deployment of research innovations to industrial commercialization and protection of intellectual property; and the adequate supply of scientists and engineers.

These attempts to address the complex technology-policy issues relied on the unique mix of resources in the areas of science, engineering, management, and social sciences. The vast experience of MIT in collaborating with industry and government and other stakeholders to focus on technology-related problems of national and international importance were crucial in supporting the research and educational initiatives of CTPID. Individual programs used

CTPID's problem-solving approach to focus on different industries. Despite different approaches and industries, common, cross-cutting issues were uncovered and addressed.

While there has been some concern regarding the extent and intensity of the policy side of the center, CTPID successfully continues to address urgent societal problems involving technological aspects. Using a three-tiered approach including (1) an interdisciplinary orientation, (2) a collaborative approach and (3) a multi-systemic focus, CTPID moves toward the creation of a knowledge base upon which informed policy making can take place and of a set of methodologies that allow for a best use of that knowledge.

Interdisciplinary Orientation

The resolution of public policy issues generated by the rapid changes in scientific and technological progress requires an understanding of the policy-making process and analytical skills in addition to technological expertise. Moreover, the increasing focus on large-scale, engineered systems with their important natural and social components requires new methods of analysis to be developed and adopted by CTPID researchers that rely on more than one discipline.

A disciplinary perspective on an issue can offer sharp, deep, rich insights into a problem, but seldom can provide a complete or radical solution or approach to solving a problem. Because of the problem focus, CTPID researchers are constrained to examine the broader contours of the problems of interest. They draw on a multiplicity of disciplines to come up with solutions to the issue.

In addition to providing a formal, administrative home for research situated at the intersection of different disciplines, CTPID also provides the opportunity for low-key, collegial interaction across disciplinary lines and provides for an independent political constituency within MIT. The center offers an environment in which the faculty and students from different disciplines can interact intellectually, identify common ground, and develop a shared intellectual core at the intersection of technology, policy, and industrial development.

The main characteristics that distinguish CTPID from external research organizations with an interdisciplinary approach in the area intersecting technology, government, and business are its forward-looking approach and policy orientation. Carnegie Mellon University's Center for Business, Technology, and the Environment, founded in 1993, focuses in areas of economic development with a historical perspective on social issues. The Alliance for Innovative Manufacturing at Stanford University, established in 1982, focuses more strictly on the management processes and technological innovations necessary for industrial development.

The Ford-MIT Alliance and the Hazardous Substances Programs are two center initiatives integrating different disciplines at the intersection of science, technology, policy, and society. The Ford-MIT Alliance has grown beyond the initial focus areas of environmental science and policy, information technology in product development, virtual teams, and education. New interests include specialized research projects and two new program areas in active safety and power train technology research. The research projects are also linked with recruiting and MIT's educational programs, enrolling engineers and managers that bring new research knowledge back to Ford. In the context of an interview with MIT Chancellor Phillip Clay, MIT Director for the Ford-MIT Alliance, on the intellectual contributions of the program, he comments that "MIT and its faculty have demonstrated an ability to come together across departmental and disciplinary boundaries to work on interesting practical problems" (CTPID, 2002). Similarly, the quantitative risk assessments for chemical health hazards undertaken under the Hazardous Substances Program immediately after the center's establishment, relied on several disciplines including mathematics, biology, and health sciences to estimate health risk. As CTPID's prototypical effort, the program was interdisciplinary in its research (involving over 35 faculty from many different departments). In addition, the program played an important educational role by implementing a very successful sequence, "Chemicals in the Environment", including four integrated courses.

Another example is the Research Program on Communications Policy (RCP), initiated to study technical, economic, and policy challenges in the quickly evolving communications industry. Now called the Communications Futures Program (CFP), it covers a wide range of focus such as: developing alternative measurement techniques for assessing how people respond to media technologies and tradeoffs among them, evaluating the role of audio in the perception of television, exploring interactive media and high definition television, and relies on several disciplines to achieve this focus. These initiatives developed in the framework of the RCP, have contributed to the development of new forms of data and analytical tools that can be put in use to assist decision makers in reshaping network structure.

The Cooperative Mobility Program (CMP) was grounded in empirical research on travel behavior, technological approaches, and public policies that affect mobility in both developed and developing countries. The members of the interdisciplinary research network working under the auspices of CMP included scholars and analysts, representing a number of engineering disciplines, as well as planning, economics, and political science. They brought a wide spectrum of professional skills to CMP's work.

A final example of the interdisciplinary approach that characterizes CTPID programs is the Materials Systems Laboratory (MSL) which uses an analytic framework based on economic and engineering assessment to develop robust, credible, and defendable product strategies.

An interdisciplinary approach is adopted by CTPID in research as well as educational activities. The Technology and Policy Program (TPP) that began in 1975 represents a graduate program that marries engineering skills to management and policy expertise. In 1989–1990, the TPP added a new track for students wishing to emphasize more the political, economic, and organizational aspects of technology and policy. The intellectual contributions of interdisciplinary research are always greater than approaches based on sole disciplines, and provide students and researchers with a unique set of intellectual perspective and academic opportunity.

Collaborative Environment

The large-scale systems that CTPID is concerned with are characterized by major scientific or technological components that require cooperation among many decision-making groups in the public and private sphere. In addition to collaboration between different MIT departments, centers, and laboratories, CTPID puts a great emphasis on bringing together industry, government, and academia. The increasing concern with the declining competitiveness of U.S. industries in the global arena in the early 1980s generated considerable governmental support for organizations that facilitated long-term partnerships between government, industry, and MIT. Contemporary processes of policy design and implementation often generate divisive, adversarial debates, delays, and inaction. To obtain the crucial input of these different stakeholders from the public and private sectors in addressing societal problems with important technological components in a comprehensive and realistic fashion, CTPID provides a neutral arena and organizational flexibility to foster collaboration.

CTPID aims to work with these stakeholders to discern alternative action plans and evaluate their impact on the parties affected by their implementation. In order to set up an institutional structure that provides an adequate framework for the adoption of such a collaborative approach, an external advisory board was established in 1987 with distinguished members from government and industry. Insights of the main stakeholders throughout the different projects undertaken by CTPID are shared through joint research projects, technology transfer, seminars, and other mechanisms as we will discuss below in the Spreading Knowledge section.

A unique characteristic of CTPID is its considerable flexibility to accommodate a wide range of patterns of collaborative research. The activities undertaken within its frameworks thus present a variety of scenarios as far as the type and extent of partnerships. While some projects focus on policy related issues, others collaborate less with government and focus almost exclusively on the private sector.

Government Collaboration

An example of a research project that relies mainly on governmental involvement is the Lean Sustainment Initiative (LSI) that was created in 1997 as a joint project of Headquarters Air Force Materiel Command, Air Force ManTech, and MIT to focus on the systematic changes required by the U.S. military in order to ensure a more efficient use of its logistics support. During its tenure, LSI undertook the research that the Air Force combat support community needed to initiate fundamental, systematic change. Program objectives were to facilitate the collaborative process to increase the involvement of government and non-government sustainment stakeholders and to assist the Air Force to develop a 21st century high-value sustainment enterprise.

The Labor Aerospace Research Agenda (LARA) is another example of collaboration between MIT and governmental agencies such as the U.S. Air Force, and later the Department of Labor, aimed to investigate the impact of instability on employment and work practices in the aerospace industry. The program promoted a vision of catalyzing leaders in government, industry, labor, and academia to ensure this industry's future prominence.

Industry Collaboration

The International Motor Vehicle Program (IMVP), on other hand, was established to work primarily with private stakeholders in the automotive industry. The program brings together industry and academia to create a knowledge base that allows better understanding of what constitutes superior industrial performance and competitive advantage in the automobile industry. The program has a commitment to making its research findings available to senior executives, government officials, and union leaders from the major auto producing countries. Sponsors contribute funds to IMVP, which channels resources to researchers at leading universities around the world. Researchers present findings and insights to sponsors at international and regional meetings and sponsor executive briefings. Through the knowledge relayed to governments and industry, the program helps sponsors provide better products and services, navigate the complex business environment, and develop sustainable ways to meet the global demand for mobility.

Academic Collaboration

IMVP is also an example of a program that fosters collaboration between a series of academic units from the United States and different nations. The Cooperative Mobility Program is another – during its tenure, it was an active partnership between transportation researchers and sponsoring firms concerned with mobility issues. The program brought together transportation scholars from MIT and other universities around the world, including Harvard University, University of California, University of Tokyo, Universite de Paris XII, and ETH Zentrum and researchers affiliated with other institutions. A third example is the Communications Research Network (CRN) a sister program to the MIT Communications Futures Program (CFP) led by Cambridge University, and University College London. Members of each program have access to research across both institutes. The analogy the programs use is one room, two doors.

CFP and CRN are two doors to access leading researchers across MIT, Cambridge University, and University College London who are focused on defining the future of the communications industry and its impact on adjacent industries.

Different Collaborative Models

An inclusive collaborative model between industry, government, and academia is the Lean Aircraft Initiative (LAI) that began in 1992 as an active research partnership among 22 aerospace companies, 14 U.S. government agencies, labor representatives, and MIT to explore the applicability of lean production principles in the defense aircraft industry. This initiative's mission is to achieve a fundamental transition of the defense aircraft industry to generate substantial improvements in both industry and government. The program focuses on issues such as product development, fabrication and assembly, supplier relationships, organization of human resources and policy and external environment. Collaboration among these stakeholders is achieved through periodic workshops and special research discussions.

While most CTPID programs focus explicitly on particular industries, there are also exceptions. The Technology, Business and Environment Program (TBE) is an example of a project that researched multiple industries.

The projects with strong industry participation also differ in the number and geographical span of corporations involved in their activities. The IMVP focuses on one global industry and examines core issues in automotive development and production for several global corporate sponsors including Honda Motor Company and the Hyundai Motor Company. The MIT-Ford Alliance, on other hand, is much more restricted. Collaboration with industry is restricted to one corporation in the case of the MIT-Ford Alliance because the research conducted within the framework of the program involves proprietary issues.

Other programs, however, host pre-competitive research activities that industrial actors have a collective interest in like the IMVP and the research program on Communications Policy (RPCP). The cross-cutting partnership between university and industry was established to face the emerging and destabilizing events taking place in the communications industry as its structure is altered by new technical progresses. These changes are likely to have a great impact on the industry; similar to the impact of Internet, PC wave, and digitalization, and the mission of the program is to help industry partners recognize the opportunities and threats from these changes.

Realizing that many of society's most important engineered systems feature organizational and institutional stakeholders who must become better aligned in order to enable systems change and avoid catastrophic failures, CTPID/ESD has spawned a unique type of research program that focuses on alignment across stakeholders associated with the architecture and implementation of the Next Generation Air Transportation System (NGATS). The Lateral Alignment Working Group aims to identify the formal and informal patterns of interaction that orient and connect inter-dependent stakeholders over time so as to advance both their internal, separate interests and their combined, system-wide interests. This attempt is very relevant since contemporary and future engineered systems such as the next generation air transportation system, electrical power grids, and extended supply chains, all involve stakeholders that will not and for the most part can not operate together on just the basis of top-down command and control leadership. Because the challenges are complex and multidimensional, there will not be a single-point solution. In systematically working through these challenges, however, valuable lessons will be learned for stakeholders associated with aviation and the environment, all of whom will also have to build internal alignment in various ways.

Multi-Systemic Focus

In the contemporary world, the complexity and dynamic character of technical change and scientific progress has significant implications on the economy, social communities, and the environment. They touch us in many different ways and shape activities that we do not normally think of as scientific or technical. One of the center's major concerns is thus to evaluate the impacts of technological development on individuals, organizations, and natural resources. CTPID aimed to address the need for an effective coordination of technological projects and their economic and societal implications by adopting a multi-systemic view that expands the focus beyond the technical components to the social and natural realm. This coordination had not been achieved in the past as a result of the gap between policy making and technical change.

While the interdisciplinary work of CTPID refers to the use of a wide set of tools, techniques, and theories as part of its methodology to solve large-scale engineering problems, the multi-systemic view refers to the broadened focus, open character of the object of analysis that expands beyond the strictly technological components.

Since its inception, CTPID research activities emphasized the interconnectedness of the physical, economic, and social environments especially as the issues that it was concerned with were becoming increasingly international in scope, forming large-scale systems of global significance. CTPID aims to address the harmful side-effects of technology by focusing on such issues as the prevention and clearing of hazardous wastes, the future of infrastructure of the United States, the role of nations and resources in the international marketplace, occupational disease and injury, labor displacement by automation, and problems resulting from acid rain. Studies conducted by CTPID include investigations not only of human impact on natural and social processes, but also the social, cultural, and political environments which shape these interactions.

Studies conducted by the International Motor Vehicle Program to determine the underlying determinants of Japan's competitive advantage in the auto sector indicated that the fundamental advantage of Japanese companies was their systemic approach. This approach to the manufacturing process of automobiles led to lean manufacturing and superior productivity, improved quality, rapid product development, and production flexibility. IMVP researchers have since been working on developing a view of the automobile industry as an interlocking system, in which technology, human resource management, international economics, and political conditions worldwide must be considered in the making of effective public and private policy.

In the past, environmental concerns have not been part of the strategic planning process of companies. As a result of the social and political contexts presented in the previous chapter, producers became much more reactive to a set of government regulations of environmental issues. The Hazardous Materials Management Program (HMMP) thus sought to identify techniques to evaluate the impact of hazardous materials on the natural and social environment, as well as to develop improved strategies to optimize the regulations of hazardous materials by minimizing their negative impact on the natural environment and social habitat.

The International Motor Vehicle Program (IMVP)

For close to 25 years, the International Motor Vehicle Program (IMVP) has been the largest and most influential international automotive industry research consortium. It formed CTPID's foundation and led the way for other programs, such as the Lean Aerospace Initiative. IMVP's early research changed the automotive industry by providing the keys to lean production to industry worldwide. It promoted the lean manufacturing methodology and spread concepts like "just-in-time" and "supply-chain management". IMVP is integral to CTPID's history and development as it is a model of so many of the center's defining characteristics: an interdisciplinary approach, collaborative environment, multi-systemic focus. It created and continues to create and spread a knowledge base to address issues presented by engineering systems.

Today the global auto industry is facing critical decisions about its future. Challenges include tightening profit margins and rising customer demands. Global operations and technological options from telematics to green drive trains call for new value propositions. Competitive dynamics and the ground rules for collaboration are changing as automakers consolidate and form alliances and as new mega-suppliers emerge. To make the strategic decisions that will drive a new paradigm for success, each company needs industry-wide knowledge and insight. IMVP will continue to provide this.

The initial focus of the MIT-Ford Alliance also consisted in environmental science and policy, promoting an attempt to integrate the natural system in the studies of the auto industry. Similarly, MIT's Cooperative Mobility Program aimed to work toward discerning a sustainable, multi-modal transportation system to provide the mobility necessary to foster global economic development, while remaining compatible with social needs and environmental protection.

The current tendency is to take a proactive approach by factoring environmental considerations into early stages of the manufacturing process. The research undertaken within the Materials Systems Laboratory, for example, seeks to enable design and manufacturing people (even suppliers) to work together at early stages of product development to achieve environmentally-friendly manufacturing.

Finally, an illustrative example of a CTPID research program focusing on the social components of technology, policy, and industrial development is the Labor Aerospace Research Agenda program (LARA). The LARA program was established on the belief that people are at the heart of new work systems and was designed to focus understanding on the critical social dimensions of the lean principles in the aerospace industry.

Having discussed CTPID's focus and approach toward the creation of a knowledge base, we turn to how the programs used that knowledge.

CTPID's Impact: Spreading Knowledge

CTPID's focus on policy issues and industrial development through the three-tiered approach described above, has had a great impact over the past 20 years. As we have shown, CTPID's focus has been oriented toward problem solving and a goal of the center is to develop and promote pragmatic concepts and principles that will be widely adopted by government and industry. CTPID disseminates knowledge by publishing articles, papers, and books and by hosting and participating in conferences, workshops, and seminars.

Books Published by Center Researchers

We have chosen just six books as strong examples of works published by members of the CTPID community. Appendix D provides a more extensive, although not completely comprehensive, list of books published by members of the CTPID community. The first four books mentioned here helped to spread methodologies. The fifth and sixth are clear examples of CTPID's focus on technological transformation and its impact.

A groundbreaking work and a bestseller to come out of the center is the International Motor Vehicle Program's *The Machine that Changed the World*, by James P. Womack, Daniel Jones, and Daniel Roos (Rawson Associates, 1990). In the spirit of CTPID, the book's findings were aimed at industry and government. The *Financial Times of London* named the book the best business book of 1990 and it has been translated into several languages.

The book explains Japan's superior manufacturing system for cars and suggests that to compete effectively against the Japanese, U.S. and European companies need to adopt the lean production system. Japan's fundamental advantage is system thinking, which led to lean manufacturing and superior productivity, improved quality, rapid product development, and production flexibility. Lean manufacturing requires different organizational structures, accounting, corporate culture, information structures, incentives, and rewards. This book and IMVP promoted the lean manufacturing methodology.

The Machine that Changed the World's findings have had implications that go far beyond the auto industry. Its publication prompted the U.S. Air Force to ask: "Can lean principles be applied to military aircraft production?" which led to the formation of the Lean Aircraft Initiative and then the Lean Aerospace Initiative (LAI). In 1999, LAI moved beyond examining lean practices at the factory floor to begin enterprise level research from which came the publication of another important book from a CTPID program. *Lean Enterprise Value: Insights from MIT's Lean Aerospace Initiative* (Earll Murman et al., Palgrave Macmillan, 2002) has been likened to *The Machine that Changed the World* in that it promises to do for the aerospace industry what *The Machine that Changed the World* did for the automotive industry. *Lean Enterprise Value* redefines lean production as a framework for enterprise transformation. Extending the prevailing view of lean to one of not only eliminating waste, but of creating value for all stakeholders, the authors explore the core challenge for technically complex industries in the new century. The enterprise focus is part of the evolution of LAI: from the factory floor to the transformation of the entire enterprise, and eventually the entire aerospace sector.

Another landmark book from a CTPID professor, *Clockspeed: Winning Industry Control in the Age of Temporary Advantage* (Charles Fine, Perseus Books, 1998), marked a turning point in strategic supply chain design and provides another example how some CTPID programs advanced new methodologies. The focus on the supply chain came from the growing sense in industry that companies could become more competitive by expanding their focus that was traditionally limited to the production line within their well-defined boundaries. Companies needed to look at how they interacted with suppliers and customers, how they distributed their goods, cooperating along the supply chain for improved performance (Roos, 2004). *Clockspeed* shows how choices in supply chain design can drive company and industry evolution. Fine introduces powerful tools for anticipating and mastering the forces of change in a world where business advantage is temporary. He provides models of industry dynamics and supply chain dynamics that are helpful for getting people to think about how their industry, their business, and their supply chains will change over time. Fine and his colleagues' work in the Communications Futures Program led to the development of value chain road mapping – mapping business dynamics and policy dynamics as well as technology dynamics to better understand how an industry might evolve over time.

In *Future Cities: Dynamics and Sustainability* (Kluwer Academic Publishers, Dordrecht, The Netherlands, 2002) Fred Moavenzadeh et al. (eds) provide new ideas for sustainable management of the burgeoning megacities of the future. The authors dispute the conventional wisdom that cities distort natural processes and claim, in fact, that the opposite is true. Properly managed cities can be transformative arenas where raw materials may be rationally and economically developed to support people. In true CTPID fashion, *Future Cities* takes a multi-disciplinary, multi-cultural approach to detail methodologies, analyses, and policy recommendations focusing on the synergy of technological options and policy requirements for sustainable cities in an urbanizing world.

A slightly earlier example of a CTPID publication, *Technology, Law, and the Working Environment* by Nicholas A. Ashford and Charles Caldart (Island Press, Washington, D.C., 1996), deals with a common CTPID theme – technological transformation. The book addresses a variety of scientific, legal, and policy issues growing out of the technological transformation of the American workplace. It discusses the evolution of technology, work, and health and traces the economic and political forces that spurred the development of modern workplace law. The authors present workplace health and safety issues in terms of the real costs of disease and injury, stressing the importance of undertaking economic analysis along with scientific and legal analysis. They believe that a combination of disciplines is needed to encourage the processes of technological innovation and diffusion necessary for societies to integrate environmental, workplace, and industrial policies in ways that alter the technologies of production and products to improve health, safety, environmental quality, and economic growth.

The Cooperative Mobility Program's (CMP) *International Mobility Observatory: Window on the World of Transportation and Innovation* prepared by C. Kenneth Orski (CMP, 1996, 1997, 1999) is a publication that documents the state of transport innovation throughout the world and tracks innovative developments in transportation policy, management, and technology. *The Mobility Observatory* was produced and distributed by the CMP with three purposes in mind: (1) to provide an overview of change and innovation in the field of surface transportation; (2) to identify and assess trends likely to affect the transportation sector in the years ahead; and (3) to serve as a source of insights and stimulation to the CMP research team. When published, it represented the most comprehensive effort of its kind to document the state of innovation in surface transportation.

CTPID Seminars and Conferences

Another way that CTPID ensures the dissemination of its research results and promotes dialogue among the academic community and representatives from government and industry is through hosting seminars and conferences. These venues can range from small, working group sessions to large, institute-wide events and everything in between.

An example is “The Third Wave: Industry Opportunities for the Internet-Enabled Future”, which nearly 100 industry, government, and academic representatives attended in November 2000. The conference brought together MIT faculty, industry, and government leaders in the fields of automobiles, mobility, aerospace, construction, materials systems, telecommunications, business and environment, and technology and law to define major challenges and discuss emerging options. Keynotes focused on the impact of the Internet on the automotive industry, trust-based marketing on the Internet, and the future of the Internet itself. The conference was designed to help CTPID’s sponsors understand and respond to rapid changes in the marketplace.

Another example of the rich information sharing at CTPID is an international conference entitled “Broadband Divides” hosted by the Oxford Internet Institute and co-sponsored by CTPID’s Internet and Telecoms Convergence (ITC) and Syracuse University in March 2003. At the conference, ITC leaders sketched a path toward a broader digital future and offered lessons from America’s residential broadband deployment experience. The participants tackled issues involving equity, economic competitiveness, and policy incentives.

A final example of the many productive conferences, seminars, and workshops organized by CTPID programs over the years is the very successful MIT Industry Leaders in Technology and Management Lecture Series that ran from 1995–2005, co-sponsored by CTPID and the Office of Corporate Relations. This series brought America’s most influential and innovative business leaders to campus to share their insights about contemporary industry developments with the MIT community. These lectures strengthened the dialogue between the MIT student body and faculty and the dynamic CEOs, presidents, and board chairs of major international and U.S. companies who are shaping their businesses and the future of their industries. Companies whose leaders who have lectured through this series include: 3M, Amgen, Bell Atlantic, Eastman Kodak Company, EMC, Ford, General Motors, Genzyme, Intel, Lucent Technologies, Merck, Merrill Lynch, Motorola, Nokia, Raytheon, Texas Instruments, and UPS.

CTPID's Impact: Informing Policy

While conferences, seminars, and publications can indirectly have an impact on policymaking, a more direct input on policy is provided by the approximately one-third of TPP and TMP graduates who go work in government agencies. These include: Hydro-Quebec, the U.S. Environmental Protection Agency, the French Ministry of Defense, and the Japan Ministry of Transportation.

In addition, CTPID faculty and researchers are often called upon to give advice or input on policy choices (see *Impacting Policy: The HDTV Example*, p. 45). For instance, in 1987–1986, the Hazardous Substances Management Program developed a new guide for policies for the state of New Hampshire on the management of household hazardous wastes and other non-regulated wastes and municipal solid wastes that are potentially hazardous. In a similar vein, over the years, LAI has delivered major policy recommendations to the Department of Defense.

In 2002–2003, the Labor Aerospace Research Agenda (LARA) presented testimony to the Presidential Commission on the Future of the Aerospace Industry based on its white paper, “Developing a 21st Century Aerospace Workforce”. After giving their testimony, the LARA team continued to work with the U.S. Department of Labor on the implementation of recommendations from this commission. The project called attention to the faltering underpinnings of the aerospace industry, highlighting massive consolidation, job losses, and revenue cuts over the past two decades. LARA offered a vision to catalyze leaders in government, industry, labor, and academia to ensure this industry's future prominence. Another very recent and ongoing example of a CTPID researcher involved in informing policy decisions is Sharon Eisner Gillett, principle research associate, CTPID's Communications Futures

Impacting Policy: The HDTV Example

An example of industry, government, and academia working together to change policy was MIT's influence on the national agenda for open high resolution systems and HDTV. With the Japanese pushing for new TV technology, Congress was about to pass legislation requiring that type of high-quality TV, but MIT research showed that the Japanese were supporting a choice that was already obsolete.

The Committee on Open High Resolution Systems (COHRS) was formed to define an open high resolution systems architecture arrived at by cross-industry consensus. This committee understood that poor technical choices for standards may create high social costs; e.g., limiting the ability of people to communicate freely and inhibiting innovation. A group of companies and researchers known as the Grand Alliance was formed, whose task was to develop a high definition TV standard that would both surpass existing Japanese HDTV technology and take advantage of digital transmission over telephone, cable, and wireless data networks instead of current analog broadcasting technology (CTPID, 1996). MIT was the only university to play a role. COHRS members drafted and signed a letter to the Secretary of State, urging him to prevent adoption of obsolescent standards harmful to U.S. interests (CTPID, 1991). They were ultimately successful in this endeavor.

Program, who was named by Boston Mayor Thomas Menino in early 2006 to the City of Boston's WiFi Task Force which investigated how a wireless fidelity connection to the Internet could be deployed throughout the city and thus available to every resident. On July 31, 2006 Mayor Menino acted on the task forces' recommendations to begin with two initial wireless hotspots in Boston and spread from there.

CTPID's Impact on Industry

Different CTPID programs that work with industry are aimed at one or more of the following motives: improving industry for the benefit of the industry itself, its customers and potential customers, the environment in which the industry exists, and the greater community. We may take it for granted, but it is worth stating: one very important way industry is impacted is when an MIT graduate who has been affiliated with CTPID takes a position within industry. Over the past 20 years, CTPID has supported many, many students through research assistantships and has taught many others through the Technology and Policy Program and all the departments in which our faculty teach. The last date from which we have figures is 1998–1999 when over 600 TPP/TMP alumni were working in industry, government, consulting, and academia. At that time, about one third of graduates took government jobs; another third pursued careers in business management; and the remainder went into academic positions or consulting firms. Alumni hold leadership positions in industry at Lockheed Martin Astronautics, Ford Motor Company, IBM, Merrill Lynch International, Shell UK, and Telecom New Zealand.

A bit more concrete is the impact of CTPID research programs on industry. The Lean Aerospace Initiative (LAI) is a good example of an active collaboration that strives to help move its members forward in their lean journeys. It does this by participating in integrative research that addresses the various stages of aerospace systems – planning, contracting, development, production, and operating. LAI research examines manufacturing systems, supplier networks, product development, acquisition, organizations and people, and test and space operations. LAI has developed products, creating a foundation of reference tools for common awareness, language, and understanding of lean principles.

One sign of LAI's impact in "leaning" the U.S. Aerospace Enterprise was the announcement in November 2005 by the Secretary of the U.S. Air Force of a new program Air Force Smart Operations 21st Century (AFSO21) that will lean the entire service. LAI's fingerprints are on several different lean initiatives throughout the Air Force – at the depot level, at the Air Force Air Logistics Centers and through support from the Air Force's Materiel Command.

There is no better example of a project that has greatly impacted industry than IMVP. As we discussed above, *The Machine that Changed the World* (1990) brought the lean production system perfected in Japan to the United States and Europe and thereby improved quality, productivity, and flexibility in automotive assembly.

On a smaller scale, but still with very significant implications for the aerospace industry, was the Labor Aerospace Research Agenda's examination of operations at Boeing's St. Louis IDS (Integrated Defense Systems) plant where both the union and the employer agreed to compress approximately 47 job classifications and numerous sub-classifications into eight integrated categories. The initiative's just-in-time delivery system for relevant skills training allows more flexible utilization of the workforce by the employer and increased worker employability. The LARA team found that the plant is at the frontier of fostering workforce flexibility and new investment in skills and this experience points the way toward a model of skill development that meets employer needs for continuous adaptation and employee interest in lifelong learning.

Conclusion

The establishment and functioning of the Center for Technology, Policy, and Industrial Development reflects the dedication of MIT to societal problems of contemporary relevance. While technology greatly contributes to increased productivity and economic wealth and growth, the distributional effects pose important policy questions that need to be considered. In order to achieve a broader approach to engineering projects that address these issues, going beyond the traditionally narrow focus on the technical aspects, the center facilitated the management of interdisciplinary programs with multi-departmental and multi-stakeholder participation.

Technology is becoming increasingly pervasive in society and breakthrough technologies continue emerging with accelerating speed. The importance of policy is therefore increasing to regulate the societal and environmental impacts of applying old and emerging technologies. The need to address the uncertainties of large-scale socio-technical projects generates the necessity for a problem-solving environment working at the intersection of where technology meets public policy (Lane, 2006).

This chapter addresses this growing importance of the interactions between policy and technology and large-scale, socio-technic projects. CTPID developed from the realization that policy implications of technology cannot be investigated adequately without a multi-systemic, interdisciplinary, collaborative approach. Technology and policy are interconnected in a complex manner so that sector-specific studies benefit greatly from relying on collaboration between government, academia, and industry to address aspects involved in their development and implementation. CTPID's main intellectual contribution thus consists in this problem-oriented focus supported by its interdisciplinary work and collaborative approach.

While each of the programs undertaken within the framework of CTPID is unique and relatively independent from each other, they have cross-cutting themes that focus on a common agenda with issues such as competitiveness, environmental safety, and societal equity. The synergy resulting from the various forms and depths of partnerships between different disciplines, stakeholders and systems, has generated substantial resources and intellectual mass with significant pragmatic relevance.

The academic programs at CTPID that ensured the spread of the accumulated knowledge also reflected a shift in conceiving the role of engineers by emphasizing the importance of their alignment to society. The two academic programs formerly associated with CTPID, the Technology and Policy Program's (TPP) SM and the Technology and Management Program's PhD, thrived and evolved into institutional innovations with significant weight in the School of Engineering and are now under the Engineering Systems Division (ESD). CTPID continues to provide research opportunities for the students in ESD programs and, until recently, provided administrative support to these two programs. A big part of CTPID's success is being part of these students' education and what they bring with them from CTPID to their careers.

Chapter IV

Engineering Systems Division

Traditionally, the field of engineering endeavored to keep its systems linear as they are simpler to build and to predict. In time, engineering projects grew in scale and complexity, incorporating an increasing number of system components at many different levels and connected in non-linear fashion. With complexity comes an interdependency of the different parts of the system – changes in one part may affect other parts of the system. In addition to the increased complexity of the interconnections between the different components, technological systems also penetrated more deeply and extensively the social and natural realms. Such interactions among components and between the technical parts and the natural and social environment are difficult, if not impossible, to understand and anticipate by traditional means. Therefore, the need to develop systematic techniques to address the increasing complexity and pervasiveness of engineering projects emerged and engineering practice had to reconsider its reductionist approach to include elements of systems research. This study of complex systems with dense and significant connections to social and natural systems brought new vitality to the field of engineering.

This chapter discusses the role of CTPID in generating a knowledge base to address the issues presented by engineering systems, as well as in demonstrating the need for a formal, institutionalized home for research and education on large-scale engineering systems. Special consideration will thus be given to the contribution of CTPID in the emergence, consolidation, and institutionalization at MIT of a new approach in the field of engineering that focuses on large-scale, complex, socio-technic systems. These contributions set the stage for significant institutional and organizational modifications within the MIT academic environment.

CTPID's Role in the Emergence of a New Knowledge Base

Systems thinking in engineering emerged during the decades after World War II. While great engineers of the past tried to deal with the "messy complexity" of large technological projects in an unsystematic way, the systems techniques of the 1950s tried to eliminate uncertainty and to reduce complexity to calculation. It had a characteristic set of assumptions regarding how various social and natural phenomena can be understood in abstract, quantitative terms and modeled with a series of feedbacks, flows, and dynamics. The use of computers allowed for social and technical systems to be modeled with similar techniques. Systems thinking characteristic of the decades after the 1950s was thus arranged around modeling and had a top- down, hierarchical view (Hughes, 2004).

This narrow, technical definition of systems started to broaden and flatten as systems techniques were brought to bear on a variety of civil problems during the 1970s such as urban poverty, mass transportation, health care, education, and housing. In contrast to defense problems where military organizations had authority to effect solutions, these civil issues involved more negotiations, compromise, and consultation. They pointed to the limitations of the technical models which excluded politics and the social world as exogenous variables, outside engineering models, and broadened systems thinking by bringing these issues to the fore.

In the 1980s and 1990s, engagement with industrial issues, especially productivity and competitiveness, emphasized the importance of large-scale engineering and generated major interdisciplinary efforts such as the MIT Commission on Industrial Productivity, the International Motor Vehicle Program, and CTPID.

The problem-solving approach adopted by CTPID to address challenges put forth by large-scale systems, lies at the nexus of three distinct structures: natural, social, and technological systems, and takes an interdisciplinary approach to understand their interactions. The social system sets the rules, extent, and nature of the demand for large-scale systems. The natural domain is the physical context or the natural environment with its role both as a source of resources and as a sink for pollutants. The technological components enable the means for realization and operation of the engineering projects.

In addition to the traditional goals of engineering – functionality, performance, and cost, the large-scale system orientation of CTPID required that researchers address an additional set of non-traditional goals such as sustainability, safety, flexibility, robustness, maintainability, durability, scalability, and quality – the so-called "ilities" (Moses, 2004). Fundamental issues in engineering systems include the relationships between traditional system properties and non-traditional characteristics and goals.

These goals often involve long time spans and life-cycle issues. The incomplete understanding of the numerous and non-linear interdependencies between the system components, and lack of ability to anticipate the outcomes of these interconnections by using formal models, generate a high level of uncertainty that represented a significant challenge to CTPID researchers in the development and management of these systems.

The large-scale and complex system thinking adopted by CTPID enabled researchers to study engineering projects in a holistic way.

The problem-oriented, empirical work conducted at the center to address traditional and non-traditional goals of engineering, given the constraints imposed by the fundamental characteristics of large-scale systems, generated an intense intellectual process that greatly contributed to understanding the behavior of large-scale systems. This intellectual evolution emerged and continued to grow from the conjunction of four modes of intellectual inquiry – interdisciplinary work, a holistic view, subjective and objective learning, and a convergence of formalized and non-formalized knowledge. These four intellectual strands converged in the formation of the new knowledge base with a pragmatic focus.

First, the origins of this new knowledge base can be traced to the *holistic perspective* adopted by CTPID researchers who see analytically distinct aspects as constituting an integrative whole. This approach enabled the realization and deployment of successful engineering projects integrating social and natural components.

Second, the *interdisciplinary approach* applied to understand the interactions between the structures and processes of these different subsystems retains a distinctiveness that cannot be reduced to mere combination of theories, models, and methods particular to other disciplines.

The third intellectual strand leading to this new knowledge base focuses on different ways in which humans learn and interact with the world around them, and methods of gaining understanding – what we call the *objective and subjective aspects of knowledge formation*. The objective aspect is that which is externally demonstrable, and possibly measurable, and essentially able to be communicated and verified through scientifically agreed upon methods of inquiry. The subjective aspect is that which is uniquely embodied in the individual and that individual constitutes the "knowing subject". Part of knowledge generated through CTPID activities is thus embedded in the numerous individual researchers and the vast research community formed by MIT faculty and students who have been collaborating in the framework of the diverse and innovative research projects conducted by the center throughout its existence.

Large-scale systems are invariably characterized by knowledge-needs that are not exclusively "objective" or entirely "subjective" and where an *interactive synergism of formal and informal knowledge* generally yields the most pronounced payoffs. The latter process represents the fourth intellectual strand leading to the new knowledge base that came about due to CTPID's activities. Formalized knowledge is experiential in nature that has been systematized and (usually) causally explained and amenable to replication. Formalization is based on rational explanation. Non-formalized knowledge, by contrast, is experiential knowledge that does not require explicit causal understanding of events and is capable of taking into account phenomena that have not been understood through objective or scientific scrutiny or predicated on any degree of certainty. Nonetheless, this latter form of understanding is as crucial as the heuristics of experts when analyzing practical problems.

These four intellectual stands led to the incremental progression of the integrative body of knowledge pertinent to large-scale and complex engineering problems. They reflect the realization of the diversity of technological change in terms of the richness of the world that is studied and the appreciation of the complexity of the ways we interact with it. By recognizing the essential characteristic features of the intellectual evolution relevant to solving large-scale, complex engineering problems, a significant step was taken. A robust strategy was needed for expanding this experiential knowledge-base and strengthening its domains of applications in a more intellectually formalized and systematic way. CTPID made an essential contribution in laying down the foundations of this knowledge base, but it also brought about the realization that a concerted intellectual strategy, combining academic inquiry and research activity, is needed for the maturation of this new knowledge base as a distinctive form of engineering knowledge approach to large-scale systems.

Engineering Systems: An Emerging Mode of Thought

With the progressive work on large-scale systems, CTPID facilitated the emergence of engineering systems thinking. Engineering systems are systems designed by humans, with functional purposes, and composed of interacting technical, social, and natural components. The need for this new approach within engineering was generated by the growing importance of existent and emerging technologies in the social and economic arena – the increasing complexity of engineering systems that were being designed, manufactured, and operated at this time, and their growing societal pervasiveness. The elegant simplicity of a science-based approach did not suffice any longer. Engineering systems is about embracing real world complexity and uncertainty and seeking to understand and manage the changes that occur throughout the lifetime of systems.

In the tradition of CTPID's approach to large-scale systems, an essential feature of the engineering systems mode of thought is the holistic understanding of system structures and processes. A holistic approach by definition means the consideration of the system as a whole rather than just a mere aggregation of the component subsystems. It thus relies on a distinctive body of knowledge to address the problems posed by such systems, which is different from a mere aggregation of multiple disciplines or a multidisciplinary approach. Engineering systems relies more on the integration, rather than mere aggregation, of formerly separated disciplines. The spheres of knowledge thus intersect. An interdisciplinary environment is much needed for resolution of many contemporary issues in the field of engineering systems.

Within the field of engineering systems, however, interdisciplinary work does not consist in the mere application of the theories and/or methods used in one discipline to the problems that other disciplines tend to focus on, but rather it refers to an integration of different disciplines to address a new set of problems that had not been characteristic to any of the pre-existing disciplines. The intellectual inquiry that is required to address the problems set by large-scale, complex systems makes it necessary to open up the boundaries between different academic disciplines to discover the optimal problem-solving approach. This leads some academicians to argue that the term *transdisciplinarity* better describes the problem-solving approach that engineering systems adopts.

Engineering systems professionals position themselves somewhere at the intersection of engineering, management, and policy studies. They do not work purely on technologically enabled systems or exclusively on mathematical or social science methods. They do not just address enterprise level management issues nor do they focus solely on societal concerns. Engineering systems does not treat models as sacred and it does not seek to educate engineers as mere scientists, but as managers, inventors, and policymakers as well.

This is systems thinking in a much broader interpretation that includes humans, organizations, nature, and technology. It is indeed a more adequate approach to address the problems of today's world that cannot be solved by new inventions or devices alone, but requires properly conceived, implemented, and managed complex and large systems.

Engineering systems is thus a field of inquiry that is broader in scope than other interdisciplinary approaches within the domain of engineering such as operations research, systems engineering, technology and policy, and management of engineering, mainly because it deals with issues such as safety and sustainability which involve the social and natural systems. While there is still some ambiguity regarding the underlying differences between the concepts of engineering systems and systems engineering, there is an increasing consensus in understanding the distinctions between these two fields. While systems engineering treats politics, society, and the natural environment as external constraints on the system, engineering systems tends to interpret them as essential components of the system that interact with other components.

In the tradition of the problem-solving approach set by CTPID and other research centers focusing on large-scale, complex systems, a final feature of engineering systems thinking we will make note of is it defines customer needs and required functionality early in the development cycle. Upon consideration of the business and technical needs of customers and the wider public interests, engineering professionals who adopt this broader view on systems proceed with the design synthesis and implementation stages, and manage these throughout the system lifecycle.

The underlying principles of engineering systems as a mode of thought are thus:

- Holistic thinking emphasizing the use of abstractions in foundations;
- Interdisciplinary orientation;
- Thinking in life cycle terms;
- Managing change (technological, enterprise-level, societal context);
- Internalizing the externalities;
- Realizing the existence and use of feedback.

Recognizing engineering systems' essential features is a significant step, but this emerging paradigm in still very much in formation. The problem-solving approach of the Center for Policy, Technology, and Industrial Development and other research centers established during the 1970s and early 1980s made essential contributions to laying down the foundations of a new knowledge base that focuses on large-scale, complex, technologically-enabled systems. A robust strategy is needed for expanding this knowledge-base and strengthening its domains of applications in a more formalized and systematic way.

Building the Engineering Systems Division at MIT

The establishment of several interdisciplinary programs and research centers at MIT between 1976 and 1985 to address current societal concerns coincided with a shift from a narrow focus on engineering problems to a much broader one. Since the 1970s, faculty members and several MIT committees had been calling for a stronger emphasis on the integrative role of engineering as engineering projects were increasingly becoming subjected to open system influences. This new approach had a combined focus of technology and its interaction with management and society. In order for MIT to maintain leadership in engineering education and research, it was necessary to build strength in both the functional aspects of engineering science as well as the integrative aspects of engineering systems design and engineering management.

Recognizing the benefits of combining engineering with broader societal concerns, MIT established a Committee on Engineering and Human affairs chaired by Ira Dyer in 1979 that recommended diffusing the basic ideas of engineering and human affairs into undergraduate education. The committee did not call for institutional changes, but suggested the need for more faculty trained in the social sciences in the School of Engineering and closer ties between policy research groups and undergraduate teaching. This broader engineering thinking that encompassed social sciences to address policy issues and societal problems was promoted by the activities of the Center for Transportation Studies, the Center for Technology, Policy, and Industrial Development, the Technology and Policy Program and later the Industrial Performance Center (IPC).

In a similar fashion, the initiatives brought about by the increasing concerns over U.S. competitiveness – the MIT Commission on Industrial Productivity, Leaders for Manufacturing Program (LFM) and the International Motor Vehicle Program, further broadened the engineering perspective by emphasizing the concept of “Big M manufacturing” that encompasses the entire production process, not just what happens on the manufacturing assembly line. Engineering systems activities in the School of Engineering thus intensified considerably in the late 1980s and beginning of the 1990s. System design and product development became the main focus of these competitiveness-oriented programs and as these activities evolved in time, a series of system-oriented educational programs were started: Master of Science in System Design (SDM), a Master of Engineering in Logistics (MLOG), and the Center for Innovation in Product Development (CIPD).

These systems-oriented academic and research activities, however, existed rather independently from each other, and as awareness of the importance of large-scale systems was increasing within the School of Engineering, several committees put forth the idea of some sort of institutional change to bring these initiatives together. The Large Scale Systems Committee of 1987, co-chaired by Dean Joel Moses and CTPID director Dan Roos thus identified large-scale systems as an important emerging area of concern. A retreat on the topic increased awareness among MIT faculty involved with these different programs and centers of the need for concerted efforts to address the problem of systems engineering. In response, the Technology, Management, and Policy (TMP) PhD program was established in 1993 to bring together faculty with common engineering system interests and to provide an education in engineering systems at the doctorate level.

Institutional support for systems thinking continued as these educational programs (Technology and Policy Program, Master of Engineering Logistics, Systems Design and Management, and Leaders for Manufacturing) had a high number of excellent and experienced students enrolled, and as the research centers with a systems focus (CTPID, Center for Transportation Studies, Center for Innovation in Product Development, Industrial Performance Center) continued to develop intellectually and financially rewarding interdisciplinary research activities significantly impacting industry and government. Successful as they were, the inability to hire, promote and tenure faculty or to admit students directly by these academic and research programs represented considerable organizational barriers that prevented further progress in integrating engineering with social sciences and management.

In 1989 a committee chaired by Joel Clark produced a white paper entitled "Structuring Science, Technology, and Policy Studies at MIT" which recommended that a science, technology and policy unit be formed at the Institute. That same year, CTPID's external Advisory Board found that "Although CTPID has done an excellent job in fulfilling its objectives as a center, it is somewhat limited in what it can further achieve within the current structure of MIT. There is a compelling argument for the creation of a new unit which would serve as an intellectual home for technology policy study activities at MIT . . ." (as quoted in Clark et al., 1989, p. 7). Following the Advisory Board recommendation, more committees discussed the best way to proceed. These included committees chaired by David Marks, Kenneth Keniston and Daniel Roos, and one chaired by Harvey Sapolsky.

The committee formed under the leadership of Michael Dertouzos in 1993 suggested a drastic organizational change. His committee recommended setting up a separate policy school for engineering systems – not to be housed in the school of engineering. The idea was to set up an institutional unit similar to the Kennedy School of Government at Harvard University. While the Kennedy School was established to focus strictly on public administration and policy issues based more in economics and analytic studies, the new institution unit at MIT would address the needs of the private industrial sector by converging engineering with management studies and the social sciences. Even though this recommendation was not adopted, it is evidence of the growing importance of engineering systems at MIT and the progression toward ESD.

The educational and research initiatives in systems thinking continued to spread among various centers and programs in the 1990s, including CTPID. There was no home to collectively develop a common intellectual agenda.

As for the curriculum, while engineering systems subjects existed within the school, they were most often specific to a single department, limited in number and scope, and lacked coherence and richness.

Educational institutions in general, but MIT in particular, could no longer afford to downplay the importance of a holistic approach and interdisciplinary methods and principles in engineering education, and they realized that this new approach needed to be institutionalized into a structured and well-established system. "Big E" engineering, that is engineering systems and the broader aspects of engineering including concerns with policy, engineering management and the like, thus became a priority of the Institute. Big E is closely coupled with large-scale systems, where the connections and interactions between the subsystem components are as important as the subsystems.

Building on the findings and recommendations of previous committees, especially on the Large Scale Systems Committee, a committee chaired by Professor T.W. Eager emphasized the need for engineering projects to be conceived in a hierarchical way with several subsystems that need to be economic, efficient, and socially responsible on their own and as an integrated system. The Eager report entitled "Hiring and Promotion of Faculty Interested in Big E Engineering", issued on September 15, 1996, concluded that "Higher in the hierarchy, the solutions are influenced less by the tools of physics and chemistry, and mathematics and more by human relations, policy, and economics" and recommended that the School of Engineering create a division of Engineering Systems that would cut across the eight engineering departments. This division would develop curricula, admit students, and hire and promote faculty. Faculty members would be shared between the division and at least one department. The Eager Committee found that "the School of Engineering currently has about one-half as many faculty spending time in integrative activities as is desirable".

Even after the Eager report, it was more than two years before ESD was formally established in 1998. Part of the delay was due to doubts expressed by traditional School of Engineering faculty, who questioned the legitimacy of engineering systems because of its broad perspective and the inclusion of management and social sciences. The Sloan School of Management was concerned that the School of Engineering not develop what it considered a second-rate engineering management program. In spite of these concerns, ESD was approved because of the success of the pre-existing programs it built on such as TPP and

CTPID, and the recognition that MIT needed to address large-scale, complex engineering systems in the 21st century (Roos, 2004). The Eager Committee's proposal was thus successful because of the impressive track records and excellent students of the existing engineering systems programs, and because the problems addressed by engineering systems were increasing in importance.

ESD continued to give a home and support to existing academic programs, but its bolder mission was to define and develop engineering systems as a new field of study. ESD was created to be transformative of what the guiding principles and methods of the field are and to redefine U.S. engineering education thus achieving a major impact on society, education, and thought.

In the "Engineering Systems Division (ESD) Proposal for Formation" written by the Engineering Systems Council, May 1998 the mission of ESD was written as follows:

> ESD will establish engineering systems as a field of study that focuses on complex systems and products in which technology is considered in a broader context as part of a larger whole. ESD will develop academic programs in engineering systems at MIT to educate future leaders, serve as a model to broaden engineering education generally and expand the scope of the practice of engineering. To support is educational programs, ESD will initiate research which will focus on issues of national and international importance that have science and technology components. ESD will develop innovative working relationships with industry and government in educational, research and outreach activities. To achieve its objectives, ESD will collaborate with and broaden the Engineering Departments and interface with management and social science faculty colleagues in the other Schools at MIT.

ESD focuses on complex, technology-based products (i.e. automobiles, airplanes) and systems (i.e. transportation, telecommunications, energy) with an approach that emphasizes the belief that while technology is a fundamental part of the systems, issues of managerial and, more generally, societal interactions are as well.

As ESD is still new and evolving, its architecture, standing as a discipline, and core concepts continue to be discussed and debated. School of Engineering Dean Thomas Magnanti pondered these questions at the October 2004 Brunel Lecture Series on Complex Systems and said, "If we think about what will be the greatest achievements of the 21st century and we think about engineering engineering systems, how are we going to design our program and research to have an impact . . . ?"

In the tradition established by CTPID and other research centers with a systems thinking, ESD research and educational programs are deeply involved with industry and government to define research and educational needs and address the identified needs. ESD works with industry in a partnership mode where industry serves as a real world laboratory to test new concepts, provide data and facilities, and help faculty and students better appreciate the context of their research. 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.

Conclusion

As engineering projects were growing in size and becoming more interconnected and dependent on multiple technologies, enterprises, and societies, large-scale systems thinking in engineering became increasingly prevalent. The public is relying on these systems more than ever and industry can no longer be expected to fully understand how to analyze and design systems in the traditional way.

The need to study, design, and implement these large-scale complex engineering systems with their social, environmental, and political implications, led to the adoption of a different approach toward engineering that was put forth by CTPID research and educational activities. The success of CTPID thus consists in establishing a tradition of a multi-systemic or holistic view, interdisciplinary work focusing on societal problems and enterprise-level issues, while bringing together and encouraging collaboration among various stakeholders. It demonstrated that there is need for research done where academia, government, and industry overlap. Its educational program, the TPP and the other system-oriented academic programs established throughout the decades were not merely important, but necessary for the further growth of industry.

The ESD at MIT thus builds on the successful research centers and practice-oriented educational programs that were established before its formation, including CTPID and TPP. A testament to the success of ESD's approach in addressing contemporary engineering problems is the emergence and growth of interdisciplinary programs at other universities addressing complex engineering systems, at home and abroad. As with any new organizational unit that aims to change existing engineering education or to establish a new approach as a distinct field, ESD still has a long way to go to consolidate and further develop the progress of the last years.

Chapter V

Conclusion

The environment in which CTPID began was one of increasing concern with the competitive edge of U.S. manufacturing in a rapidly integrating world economy. In this context, the belief in the technological determinism of economic growth became very salient. Government, industry, and academia explored their interconnections and formed partnerships to strengthen the competitive advantage of the U.S. economy and to generate knowledge that would prepare the new technologically intelligent workforce.

As part of this report's exploration of the evolution of CTPID toward ESD, we have shown that the issues related to large-scale engineering projects acquired importance over time, and due to their complexity they could not be addressed simply by bringing different disciplines together and applying them to solve the challenges put forth by these systems. The solutions to these concerns require a profound understanding of individual disciplines and their integration at an advanced level.

CTPID thus acted as a knowledge integrator by providing the ideal setting for scholars of different disciplinary backgrounds to come together and collaborate with industry and government to solve problems posed by large-scale, complex engineering systems. Scholars were brought together not so much to deepen knowledge within their disciplines, but rather to integrate the theories and methodologies into a new body of knowledge with a pragmatic character that is pertinent to large-scale engineering systems.

As the prevalence of the interconnections between large-scale engineering projects and society grew in time, reliance on the social sciences to capture the implications of engineering systems on society and to understand the impact of society on technological development and projects became a necessity. Capturing the social and environmental dimensions of these engineering endeavors – understanding the ways they would impact society and the natural ecosystem, and the ways societal and environmental needs will impose changes on the existing systems throughout their lifecycles, still represent important challenges for the architects and managers of engineering systems.

CTPID was one of the centers MIT established to address these challenges. Along with the Technology and Policy Program (TPP) that functioned under the auspices of CTPID for 15 years, CTPID had to prove its success at addressing the complex policy and competitiveness issues of complex systems, prior to more fundamental changes in engineering education and more permanent modification of academic institutions.

CTPID thus demonstrated that the problems presented by extensive and pervasive engineering systems cannot be investigated in the traditional manner and required a holistic view and interdisciplinary approach that is built on collaborative work between government, industry, and academia.

CTPID and TPP were able to show their success in addressing issues of great concern in the public as well as private sectors, through the important impact the different research programs had on industrial practices and governmental policies, the considerable support CTPID research activities have received from the public and private sector throughout the last 20 years, and through the essential contributions made by the graduates of the TPP program to industry and government. Their success has been reflected by the large number of applicants to the TPP program, the enrollment of high-quality students, as well as through the considerable recognition the numerous faculty members and other scholars gain by working on the different research programs at CTPID.

The accomplishments achieved by CTPID, TPP, and other programs and centers with a systems focus at MIT showed the MIT administration that this field of endeavor required formalization in order to achieve further progress. They indicated the importance of establishing a separate academic entity that would give an intellectual home to the activities initiated and to scholars recruited by these organizations. These centers and programs had an essential role in convincing the top administration of the School of Engineering and MIT that this new approach toward engineering was growing into an important field and to approve the establishment of the Engineering Systems Division (ESD).

ESD provided the organizational framework and structure to consolidate and administer these prior initiatives. However, there is a problematic disconnect between ESD's predecessors' (including CTPID's) orientation and the Division's focus. We have shown that CTPID, following in the MIT tradition of Met and Manus and defined by post-World War II forces, is pragmatic and mission oriented. CTPID expands the experiential knowledge-base of large-scale, complex systems by exploring the diversity of technological change and gives an appreciation of the complexity of the ways we interact with these changes. ESD needs to build on this knowledge base. The intellectual core is important and rich and has to be handled with a great deal of care. The domains of application need to be strengthened in an intellectually formalized and systematic way.

While it is difficult to come up with common principles of large-scale, complex systems, the knowledge gained from CTPID and other research centers needs to be consolidated to apply to a more general set of problems. Large-scale systems and the increasing pervasiveness of technology call for engineers in leadership positions to have training that goes beyond traditionally defined engineering disciplines. This is one of ESD's tasks.

While ESD has been successful in bringing intellectual capital together and providing an adequate organizational unit to administer it, a consolidated body of knowledge is still not properly identified and structured. The educational and research focus of ESD activities in recent years also reflect a lack of progress in the policy domain, with scarce attempts to consider and integrate the social sciences.

An important source of this lack of consolidation and narrow focus on applied projects consists in the dual character of ESD's mission. On one hand, it aims to serve as an intellectual platform, to develop a new body of knowledge that would address problems specific to large-scale, complex engineering systems with their social and environmental dimensions, and channel that knowledge to the existing demand through the educational program provided by a separate division. On the other hand, it aims to act as an agent of change in the School of Engineering, to influence the existing departments by making them more aware of the particularities of large-scale engineering systems and impact engineering education in this manner. While there are advantages and disadvantages to both of these aspects of ESD's mission, by and large they point in opposite directions.

As for developing its educational platform, this needs to be paramount. ESD should focus on developing its educational platform around the engineering systems mode of thought. ESD's function should be to develop a curriculum open to other departments – perhaps eventually offering an undergraduate minor in engineering systems. In this way, engineering systems can be understood by students in civil engineering, mechanical engineering, and the other engineering disciplines, and the Engineering Systems Division will be providing an important service to these students.

ESD has a major role to play not just in educating future leaders, but in shaping future research agendas. Another cycle of intrusion of technology into natural and biological systems is beginning, especially with the massive technological changes in the life sciences. ESD can help figure out how science and technology can contribute to the betterment of society and move toward an improved understanding of how technology can be helpful and harmful. The division needs to address the uncertainty surrounding emerging technologies.

The fact that technology affects policy and policy affects technology is irrefutable and the sequential model of developing technology and then addressing the policy that controls it does not work. Nor does leaving the responsibility of how to carry forward these technological and scientific innovations (managing them, organizing them, and structuring them) to private companies or organizations. These issues must be addressed simultaneously, in a holistic, interactive manner – not with a unilateral view. ESD can and must advance this approach, taking into account the impacts of change on society, the economy, and the environment.

The current duality of ESD's mission has generated some degree of academic and intellectual debate that reflects the complexity of these issues and the novelty of the organizational innovation to address them. The challenge is not over yet, and many skeptics still need to be convinced of ESD's success. The quality of the excellent students enrolled in ESD programs and the support industry and the government provide the research activities connected to or developed by ESD, represent an excellent starting point on this road to success.

In order for ESD to develop an integrated intellectual platform that addresses the problems posed by large-scale systems, ESD needs to address some of the institutional issues that were put in place at its early stage of development, but now hamper it from serving as a genuine intellectual platform for this new field of endeavor. The ESD community should focus on solidifying the intellectual progress that has been achieved in the past years and strive for more administrative independence within the School of Engineering. Focusing on developing a body of knowledge and integrating it will make ESD a true leader that others will want to follow and participate in by choice.

Appendix A: CTPID and ESD Leadership

Center for Technology, Policy, and Industrial Development (CTPID) Leadership
Daniel Roos, Founding Director
Michael Piore, Associate Director
Charles Fine, Associate Director
Joel Clark, Acting Director
Fred Moavenzadeh, Director
Joel Moses, Acting Director

Engineering Systems Division (ESD) Leadership
Daniel Roos, Founding Director
Daniel Hastings, Associate Director, Co-Director, Director
Joel Moses, Acting Director

Appendix B:
Partial List of CTPID Sponsors

Acxion
ADEF Argentina
Agency for Toxic Substances and Disease Registry
Akebono Brake Co. Ltd., Japan
Alfred P. Sloan Foundation
American Iron and Steel Institute
Applied Materials Inc.
Army Aviation and Missile Command
Ascential
Bayerische Motoren Werke AG
The Boeing Company
Boeing Space Transportation
British Telecom
Cambridge-MIT Institute
Cambridge Technology Center, Division of Alcan Aluminum Corporation
Chromally Gas Turbine Corp
Chrysler Corporation
Cisco
Comcast
DaimlerChrysler AG
Defense Advanced Research Projects Agency
Defense Logistics Agency
Delphi
Deutsche Telekom
EDF (Electricite de France)
The European Commission, Belgium
Fiat Auto S.P.A.
First Logic
Ford Motor Company
France Telecom
GenCorp Aerojet
General Electric Aircraft Engines
General Motors Corporation
Goldman Sachs Group, L.P.
Hewlett Packard
Honda Motor Car Company, Ltd.
Hoogovens Groep BV
Hughes Space & Communications
Hydro Aluminum Metal Products
Hyundai
IAPMEI
ICU
Intel
Lockheed Martin (Aeronautical Systems Sector, Electronics & Missiles, Space and Strategic Missiles)
Marist College

Mercedes Benz of North America, Inc.
Motor Industry Development Corporation
Motorola
National Aeronautics and Space Administration
National Reconnaissance Organization
National Science Foundation
Naval Air Systems Command
Nokia
Nortel
Northeastern University
Northrop Grumman Corporation
Office of the Undersecretary of Defense: Acquisition and Technology
Owens Corning
Pratt & Whitney (Government Engines, Space Propulsion)
Raytheon Aircraft Company
Raytheon Systems Company
Renault S.A.
Robert Bosch Corporation
Rockwell Collins, Inc.
Rolls Royce Allison
Samsung
Sundstrand Corporation
Swatch
Systems Program Offices: Joint Strike Fighter, F-22, C-17, Training/JPATS
Telecom Italia
Telmex
Textron Systems Division
Toyota Motor Corporation
TRW, Inc.
United Technologies Automotive
United Technologies Corporation
The University of California, Berkeley
U.S. Air Force Manufacturing Technology Initiative
U.S. Air Force (Aeronautical Systems Center, Air Force Research Lab, and Space and Missile Center)
U.S. Department of Energy
U.S. Department of Labor
U.S. Environmental Protection Agency
US Steel
Volvo AB
Volkswagen AG

Appendix C:
CTPID Programs over the Years

- Agile Manufacturing Program
- Communications Forum
- Communications Futures Program
- Cooperative Mobility Program
- Fast and Flexible Communications Project
- Ford-MIT Alliance
- Hazardous Materials Management Program
- Hazardous Substances Program
- International Cooperative Mobility Research Project
- The International Motor Vehicle Program
- Internet Telephony Interoperability Consortium
- Labor Aerospace Research Agenda
- The Lean Aerospace Initiative
- The Lean Aircraft Initiative
- The Lean Space Initiative
- The Lean Sustainment Initiative
- Materials Systems Laboratory
- MIT Communications Forum
- MIT Information Quality
- The Program in Environmental Studies
- The Program on Internet and Telecoms Convergence
- Program on Science, Technology, and Environmental Policy, jointly sponsored by CTPID and the Laboratory for Energy and the Environment
- Research Program on Communications Policy
- Technology, Business, and the Environment Program
- Technology and Law Program
- Technology and Policy Program
- Technology, Management, and Policy Program

Appendix D: Partial List of Books Written by CTPID Affiliated Faculty, Staff, and Researchers

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