Managing Technology in Society

The approach of Constructive Technology Assessment

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Beyond the CAD/CAM Fix

At first glance, computer-aided design and computer-aided manufacturing (CAD/CAM) appear to provide a technological fix for constructive technology assessment (CTA). CTA strategies combine an analytical project with a normative project. The script for the analytical project involves synthesizing sociological, historical, and economic analyses of technology into integrated theories of the dynamics of technology. A central intellectual achievement of recent research on the dynamics of technology has been to reconceptualize technology from an independent force that acts upon society from the outside to a social activity in itself (Noble 1978:318). An implication of this claim is that technology development within corporations, for example, is shaped by interests and considerations that extend well beyond both the organizational boundaries of the firm and the narrow economic logic of profit maximization (compare Coombs, this volume). The script for the normative project is to formulate strategies for steering technology development in socially desirable ways, where "socially desirable" generally means the reduction of social inequity. This dual orientation provides both intellectual and political considerations for evaluating CTA accounts and modulation strategies.

CAD/CAM technology looks exciting at first because it appears to be a technology designed for CTA purposes. Do you not already believe, for example, that integrating computer technology into engineering design will somehow improve the development of new products and increase the range of variations that engineers consider in designing new products? In principle, many new types of considerations can be factored into design decision making using CAD/CAM

technology. Following this logic, if CTA advocates could only convince engineering designers to integrate social equity considerations into design decision making, then perhaps the CTA movement could become entrenched politically through relatively minor modulations. CTA activity might even then focus on writing CAD/CAM software to integrate the socially desirable design criteria. In short, CTA would have a technological fix.

But our analytical project suggests that technological fixes are always more complex than they first appear. Using a technological fix to solve a social problem *appears* attractive when inserting that technology into society requires little, if any, social adjustment. But if technological development is a social activity shaped by heterogeneous considerations, then achieving a technological fix is a genuine, and probably rare, social accomplishment. Getting caught up in the enthusiasm of CAD/CAM technology without examining its heterogeneous developments and implementations is to fall victim to precisely the form of technological determinism that research in technology dynamics is designed to overcome.

In the account below, I present a picture of CAD/CAM implementation that differs from its more usual image as a technological fix. Focusing on the United States, I describe CAD/CAM implementation as the production of three distinct technologies — two dimensional drafting automation, three dimensional wireframe and surface modeling, and solid modeling — that are endowed with the agencies of three different types of users. Although a nationalist script has positioned CAD/CAM as a technological fix that will unite design and manufacturing activities in a coordinated, integrated, and flexible manufacturing enterprise, none of the three technologies is oriented toward uniting design and manufacturing.

In varying ways, the implementation of CAD/CAM technologies challenge previously stabilized design activities and serve as resources to empower some groups while marginalizing others. The implications for CTA concerns could be significant. Most important, accepting CAD/CAM technologies means accepting the increased mathematization of design. That is, CAD/CAM use grants new importance to mathematically based design activities, increasingly demanding engineers and managers to place confidence in mathematical methods they are unlikely to master themselves. This is particularly true for 3D wireframe and surface modeling, the technologies that could be modulated most easily to pursue CTA objectives. I illustrate both the opportunities and the likely problems involved in steering technology development through CAD/CAM technology by means of

a brief case study: an ongoing attempt of aircraft designers to minimize the sonic boom produced by the High Speed Civil Transport (HSCT), a proposed commercial aircraft that would fly at supersonic speeds.

Localizing CTA Strategies

This paper constitutes a theoretical argument for localizing strategies to realize the social equity objectives of constructive technology assessment. The dual orientation of the CTA movement provides a mix of audiences for CTA theories and strategies. To have influence, these theories and strategies must be meaningful not only to CTA analysts but also to those involved in implementing CTA policies. Granting policy managers and recipients some authority over the content of CTA theories and strategies is an innovative move that generates new conceptual considerations. I would argue that CTA theories should be relatively easy for nonspecialists to understand and should have culturally positive significance. For example, the term "constructive technology assessment" indicates that the CTA movement wants to construct rather than destruct, and the term "modulation" suggests strategies for change in society that do not alter its fundamental character. In similar fashion, the conceptual objectives of CTA theories should include not only descriptive plausibility and explanatory power but also accessibility to nonspecialists and a supportive disposition toward stakeholders in areas of proposed change. If the implications were otherwise, constructive technology assessment might marginalize itself sufficiently to be ignored as irrelevant.

I do not consider developing a general theory of technology dynamics a necessary CTA objective. A theoretical implication of viewing technology as a social activity is that technology indeed becomes a social activity. That is, the value of technology-specific theory reduces as the focus shifts to account for heterogeneous social processes. This analytical trend appears to cut across the normative project of promoting equity, for the more usual strategy for cultivating allies in policy positions is by advancing theory that appears to be both systematic and predictive. It is difficult to posit heterogeneity and be systematically predictive at the same time.

The many models of technology dynamics that economists, sociologists, and historians have devised are enormously useful, for these provide taxonomies that help one to categorize and interpret case material. But models are context specific; they abstract bounded structures that do not apply equally to all cases. Developing a relatively

shared set of taxonomic categories can be important for integrating contrasting academic communities into the CTA movement, as has been the case for the rhetoric of selection and variation in the evolutionary model. But not only should such models be shaped so that nonspecialists can understand them easily, there is also no reason to expect an accumulated mega-model of technology dynamics, or even a set of sector-specific models, to generate more than some general categories of modulation strategies. The more difficult task, and the area in which CTA theory is least developed and most vulnerable, is to make these strategies work by sensitively overcoming local opposition and fitting them into local scenes.

Cambrosio and Limoges (1991) offer the interesting insight about technical controversies that each one establishes a unique "controversist space" within which decisions must be made in order to prove acceptable. In other words, the form and content of acceptable solutions vary from controversy to controversy. In similar fashion, I believe that implementation of CTA strategies is likely to produce many mini-controversies with controversy-specific solutions. Viewing CTA from the perspective of controversy theory, the types of theories that the CTA movement needs most to guide its strategies are "theories of acceptance," i.e., accounts of people and groups agreeing to follow CTA policies. Theories of acceptance are theories of actor interactions that can link models of technology dynamics to modulation strategies.

Several candidate theories are already in use, each with its special strengths and limitations. The Dutch hosts for the CTA workshop locate acceptance in a willingness to follow the rules and participate in strategic games (e.g., Rip and van den Belt 1988; Van der Meer 1983). Actor network theory portrays actants in power terms, locating acceptance in submission to occupy a place in another's network (e.g., Callon 1986). Social constructivism locates acceptance in a group becoming convinced by another's problem definition (e.g., Bijker 1987). Participating in recent developments in cultural anthropology, I view acceptance as varying according to the manner and extent to which some action reproduces or transforms the "positional identities" of participants in an interaction (e.g. Rosaldo 1989; Downey 1992a, 1992b, 1992c).

I use the concept of positional identity to characterize how cultural objects endowed with agency move themselves around in relation to other cultural objects by positioning and repositioning themselves. The term identity accordingly refers to the positional meanings and powers of cultural agents in relation to one another. Agents can be human or non-human actors, including groups, organizations, and

even technologies. The identity of any particular agent consists of its configuration of positions in relation to other agents, and the production of identity for an agent is simultaneously an attribution of meaning and an act of empowerment. For example, the CTA workshop and this volume produce a distinct identity for constructive technology assessment by positioning it in relationship to technology assessment, social impact assessment, science and technology studies, Netherlands Organization for Technology Assessment (which provided financial support), etc. In other words, CTA seeks meaning and power as an agent that extends far beyond the academic community. One pathway toward success would consist of agents from these other realms reproducing the same identity for CTA in their actions.

Each event of action raises a key question about positional identity: How does the event reproduce or transform existing positions and, therefore, power relations? Four different types of process occur regularly. A particular action may remake an existing identity by (1) fulfilling or reproducing some positions; (2) transforming some positions; (3) generating internal tension by reproducing some positions while transforming others; and (4) having no relevance to some positions.

A theory of acceptance built on the concept of positional identity focuses on the relation between who the agent *is* and who the agent *seeks to be*. From this perspective, accepting or rejecting a particular position is a choice about who an agent seeks to be, but the content of that choice also depends upon who the agent is. For example, gaining access to CAD/CAM technologies transforms users by empowering them with new agency, but the precise changes in meaning and power that occur depend upon whether the user already occupied the position of draftsman, design engineer, or manufacturing engineer.

But the implications of accepting or rejecting particular positions can often be unclear, for positional changes frequently produce tensions and ambiguities among the constituent positions of an agent's identity. The experience of change becomes an exercise in the management of tension and ambiguity. I show below that some CAD/CAM developments have been accepted readily because they empower design positions without restructuring the relation between design and manufacturing, while others have received varying levels of acceptance because they empower design positions at the expense of manufacturing positions or they produce tensions and ambiguities among the positions of design personnel.

Positional identity theory can be used in conjunction with other theories of acceptance to develop CTA strategies, for other theories

tend to pay attention more to agents' objectives—who they want to be—than to who they are when they define their objectives. But CTA theory must link the two in order to ground acceptable strategies, or risk offering recommendations for change that could prove unattainable because irrelevant. At the same time, a theory of acceptance built on positional identity is not simply a restatement of interest theory, which holds that who agents *are* causally determines who agents *want to be*, i.e., their interests. Interests indeed occupy the space between who agents want to be and who agents are (cf. Latour 1987:108), but who an agent wants to be must be determined empirically and locally rather than be predicted blindly from an analysis of who the agent is. Accounting for agency as a product of interests is a *post hoc* rationalization.

A Nationalist Script for CAD/CAM

CAD/CAM technologies produce new agency in design by linking together previously distinct design activities and concentrating them in fewer locations at earlier points in product development. Each CAD/CAM technology is produced by identifying the 'informational'[1] content in various engineering activities, transcribing that information into binary code, and then reinserting the resulting technology back into those activities. For engineers involved in product design, accepting the agency of CAD/CAM technologies into their working lives generally does not involve simply a shift "from board to scope,"[2] i.e., from drawing board to computer scope. It also means bringing together such activities as drawing, checking, redrawing, doing analysis, calculating sensitivities, building prototypes, and planning manufacturing operations. In the process, it frequently means transforming engineers' career identities and pathways in varying ways.

In the United States, one component of this identity change has clear national significance and legitimacy. Both insiders in CAD/CAM development and representatives of American government and industry have stabilized an image of CAD/CAM technologies as a key agent in solving a national identity crisis. Since about 1980, many Americans have felt themselves under attack by outsiders in a new way. The dominant image has been a nation put at risk by economic defeats at the hands of international competitors, especially Japan. Since the late 1980s, the belief that the military threat from the Soviet Union has been reduced dramatically has intensified attention to the economic dimensions of national identity.[3]

Reproducing a cultural tradition of defining and solving social problems in technological terms (Downey 1992b), Americans have turned to technology and technology-driven industry as strategic agents for achieving national regeneration and resurgence rather than re-evaluating and restructuring institutional forms more directly. From this perspective, other social adjustments, such as modulating relationships among government, industry, and universities, have then been proposed and accepted as necessary to fulfill the technological fix. That is, technological developments have themselves served as the source of legitimacy for social policies needed to adapt to those developments.

The concept 'productivity' is now linked inextricably with the empowerment of national identity. That is, economic productivity now serves as a major vehicle for national redefinition, granting power and authority to all those individuals and groups who successfully incorporate into their own identities the national quest for increased levels of production with improved quality at competitive costs. Americans' cultural understanding of their nation has been tied to their understanding of productivity, changing the meanings of both at the same time.

In the context of national crisis, CAD/CAM technologies gain agency as "productivity tools" and CAD/CAM vendors sell productivity. For example, the leading vendor in 1980, Computervision Corporation, published a 300-page handbook (Machover and Blauth 1980) detailing the potential links between the technology and increased industrial productivity. This highly popular book begins with a warning that "U.S. Productivity [is] Slipping," and an announcement from the Chairman of the Board that "a new technology has evolved which . . . will benefit all by improving mankind's standard of living and quality of life." "The technology is CAD/CAM," he proclaims, "and the benefit is increased productivity." CAD/CAM vendors have since repeated this message thousands of times.

If one extrapolates from vendor data, CAD/CAM technology appears to be enormously successful. For example, the major market research firm for CAD/CAM reported that between 1985 and 1988 the total number of computers worldwide using mechanical CAD/CAM, which is the major area of engineering application, increased by more than a factor of five (50,000 to 280,000 computers) (Dataquest Incorporated 1990). The company further projected that this number would nearly triple again inside four years. Clearly, something significant is taking place.

But the focus of nationalist agency also masks some important internal differences among CAD/CAM technologies. The technology that promised to save the American nation in 1980 was the integration of computer-aided design and computer-aided manufacturing, but CAD/CAM integration has fared poorly. As the nationalist script has been translated into localized searches for productivity, the determinist dream of CAD/CAM-induced integration has lost some of its rhetorical power. Rather, the development of CAD/CAM has produced technologies endowed with the agencies of different types of users, none of whom is oriented to uniting design and manufacturing. I believe that preoccupation with the image of a unified technological fix has inhibited insight into some of the more difficult power and identity issues raised by endowing CAD/CAM technologies with agency.

Waves of New Design Activities

By inquiring into how CAD/CAM technologies structure design activities,[4] I have discerned three different waves of development: (1) 2D drafting automation, (2) 3D wireframe and surface modeling, and (3) solid modeling. These waves have appeared and grown in roughly historical sequence, but they now travel concurrently. Not all organizations have experienced all three, nor necessarily in this sequence.

The first wave, drafting automation, shifts the engineering drawing process from board to scope. Engineers understand drafting as the process of producing detailed engineering drawings, which typically represent product parts in terms of 'views' in 'two dimensions', following mathematical rules of descriptive geometry. For example, an engineering drawing of a machine part might present how it looks from the 'top view', 'front view', and 'right side view' (e.g. Dent et al. 1983). The automation of drafting has been constructed on the image of a draftsman working at a drawing board, positioning 2D technology as a 'drafting tool.'

To the draftsman, designers, and engineers who do engineering drawing, automating the drafting process means replacing T-squares, triangles, compasses, French curves, and pencils with 'input devices' (e.g., keyboards, mouses), 'output devices' (e.g., printers, plotters), manuals for 'hardware' and 'software', and small screens for projecting images. Manually drawing points, lines, circles, and curves, becomes the manipulation of graphical 'primitives' and 'attributes' by combinations of programmed 'transformations' and 'control routines.'

By far the greatest proportion of CAD/CAM activities fall in this category.

Automated drafting is not positioned to fulfill the nationalist script of integrating design and manufacturing, however, even though it can increase dramatically the speed of repetitive tasks, such as making changes to drawings. Because 2D technologies are endowed only with the agency of drawing, their implementation does not reposition design and manufacturing activities in relation to one another. Rather, drafting automation tends to restructure relations on the design side alone between draftsmen and design engineers in ways that depend upon its local positioning. For example, 2D technologies can empower draftsmen by enabling them to appropriate some of the activities of engineers (cf. Hacker 1990:175-94), but also disempower draftsmen by forcing them to work nights and weekends and thus separating drawing activities from the weekday activities of design personnel (cf. Badham 1991). Finally, for CTA purposes, drafting automation is the least significant wave of CAD/CAM development, because shifting the agency of drawing to computer technologies does not position users better to introduce new design considerations.

The second wave of CAD/CAM development, 3D wireframe and surface modeling, transforms design activities in ways that open up the possibility of new design criteria, including CTA modulation. Key to this step is the shift from transcribing the agency of drawing to transcribing the production of geometric 'models' of discrete objects in three dimensions. What makes 3D graphical representations so significant is that these can be linked to other engineering activities that make up the design process beyond drafting.

A wireframe representation constructs an object as a collection of lines depicting the object's 'edges' (cf. Groover and Zimmers 1984:59-61). Picture, for example, a visual image of an automobile portrayed only by all the edges of its many components. A surface model represents an object as a set of curved surfaces. Picture the automobile now portrayed as a set of curved surfaces, perhaps with shading to give the exterior a sculptured look.

The major benefit of 3D models is that they add a great deal of engineering information to the representation (cf. Lynch 1988). Adding these different kinds of information is called 'doing analysis', which involves characterizing the object from the perspectives of different engineering sciences. For example, with a wireframe, engineers can view the object from any perspective and can use the point and line data to calculate the object's 'mass properties', e.g., volume, weight, center of gravity (location of the balance point) and moments

of inertia (a measure of how easy it is to rotate the object in different directions, e.g., it is easier to roll a car over sideways than end over end). The point and line data can also be used to inquire into whether particular components interfere with one another.

The surface model is much more complicated mathematically because in order to represent surfaces it translates geometric data about points into differential equations about curves and then links these differential equations together. The surface model requires far more calculating time on a computer, but it intersects with a large number of analysis activities that build on information about surfaces. For example, such engineering sciences as heat transfer (how objects respond to heating or cooling), kinematics (how moving parts interact with one another), and fluid dynamics (how air, water, or other fluids behave when moving) all depend upon differential equations representing surfaces.

CAD/CAM surface models provide a common judgement site for the different groups of people who generate drawings, produce engineering calculations, and make larger design decisions. Concentrating these activities in one place can thus have the effect of blending very different identities. Repositioning agents in design, however, also rearranges power relations, which in turn defines the implications of differing levels of acceptance. For example, Kenneth Reinschmidt (1991:5), an industry leader and keynote speaker at a vendor's annual meeting, argued optimistically that linking drawing and analysis is "consistent with the trends toward shallower organizational structures and matrix management," which attempt to reduce hierarchy by giving more independence and problem-solving authority to subordinate levels. But as he further points out without recognizing the irony, the typical decision-making process to take this step "is characterized by a desire to use CAD/CAM to effect change" and "using the CAD/CAM system to impose the design structure on the engineering process ... may imply some controlling function . . . " (Reinschmidt 1991:6).

In parallel with 2D technology, 3D wireframe and surface modeling are also not empowered to integrate design and manufacturing activities. Rather, by concentrating activities at an early point in the design process, CAD/CAM technologies are positioned to increase the influence of engineering designers in product development. The power of an engineering designer increases in proportion with each engineering capability added to the graphical image. As product development activities move 'upstream', so the identity and concerns of engineering design are extended 'downstream' into other areas.

The third CAD/CAM technology has been a much smaller wave of new design activities. A solid model represents the object as a solid,

using one of two methods. The first is called 'constructive solid geometry', which builds models by adding and subtracting 'primitive' solid forms, such as spheres, cubes, and rectangular solids. Picture, for example, a model of an automobile constructed of chunks of spheres and cubes. The second method, 'boundary representation', produces a surface by linking together surface models to produce a 'closed volume.' In this case, a model of an automobile might break it down into its many components, each represented as a closed volume.

Solid models are very useful for making sure that product parts have enough space after these have been designed, i.e., for 'interference checking.' However, solid models do not transcribe very extensively the activities of either design or manufacturing. On the design side, the geometric representations in solid models are very difficult to modify using the results from engineering analyses. On the manufacturing side, engineers who turn to computers generally seek help in monitoring, controlling, and supporting manufacturing processes, which involves relating objects to their changing environments rather than simply picturing and manipulating them. Thus far, since solid models have not been very useful in either design or manufacturing, they provide poor candidates for CTA modulation.

CAD/CAM and Aircraft Design

Design engineers understand 'design synthesis' as the process of conducting different forms of analysis simultaneously on a proposed design. Although design synthesis antedates CAD/CAM development, the capabilities of 3D surface modeling are giving it greater prominence. Design synthesis has its longest and most involved history in the aircraft industry, mostly because of the close relationship between the geometric form of an aircraft and its performance in different categories of aeronautical engineering analysis. As the design engineer Richard Boyles (1968:486-7) put it, "The influence of the geometric definition of the aircraft on the analysis conducted to ascertain its performance and, conversely, the influence of the analysis upon the geometry of the aircraft are so great that the interaction between the man, the graphic interface, and the analytical capability of the computer are maximized." As a consequence, aircraft design may provide a good location for testing the use of CAD/CAM to steer technological development. At the very least, aircraft design offers well-developed cases for identifying CTA opportunities, strategies, and implications.

Consider the negotiation of ACSYNT, a computer program for the conceptual design of aircraft. ACSYNT, which stands for AirCraft

SYNThesis, was written over a twenty-year period by engineers at Ames Research Laboratory of the U.S. National Aeronautical and Space Administration. During the middle to late 1960s, a number of aircraft companies, including Boeing, Grumman Aerospace, Lockheed California, McDonnell Aircraft, and North American Rockwell, developed their own synthesis programs to aid in the early stages of design. These programs and their successors are proprietary, however, and are not open to public scrutiny. Not only is ACSYNT more available, its development has become the object of a cooperative venture involving NASA, five aircraft companies (Boeing, Lockheed, McDonnell Douglas, General Electric Aircraft Engines, and Northrop), and CAD/CAM researchers at Virginia Tech. By observing and participating in the activities of this venture, the ACSYNT Institute, I acquired a fairly detailed understanding of the program and the groups linked to it.

NASA's statutory responsibilities in aerodynamics include examining advanced aircraft technologies and evaluating proposed designs for military aircraft that contractors submit to the Department of Defense. NASA evaluation teams are minuscule compared to the engineering staffs of contractors. Ames engineers initially produced ACSYNT during the 1970s as a resource to give themselves greater independence and control in examining technologies and comparing proposals.

The engineers categorize ACSYNT as an exercise in 'conceptual design', a phase of design activities that stabilized in the aircraft industry after World War II alongside 'preliminary design' and 'detailed design.' Conceptual design practices specify the vehicle's initial geometric configuration, size, weight, and performance characteristics. During this phase engineers consider a much wider range of alternative vehicle concepts than at any other point in aircraft development. In the aircraft industry, groups responsible for conceptual design are typically small and do not command a great deal of power and authority nor play a great role in making company decisions to build an aircraft.

The leaders of preliminary design groups have traditionally held the greatest power by far in configuring a design. As both aircraft company and NASA engineers explained to me in interviews, the companies subdivide the activities of preliminary design according to the major disciplines of aeronautical engineering, such as aerodynamics, propulsion, and structures, and a combination of organization-specific considerations. Each disciplinary area has teams of engineers that can number in the hundreds. Starting with a small number of alternative concepts, these teams conduct computer-intensive analyses of ex-

pected vehicle performance in each area and then negotiate a narrowing of alternatives down to a feasible design that group leaders find acceptable.

By the time the phase of detailed design is reached, the design concept is well entrenched and very difficult to influence further. Company engineers regularly joke about the build-up of 'momentum' behind a design. Activities in this phase provide detailed specifications of all vehicle components, plan and schedule construction activities, and set up relationships with contractors. Evaluations of the design shift from computer simulations to experimental efforts and wind-tunnel testing with mock-up prototypes.

The ACSYNT Institute includes 15 to 20 regular participants from industry, all engineers working in conceptual design. A primary goal of these engineers, both individually and collectively, is to increase the influence that conceptual design has on company decision making by appropriating for conceptual design some of the functions (i.e., the agency) of preliminary design. As one engineer said in an ACSYNT meeting, "We're trying to do with the computer what we can't do with our organizations."[5]

The conceptual designers are particularly interested in ACSYNT because in 1987-88 CAD/CAM researchers at Virginia Tech wrote a surface modeler and linked it to the analysis features of the program (Wampler et al. 1988). With this CAD/CAM interface or front-end, the conceptual designer can input a geometric configuration, ask what additions or changes might be necessary for the vehicle to meet some specified mission requirements, and then view a three-dimensional shaded image of that vehicle on the screen. Prior to having access to CAD/CAM visualization, engineers had to analyze large amounts of geometric data from each computer run in order to draw visual representations manually. Participants in the ACSYNT Institute believe that having the capability to quickly analyse and then visualize alternative designs will enable them to enhance their decision-making authority.

The ACSYNT program itself consists of approximately 50,000 lines of commands, or code, that divide calculations along disciplinary lines into 'modules.' For example, the aerodynamics module determines the minimum drag on the vehicle, while the propulsion module calculates the performance of different types of engines on the vehicle, and the trajectory module uses data from both the aerodynamics and propulsion modules to calculate the fuel weights needed during each phase of specified missions. Other modules include geometry, weights, stability, takeoff, cost, advanced aeromethods, and sonic boom. Each

module consists of detailed mathematical routines whose outputs vary with a limited set of input variables, or parameters.

Using the ACSYNT program transforms an initial geometric configuration by conducting and synthesizing several different forms of analysis. The synthesis process transforms the design in three steps: convergence, optimization, and sensitivity. I describe these steps briefly both to show that they constitute new mathematical methods for design decision making and to be able to illustrate the practical difficulties raised by attempting to minimize sonic boom in the High Speed Civil Transport.

Convergence refers to the production of a point design, which is a geometric configuration and a calculation of total gross weight that meets all the design constraints that the user inputs at the start. Garret Vanderplaats, at the time a NASA engineer heavily involved in ACSYNT development, applied ACSYNT to a "typical design problem" in an early paper (Vanderplaats 1976). The objective in this problem included estimating the optimum gross weight of a tactical fighter intended to fly a specified mission and figuring out what effects reducing gross weight by using more advanced materials might have on the vehicle's performance. Significantly, a limitation of ACSYNT is that it is only capable of analysing aircraft configurations whose geometries fall within the boundaries that define conventional fighter, bomber, and transport aircraft. In Vanderplaats' case, for example, it is "predetermined" that the vehicle will have a "conventional wing-tail configuration," which means no fancy geometries. Otherwise, the design will fall outside the envelopes of experience and theory that define the analysis routines. Also, this case included only five design variables: 1) wing loading, the amount of weight per unit surface area of the wing; 2) sweep, the angle between the wing and the fuselage; 3) thickness-to-chord ratio, the thickness of the wing relative to its average width; 4) aspect ratio, the tip-to-tip length of the wing relative to its average width; and 5) engine thrust, the amount of thrust per unit total weight.

Achieving convergence is tricky because it necessarily involves circular reasoning and depends upon prior experience. The two major contributions to gross weight are the combined weights of major components and the fuel. In order to calculate the amount of fuel needed, one must analyse the vehicle's performance along the mission trajectory that is planned for it (e.g., how much thrust is needed). But calculating how the vehicle will perform on its trajectory depends upon knowing the gross weight first. Also, the weights of various components (fuselage, wings, etc.) are calculated as fractions of gross

weight, so making absolute calculations of component weights also depends upon knowing gross weight first. As a result of this circularity, to calculate the gross weight of a particular geometric configuration that meets all constraints, one has to begin by estimating it. The program then assigns values to component and fuel weights, uses these to calculate how the vehicle performs, modifies the geometry to meet all design constraints, recalculates the weight based on the new geometry, and then modifies the estimated weight to start all over again. The iterative process continues until the calculated and estimated values of gross weight agree to one-hundredth of one percent.

Although proponents of ACSYNT claim that this level of tolerance is both good and sufficient, it has no particular meaning to aircraft designers. They must simply accept that the mathematics of convergence require it. In the case of the tactical fighter, locating a single geometric configuration that would meet all specifications, i.e., the 'converged point design', took 22 iterations and 40 seconds of computer time.

The second transformation, optimization, begins with the point design and then resizes the vehicle and its propulsion system to find the geometric configuration that both meets all specifications and has minimum total weight. As we shall see below, the vehicle could be sized to minimize or maximize other parameters as well, including perhaps CTA considerations. For aircraft designers, optimization involves even more opaque mathematics than calculations of convergence. Furthermore, many competing methods exist and the field of optimization studies appears to be changing rapidly.

ACSYNT uses the 'method of feasible directions', but no one in the ACSYNT Institute fully understands how it works. Rather most everyone invokes, both orally and textually, the authority of Garret Vanderplaats, who borrowed the method from a Dutch mathematician (G. Zoutendijk). Vanderplaats refers to Zoutendijk's work without presenting any of its details. Optimization methods are necessary because one cannot optimize a design by varying one parameter at a time. Parameters must be varied simultaneously, yet in doing so the process becomes opaque to intuitions based on graphical methods.

In fact, as Vanderplaats explicitly acknowledges, the most efficient optimization strategy directly challenges standard design practices. In transforming an acceptable point design to an optimized design, the method of feasible directions authorizes moves through intermediate steps that do not converge, i.e., that do not meet design specifications. That is, rather than moving step-by-step from an acceptable configuration to an optimized configuration, optimization routinely moves

through unacceptable configurations before reaching an optimal one. This makes no sense to designers who are always mindful of initial constraints. As Vanderplaats (1976:7) puts it, "this design procedure, using numerical optimization, represents a major departure from tradition conceptual design procedures." In the fighter example, Vanderplaats located the minimum-weight configuration with 102 iterations through the discipline modules and approximately three minutes of computer time.

In sum, integrating optimization methods such as ACSYNT into conceptual design activities means granting the mathematics of optimization and the mathematicians a place of authority. At the date of this writing, only one aircraft company uses ACSYNT in routine design activities, having integrated it long before the CAD/CAM interface was completed. At an Institute meeting in May 1991, Ames engineers and Virginia Tech graduate students began training industry engineers to use it with the interface.

Repositioning conceptual design can also bring with it reorganizing relations with entrenched groups and activities in preliminary and detailed design. One company member of the ACSYNT Institute has invested tens of thousands of dollars to demystify the mathematics by locating documentation for every mathematical calculation in the 50,000 lines of ACSYNT code. However, a wider acceptance of ACSYNT by conceptual designers could put them in direct confrontation with members of preliminary design groups. By contrast, conceptual designers at NASA-Ames need worry less about their relations with preliminary design since preliminary design is entirely an industry activity. Nevertheless, as we shall see below, the empowerment of conceptual design also introduces ambiguities for conceptual designers within the NASA organization.

An additional concern is that the mathematics of optimization tends to exacerbate errors within any given area of engineering analysis by bringing different areas of analysis into relation with one another. Vanderplaats (1976:7), for example, shows by checking ACSYNT against another aircraft program design that if the trajectory module underestimated the fuel weight by 10 percent the optimization "capitalizes on this error" and resizes the vehicle to reduce total gross weight by 25 percent. Recognizing that the credibility of design synthesis is threatened by the prospect of errors multiplying to produce unacceptable conclusions, Vanderplaats repeatedly reminds readers that "every effort should be made to ensure accuracy in the discipline modules or at least to ensure that the module information is slightly conservative" (1976:7).

But how are conceptual designers to know when their discipline information is conservative if they are exploring novel vehicle concepts? The answer to this question is to remember that ACSYNT's identity as a computer program is itself inherently conservative: the range of variation it permits is radically limited by the knowledge available about existing designs and by the choices among analysis methods it makes for each area. The only way to test ACSYNT is by using it to predict the characteristics of existing aircraft. ACSYNT documentation routinely claims, notably without detailed support, that such tests are consistently accurate to within 10 percent, but there is no way to test its reliability for new concepts. Also, virtually every analysis method in ACSYNT represents a choice among competing alternatives. Vanderplaats (1976:10), for example, shows how six different equations available in published and proprietary literatures for the relationship between aspect ratio and wing weight significantly contrast with one another. Each company has its own favorite equation, and choosing among them directly affects the optimization calculations.

The third transformation, sensitivity analysis, is much more meaningful to design engineers because it translates the results of optimization into a graphical form that they use routinely. Sensitivity analysis systematically varies a single design parameter to determine its effect on the total gross weight. Changes in some parameters, such as vehicle range, might have dramatic effects on weight while changes in others, such as tail length, might have a minimal effect. The results are plotted as a series of curves whose intersection defines the range of total weights possible. Sensitivity analysis is a strategy for ranking design considerations according to how "sensitive" the vehicle design is to changes in them. It is the most time-consuming of the three activities. Vanderplaats (1976:8) points out that in a typical analysis 20 to 30 hours of computer time would likely be used to determine the design sensitivity of variations in both the mission design and the technology used.

Minimizing Sonic Boom as a Design Criterion

Minimizing sonic boom has never been a significant consideration in aircraft design. In the design of supersonic military aircraft, environmental considerations almost never play a role. According to one NASA interviewee, designers of the SR-71 (a supersonic cruise reconnaissance aircraft, or spy plane) "worried about it" because the SR-71

needed to fly over U.S. land "but they didn't do anything about it."[6] Also, all American commercial aircraft fly at subsonic speeds. U.S. law prohibits commercial supersonic flights over land, with limited exceptions granted to the British and French Concordes. Since 1985, however, negotiations among the White House, NASA, Congress, and the aircraft industry produced a research program to evaluate the feasibility of a supersonic commercial aircraft, the high-speed civil transport (HSCT).

An earlier American effort to build a commercial supersonic transport (SST) was abandoned in 1971 after a prolonged controversy. The "controversist space" for decision making on the HSCT has not yet been defined fully, but this space certainly includes contemporary interpretations of the earlier SST controversy. A recent NASA program plan, for example, explains that the earlier effort failed "because of environmental concerns [sonic boom], economic uncertainties, and objections to government-funded prototype development" (U.S. National Aeronautics and Space Administration 1989:3). Program documents and interviews typically extrapolate from the SST controversy to add three new considerations. Two are additional environmental concerns: degradation of stratospheric ozone and increases in airport noise. Ozone degradation looms as the major barrier to overcome. The third is the overriding motivation to build an HSCT: nationalist fervor stipulating "that the nation cannot and will not allow [aeronautical] leadership erosion" (Executive Office 1985:1).

The White House Office of Science and Technology Policy first granted nationalist agency to the proposed supersonic transport through reports in 1985 and 1987 that defined goals and established initial plans. These actions shifted the burden to Congress, which directed NASA in June 1987 to "prepare a multi-year technology development and validation plan that will help the United States retain its leadership in aeronautics research technology" (U.S. Congress 1987:61). Each report highlighted European and Japanese threats to the United States' large trade surplus in aeronautics. NASA produced its plan in March 1988, identifying the HSCT as necessary to serve the rapidly growing trans-Pacific market (U.S. National Aeronautics and Space Administration 1988).

Before acting on this plan, a Senate committee acknowledged the potential of renewed controversy and sought briefly to map it out by sponsoring a workshop in May 1988 through the Congressional Research Service. The workshop provided a better forum for proponents than opponents, however, for it included ten participants from industry, three from government, five from universities, and one from an

environmental lobbying group. Workshop organizers outlined the major issues in a lengthy report in January 1989 (U.S. Congress 1989), after which Congress voted to support five years of research and technology validation. Over 70 percent of this support is devoted to ozone-related research while research on airport noise and sonic boom divide up the rest.

By seeking to integrate new environmental considerations into conceptual design, the high speed civil transport program faces a problem that closely parallels the normative project in constructive technology assessment. At first glance, an obvious local solution to this problem is to integrate the agency for calculating environmental effects into CAD/CAM-based activities during design synthesis. In other words, simply optimize HSCT designs for minimum ozone damage, minimum noise, and minimum sonic boom, and then do some sensitivity studies to minimize all three at the same time. However, following this course is not likely to occur, for empowering design synthesis in such a way would significantly transform the identities of conceptual designers within NASA.

ACSYNT provides the exception that illustrates the problem. The current caretakers and spokesmen for ACSYNT at Ames Research Center have recently added a new analysis module that makes sonic boom calculations. From the perspective of aerodynamicists, a sonic boom is the product of a pressure disturbance caused by an aircraft flying faster than the speed of sound. When the aircraft cruises at supersonic speeds, the disturbance propagates behind the aircraft, intersecting with the ground to produce a 'footprint' within which people will experience a sonic boom. Aerodynamicists describe the pressure disturbance as an 'N' wave, which consists of a sharp increase in pressure when the initial shock from the aircraft's nose arrives, followed by a linear decrease to below normal pressure, then another shock from the rear of the aircraft that restores normal pressure. The geometric configuration of the aircraft plays a large role in determining the actual magnitude and shape of this pressure wave. For aircraft designers, it thus appears possible to identify an acceptable pressure wave-form and then design a geometric configuration to produce it.

It is significant that ACSYNT engineers have not attempted to add analysis modules for calculating ozone depletion or take-off noise. In the first place, doing so would appear to other researchers as a strategy for restructuring power relations within the NASA organization. Engineers at NASA's Langley Research Center gained primary responsibility for overseeing the research by having positioned themselves as advocates of HSCT for over a decade. But granting Langley

engineers complete control over HSCT research would have empowered Langley Research Center at the expense of two other research centers, Ames and Lewis, and transformed the egalitarian relations that had stabilized among them.

Since Ames Research Center had long been positioned to do research on aerodynamics, some research groups at Ames acquired funds for research on sonic boom and on some general problems in atmospheric modeling. At the same time, ozone depletion and take-off noise are both linked to engine design, the technological arena within which the Lewis Research Center had been positioned but without making significant use of design synthesis. For synthesis experts at Ames, gaining formal approval to include engine design in ACSYNT would indicate that NASA headquarters had decided to empower Ames at the expense of both Lewis and Langley, allowing design synthesis to annex intellectual territory beyond aerodynamics, and reconceptualizing engine design according to methods used by aerodynamicists. In other words, including engine design in ACSYNT would be viewed as an attempt by Ames synthesis experts to impose their understanding of design problems on everyone else, which could position them in paradoxical ways. While such a move could reposition them into a position of power in HSCT research, it could also disempower them by suggesting they were not good NASA citizens. The outcome could be more likely to shorten their careers than win them new resources.

Furthermore, modeling ozone depletion and take-off noise in ACSYNT appeared less likely to produce results that relate geometric parameters to engineering analysis, and thus less likely to contribute meaningfully to conceptual design of the aircraft. Although atmospheric scientists have stabilized chemical descriptions of the reactions through which engine emissions deplete ozone, for engineers to translate these reactions into design criteria involves inserting the chemistry equations into highly simplified mathematical models of complex atmospheric systems. Judging the reliability of these models for design purposes is impossible without an accumulated body of experience. Take-off noise can be modeled more reliably, but the code that Lewis Research Center was using to model it suggested that the link between engine geometry and noise may be so complex that including calculations of convergence and optimization in ACSYNT would be too time-consuming.

Sonic boom presents the best-case scenario for CTA purposes, yet it also illustrates why using CAD/CAM to steer technology development also amounts to a political action in support of the mathematization of design. As the sonic boom module for ACSYNT stands at present, it

does not participate in the optimization process. It cannot translate an acceptable pressure wave, even if such could be identified, into an optimal geometric configuration. Rather, after determining a potential geometry-based configuration based on other constraints, the user can only calculate the type of pressure wave that configuration would generate. According to one interviewee, integrating the sonic boom module into the optimization process would be extremely difficult because it means solving "one of the most complex optimization problems that hasn't been done yet — shape optimization."[7]

Figure I: Two Sonic Boom Waves of Acceptable Loudness
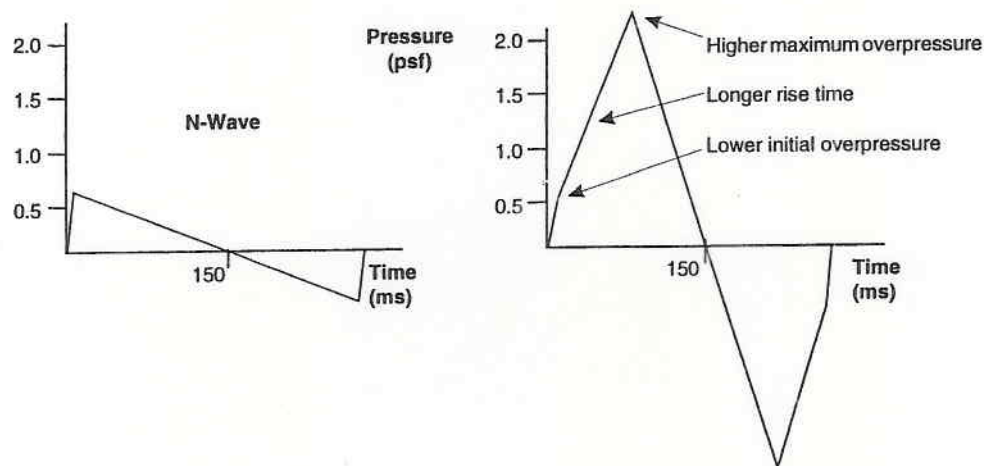
Source: Brown and Haglund (1988: 3)

The first difficulty in using the loudness of sonic booms as a design criterion lies external to the aircraft design process: how loud is too loud? After selecting some method of measuring noise from the more than ten alternatives available, design engineers must define a standard of acceptability. Langley researchers have been conducting 'human response tests' to develop proposed standards of acceptable loudness using dbA, or A-weighted decibels, which are calibrated according to the ear's changing sensitivities to different frequencies. A 1988 Boeing report used results from three such tests to identify 72 dBA as the likely highest acceptable loudness and its design goal (Brown and Haglund 1988:2). Researchers are acutely aware, however, that a new public controversy over the HSCT could affect significantly how different local groups might attribute acceptability. Four different variables in the pressure wave form contribute to its perceived loud-

ness, three of which can be translated into design variables for the aircraft's geometric configuration. Different combinations of these variables can produce the same decibel level and be judged equally loud (see Figure 1). The 'maximum overpressure' is the highest level of extra pressure produced by the wave, which is linked to the gross weight of the aircraft. Keeping a sonic boom below 72 dBA by reducing the maximum overpressure alone would likely require it to be no higher than 1.3 psf (pounds per square foot). But the Boeing report argued that for any "large commercial transport it is unrealistic to look at anything below about 2.0 psf" (Brown and Haglund 1988:3). The Concorde produces an unacceptably high overpressure of 2.0-3.0 psf.

Since reducing gross weight is not an option, designers turn therefore to relations between the 'rise time', the amount of time it takes to reach maximum overpressure and 'initial overpressure', or the pressure caused by the aircraft's nose. By reducing the initial overpressure and lengthening the rise time, one can actually produce a wave with a high maximum overpressure that sounds like a much lower-pressure 'N' wave.

Although the desired pressure wave can be translated into a point design, it is very difficult to transform this point design into an optimized geometric description. The reason for this is that the geometric form of the aircraft affects the pressure wave in two ways. The first is through its volume: a slender aircraft produces less boom than a fat one. The second is by the distribution of 'lift area', or bottom surface area: an aircraft whose bottom surface area is evenly distributed from nose to tail produces less boom than one whose surface area is concentrated along a small portion of the fuselage. The desired pressure wave can be translated into a combination of volume plus lift area that can be used to identify a point design. However, optimizing a configuration would involve separating these two aerodynamic variables, correlating each with geometry variables describing the aircraft's components (wings, tail, fuselage, etc.), and then relating the two back together. This problem pushes the field of design optimization past its current limits. The Boeing report points to this problem in lamenting: "At this point the design process becomes difficult . . . because there are a great number of possibilities and there are very few design tools available to aid in this design process" (Brown and Haglund 1988:7).

In the absence of a new technological agent that could accept responsibility for design decisions (i.e., optimization), decision makers have adopted different strategies, each balancing choices to link who they are to who they seek to be. For example, Boeing design engineers

offered a conservative solution: they simply selected a very conventional configuration and are perturbing it in small ways to reduce sonic boom. In this way, they can position themselves as leaders of a potentially successful project while posing a minimum financial risk to their company. NASA engineers are in some debate. Some endorse the industry strategy, thus positioning their organization as a research partner to industry and insuring its future stability. Others advocate a more radical concept, the oblique flying wing, which flies at an angle with the airflow rather than perpendicular to it, distributing lift evenly from the nose (one wing tip) to the tail (the other wing tip). Much more risky, this choice reproduces the dominant identity of NASA in earlier years as a producer of new ideas and technology through advanced scientific work.

Conclusion

The HSCT/ACSYNT example provides some clear insights into both the opportunities for steering technology through computer-aided design and the likely forms of resistance such efforts may encounter. Using CAD/CAM to achieve CTA objectives looks attractive because it can be applied at the earliest stages of the product design process. But even though the major features of a product may not yet be stabilized, the set and range of acceptable criteria for decision making typically are entrenched because design activities and design groups have become stabilized. Using CAD/CAM as a vehicle for introducing new agencies into design decision making does appear to allow the systematic introduction of some new criteria but only by restructuring local design activities and design groups. CAD/CAM technologies arrive not as a utopian technological fix but as waves of new, but structured, design activities.

It is important to keep in mind that CAD/CAM technologies possess the agency to affect design decision making most when they achieve reversible transcriptions between geometric models of objects and forms of engineering analysis. The first wave of CAD/CAM development, drafting automation, remakes two-dimensional drawing activities but not three dimensional design decision making. The third technology, solid modeling, fails to capture the activities of either design or manufacturing. Only in the second wave, 3D wireframe and surface modeling, is the technology achieving reversible transcriptions that restructure decision-making activities and permit the introduction of new design objectives.

Even wireframe and surface modeling, however, can only be applied to a subset of CTA objectives. Minimizing the environmental hazards of aircraft is a perfect case of using CAD/CAM to modulate decisions that affect the content of industrial products, i.e., of the objects modeled on the screen. But geometric modeling is not useful for formulating strategies to maximize levels of employment or quality of labor, objectives that pertain more to constructing manufacturing processes than producing designs.

The ACSYNT/sonic boom example shows that even though the agency in 3D CAD/CAM appears relevant to CTA product objectives, this strategy is likely to encounter at least two forms of resistance. In the first place, simply by introducing new design considerations, one injects an agency that has not been stabilized in design decision making. The design criteria for sonic boom have not stabilized, nor have those for ozone depletion and airport noise, for the controversist space for the HSCT has not yet been defined fully. Any attempt to integrate a specific criterion, such as Boeing's 72 dBA for sonic boom, becomes a politically controversial act of endorsement. The only solution for those representing new agency is to minimize the salience of this political act by considering alternative criteria acceptable to a range of participating groups.

Secondly, transcribing the agency of design activities into CAD/CAM technologies necessarily redistributes the agencies of existing human and nonhuman actors and, hence, the power relations among them. For example, not only does using CAD/CAM technologies empower design at the expense of manufacturing, it also redistributes the agencies of design engineers and draftsmen in ways that are highly variable and, hence, clear only at the local level. Thus, granting new agency to conceptual design through ACSYNT can have the effect of disempowering preliminary and detailed design. Members of the ACSYNT Institute are aware that some day they will no longer be able to characterize ACSYNT as simply a technology for conceptual design but will have to confront preliminary design directly.

Using 3D technologies for design synthesis and optimization is likely to prove most acceptable when applied to complex technological products, such as aircraft, automobiles, and ships. A wide variety of engineering disciplines inject their analyses into these product designs. A much more common occurrence, especially in smaller firms and less complex products, is the addition of information from only two or three different types of engineering analysis without any attempt at mathematically based optimization. A company might focus, for example, on fluid flow, heat transfer, or stress analysis. While

the actual sequence of design steps might be open to change through CAD/CAM, the criteria for decision making have stabilized around these limited analyses and are less susceptible to change. In such cases, second-wave CAD/CAM is making some inroads through 'parametric design', i.e., correlating geometry with one parameter at a time. But then integrating CTA objectives requires convincing engineers to use entirely new parametric design programs. The close cultural linkage between CAD/CAM and national identity may keep this approach within the realm of possibility.

A major lesson of this case is that achieving any CTA objectives, whether through the agency of technology or not, requires highly localized strategies, and identifying such strategies requires a theory of acceptance. Using the concept of positional identity leads one to inquire: In what ways does the introduction of new agency redistribute the agencies of interacting participants, including the agency of constructive technology assessment? In other words, it attunes us to recognize the diverse agencies in technology and other non-human actors without assuming that such agency always includes a desire to expand power and control. It instructs us to investigate not only who actors *are* but also who they *seek to be* in order to identify strategies that do not shift them into unwanted positions. In short, the acceptance of CTA strategies need not take the form of acceptance of a CTA political identity such that everyone need have the same politics. Rather, the CTA movement can be as diverse as the range of identities that may find in CTA opportunities to achieve locally desirable positions.

Notes

1. I use single quotes to denote native cultural categories and double quotes to denote direct quotations and my own analytic concepts.

2. Interview with Timothy Bischof, Design Engineer Trainee, Boeing Helicopter, Inc., Blacksburg, Virginia, April 20, 1987.

3. For examples of reports detailing economic risks to the American nation, see National Academy of Engineering Task Force on Engineering Education (1980), National Commission on Excellence in Education (1983), Council on Competitiveness (1988), National Academy of Engineering (1985, 1987), Shapley and Roy (1985), Prestowitz (1988), and Dertouzos, Lester, and Solow (1989).

4. Over a three-year period, I conducted over 600 hours of participant observation research.

5. Statement made at closed members' meeting, ACSYNT Institute, Blacksburg, Virginia, May 3, 1991.

6. Confidential interview, NASA engineer, April 8, 1991.

7. Confidential interview, NASA engineer, April 8, 1991.

References

Badham, Richard. 1991. *Computers, Design, and Manufacturing: The Challenge.* Canberra: Australian Government Publishing Service.

Barlow, M. Andrew. 1990. "Benefits of Solid Modeling." *MicroCAD News* (May): 20-24.

Bijker, Wiebe E. 1987. "The Social Construction of Bakelite: Toward a Theory of Invention," in: Wiebe E. Bijker, Thomas P. Hughes and Trevor J. Pinch (eds.). *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology.* Cambridge, Mass.: The MIT Press, 159-190.

Boyles, Richard Q. 1968. "Aircraft Design Augmented by a Man-Computer Graphic System." *Journal of Aircraft* 5 (September-October): 486-497.

Brown, Jessica G. and George T. Haglund. 1988. "Sonic Boom Loudness Study and Airplane Configuration Development." AIAA-88-4467. AIAA/AHS/ASEE Aircraft Design, Systems & Operations, Atlanta, Georgia (September 7-9).

Callon, Michel. 1986. "The Sociology of an Actor Network: The Case of the Electric Vehicle," in: Michel Callon, John Law and Arie Rip. *Mapping the Dynamics of Science and Technology.* Basingstoke: Macmillan, 19-34.

Cambrosio, Alberto, and Camille Limoges. 1991. "Controversies as Governing Processes in Technology Assessment." *Technology Analysis & Strategic Management* 3: 377-396.

Council on Competitiveness. 1988. *Picking Up the Pace: The Commercial Challenge to American Innovation.* Washington, D.C.: Council on Competitiveness.

Dataquest Incorporated. 1990. *Forecasts* (Mechanical CAD/CAM). San Jose, California: Dataquest Incorporated.

Dent, Joseph B., W. George Devens, Frank F. Marvin, and Harold F. Trent. 1983. *Fundamentals of Engineering Graphics.* New York: Macmillan Publishing Co., Inc.

Dertouzos, Michael L., Richard I. Lester and Robert M. Solow. 1989. *Made in America: Regaining the Productive Edge.* Cambridge, Mass.: The MIT Press.

Downey, Gary Lee. 1992a. "Agency and Structure in Negotiating Knowledge," in: Mary Douglas and David Hull (eds.). *How Classification Works: Nelson Goodman among the Social Scientists.* Edinburgh: Edinburgh University Press, 66-98.

Downey, Gary Lee. 1992b. "CAD/CAM Saves the Nation?: Toward an Anthropology of Technology." *Knowledge and Society* 9: 143-168.

Downey, Gary Lee. 1992c. "Human Agency in CAD/CAM Technology." *Anthropology Today* 8 (October): 2-6.

Executive Office of the President. 1985. *National Aeronautical R&D Goals: Technology for America's Future.* Washington, D.C.: Office of Science and Technology Policy.

Groover, Mikell P., and Emory W. Zimmers Jr. 1984. *CAD/CAM: Computer-Aided Design and Manufacturing.* Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Hacker, Sally. 1990. *"Doing It the Hard Way": Investigations of Gender and Technology.* Boston: Unwin Hyman.

Latour, Bruno. 1987. *Science in Action.* Cambridge, Mass.: Harvard University Press.

Lynch, Michael. 1988. "The Externalized Retina: Selection and Mathematization in the Visual Documentation of Objects in the Life Sciences." *Human Studies* 11: 201-34.

Machover, Carl, and Robert E. Blauth. (eds.). 1980. *The CAD/CAM Handbook.* Bedford, Massachusetts: Computervision Corporation.

Meer, Frans-Bauke van der. 1983. *Organisatie als spel: Sociale simulatie als methode in onderzoek naar organiseren.* Enschede, De Boerderij, TH Twente.

National Academy of Engineering. 1985. *The Competitive Status of U.S. Industry—An Overview.* Washington, D.C.: National Academy Press.

National Academy of Engineering. 1987. *A Technology Agenda to Meet the Competitive Challenge.* Washington, D.C.: National Academy Press.

National Academy of Engineering Task Force on Engineering Education. 1980. *Issues in Engineering Education: A Framework for Analysis.* Washington, D.C.: National Academy of Engineering.

National Commission on Excellence in Education. 1983. *A Nation at Risk.* Washington, D.C.: U.S. Department of Education.

Noble, David F. 1978. "Social Choice in Machine Design: The Case of Automatically Controlled Machine Tools, and a Challenge for Labor." *Politics and Society* 8: 313-347.

Prestowitz, Clyde V. Jr. 1988. *Trading Places: How We Allowed Japan to Take the Lead.* New York: Basic Books, Inc.

Reinschmidt, Kenneth F. 1991. "Engineering in the Future: CAD." *CATIA Operators Exchange* (Winter): 4-9.

Rip, Arie, and Henk van den Belt. 1988. *Constructive Technology Assessment: Toward a Theory*. Enschede: University of Twente.

Rosaldo, Renato. 1989. *Culture and Truth: The Remaking of Social Analysis*. Boston: Beacon Press.

Schot, Johan. 1991. *Technology Dynamics: An Inventory of Policy Implications for Constructive Technology Assessment*. The Hague: Netherlands Organization for Technology Assessment (NOTA). Working document no. 45.

Shapley, Deborah, and Rustum Roy. 1985. *Lost at the Frontier: U.S. Science and Technology Policy Adrift*. Philadelphia, PA: ISI Press.

U.S. Congress. Senate. Committee on Commerce, Science, and Transportation. 1987. *NASA Authorization Act, 1988*. Report, 100th Congress, 1st Session, on S. 1164. Washington, D.C.: U.S. Government Printing Office.

U.S. Congress. Senate. Committee on Commerce, Science, and Transportation. 1989. *Commercial High Speed Aircraft Opportunities and Issues*. Washington, D.C.: U.S. Government Printing Office.

U.S. National Aeronautics and Space Administration. 1988. *Civil Aeronautics Technology Development and Validation Plan*. Office of Aeronautics and Space Technology. Washington, D.C.: National Aeronautics and Space Administration.

U.S. National Aeronautics and Space Administration. 1989. *High-Speed Research Program*. Office of Aeronautics and Space Technology. Washington, D.C.: National Aeronautics and Space Administration.

Vanderplaats, Garret N. 1976. "Automated Optimization Techniques for Aircraft Synthesis." AIAA 76-909. AIAA Aircraft Systems and Technology Meeting, Dallas, Texas (September 27-29).

Wampler, S.G., A. Myklebust, S. Jayaram and P. Gelhausen. 1988. "Improving Aircraft Conceptual Design: A PHIGS Interactive Graphics Interface for ACSYNT." AIAA-88-4481. AIAA/AHS/ASEE Aircraft Design, Systems and Operations, Atlanta, Georgia (September 7-9).