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POSITION PAPER

Toward analysis tools for the engineering process

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1. THE PROBLEM: "DESIGN ENGINEERING PROCESSES AS ENGINEERING PRODUCTS"

Rapid development and delivery of high-performance, high-quality new products is the key to survival and success for many firms in today's high technology, global marketplace. However, shrinking time to market for complex, high technology products can be extremely difficult and costly. Even the most successful engineering managers have experienced the escalating costs of overtime, coordination and rework that are so common in fast-track, high technology, product development efforts; and they know the quality problems that can result when coordination breaks down in the face of aggressive—often "impossible"—development schedules.

Experienced engineering managers know intuitively that increasing product performance requirements increases subsystem interdependency and thus makes products more complex to design and manufacture. They also know intuitively that shrinking a product's time to market increases concurrency between activities in the design of the product and its manufacturing process, and can dramatically increase the amount of coordination that must occur between the specialists involved in designing, procuring, and manufacturing the product's subsystems. However, they have had no systematic analysis methods or tools to quantify the likely severity and cost of increased coordination, undetected or uncorrected errors, rework, or process quality breakdowns associated with critical engineering projects.

Designers of bridges, airplanes, engines, semiconductors, and other engineered systems routinely test "virtual prototypes" of the systems that they conceive, design, and manufacture. They have long had mathematical modeling tools, and more recently computational analysis tools, to model, test, and refine the design of their products. In contrast, managers of engineering projects have no way to pinpoint which subteams or vendors will be most severely impacted by the combination of escalating performance requirements and tight delivery schedules.

"Organizational (Re)engineering" is a buzzword that has been bandied about by management consultants during the 1990s. However, trial-and-error experimentation, adaptation of past organizational configurations, and consultants' intuitions, while potentially of some value, do not constitute a systematic engineering process. Systematic organizational engineering is impossible in the absence of reliable analysis tools that can be used to model and simulate the performance of "virtual prototypes" of alternative development work processes, organizations assembled to execute them, and information technologies available to facilitate decision making and communication among design team members. Yet this has been the state of the art up to now.

2. EMERGING ANALYSIS TOOLS FOR DESIGN PROCESSES AND TEAMS

Over the past 10 years, a growing group of engineering management researchers, interested in "designing organizations like bridges and airplanes" has begun developing modeling approaches and computer simulation tools that begin to allow managers of fast-paced product development products to "engineer" their work processes and organizations in the same way as they engineer their steel, composite fiber, silicon, and cellular products. The Mechanical Engineering Department at MIT and the Civil Engineering Department at Stanford have been two of the most active groups in this area. As a representative of the latter group, I can describe our approach and results to date, and suggest the likely directions and rates of progress in this field over the next decade.

The Virtual Design Team (VDT) research was initiated at Stanford's Center for Integrated Facility Engineering (CIFE) in 1989 and subsequently funded by two NSF grants (Levitt et al., 1994). The VDT research program at Stanford, borrowing from Engineering Management and Orga-

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nization Theory research done at MIT and elsewhere, has developed modeling approaches and prototype computational analysis tools for analyzing work processes, organizations, and communication tool suites in concurrent engineering design teams. The VDT approach and tools were first applied to the design of large, complex industrial plants such as refineries and power plants, and then generalized for aerospace, electronic, and other design domains. Inputs to VDT include (1) product, (2) process, and (3) organizational elements:

- product performance requirements and subsystem breakdown;
- planned development activities; along with their sequential, information exchange and failure propagation dependencies; and
- team members' skill and experience profiles; organization structure; management policies; and communication technologies available to the team.

Outputs of a VDT simulation are predictions of project duration, cost and process quality, and detailed predictions of work and communication backlog, error detection and correction, and numbers of communication failures for each project participant.

Using the VDT modeling tools a manager can thus model, test, and refine alternative "virtual product development teams." The manager can simulate execution of the project with different product performance and quality levels, more or less aggressive delivery schedules, team members with different skills and experience, different organization structures and policies, and alternative communication technologies such as project intranets. By testing many alternative product and team configurations, the manager can gain new kinds of insights about the trade-offs between product performance levels and quality versus time to market, required human resources and product development costs. This allows the manager to plan for and control development team performance, and to optimize the project's competitive market position based on relative priorities for product performance levels, time, and cost.

Results from the application of VDT to date are encouraging. Validation has proceeded from post hoc agreement, through *a priori* prediction and confirmation of results. VDT is currently being used as a planning and control tool to guide organization design and management interventions in a satellite design project at Lockheed Martin (Jin & Levitt, 1996).

3. LOOKING AHEAD: CHALLENGES AND OPPORTUNITIES

It was no accident that we and other researchers interested in this area picked engineering design projects as a starting point for the development of organizational analysis theory and tools. In this kind of organization, goals and means are both well understood and agreed upon. And one can usually assume relatively high levels of goal congruence and motivation for the engineers involved in such projects, especially when contrasted with participants in organizations with less goal and means clarity, like educational or social service agencies, which have been the focus of most organizational research to date. VDT chose to model large and complex, but relatively routine design projects initially.

In this well-structured domain, we were able to make accurate predictions and generate quite detailed prescriptions based on a pure information processing capacity analysis. This allowed us to limit our modeling framework to activities with only slightly more than CPM/PERT attributes, and to simulate only relatively simple information processing and communication behaviors for our organizational participants or "actors." The relative parsimony of our initial VDT models is attractive from a theoretical and a practical viewpoint.

However, as we branch out to less routine design domains in civil engineering, aerospace and electronics, and toward enterprise models in fields like health-care maintenance, we find that we need to model planned and contingent activities with more specific content, and we must endow our computational organizational agents with knowledge about how to create and link contingent activities, how to select and connect project participants into the team, and how to assign activities to them in a reasonable fashion. Similarly, as we model aerospace or construction organizations that are attempting to be more agile by outsourcing much of the design and manufacturing, we need to consider goal incongruity between actors, and its effect on actor behaviors. Economic theory of agency suggests monitoring, reporting, and incentive contracting behaviors that we are attempting to incorporate. And so on. The result is increasingly complex models with progressively more opaque behavior.

Clearly, we will need to simplify our models. At the same time we need to retain the most theoretically important and practically valuable abstractions in doing so. My view is that researchers in this area now urgently need to work closely with industrial partners who are willing to be early adopters of these "engineering enterprise analysis tools," to explore the availability, reliability, and "value in use" of different kinds of model inputs and system outputs.

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