CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Management and Leadership Education for Civil Engineers: Teaching Virtual Design and Construction for Sustainability

By

John Kunz, Raymond Levitt, and Martin Fischer

CIFE Working Paper #WP 079

September 2003

STANFORD UNIVERSITY

Copyright © 2003 by
Center for Integrated Facility Engineering

If you would like to contact the authors, please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
Terman Engineering Center
Mail Code: 4020
Stanford, CA 94305-4020

Management and Leadership Education for Civil Engineers: Teaching Virtual Design and Construction for Sustainability

John Kunz, Raymond Levitt, Martin Fischer

Center for Integrated Facility Engineering and
Department of Civil and Environmental Engineering
Stanford University

Abstract

We assert that the critical leadership role for Civil Engineers now is to develop and apply meaningful metrics and processes for creation, use and stewardship of the built environment, in a way that is sustainable across space and time. We set out a broad definition of sustainability, and describe a novel design process for creation of engineered systems using integrated, multi-disciplinary computer-based virtual models. *The big idea in this paper is that Civil Engineering educators should teach leadership in sustainable development of the built environment using new integrated, multi-disciplinary computer-based virtual performance models of engineered systems, using a pedagogical method and curriculum that emphasize: multi-disciplinary theory, work with real projects as part of the university laboratory and studio teaching experience, explicitly recognize the interrelated methods of science, engineering design and policy, and use multiple and integrated computer models, simulations and visualization tools.*

Keywords: Virtual Design and Construction (VDC); Management; Leadership; Education; Sustainability, Extreme Collaboration

1. Introduction

This section introduces two examples of the big idea in practice: the first from the space exploration industry and the second from our university research and teaching practice. They show how virtual models, integrated analysis tools and visualization can support extremely fast development of sustainable multidisciplinary designs.

1.1. Example-1: space mission design

The Jet Propulsion Laboratory (JPL) of the California Institute of Technology now uses "Extreme Collaboration" as a method to do conceptual and early detailed design of complicated space missions [Mark 02]. Sitting in a room with a set of desktop computers, a shared database and three large displays, a team of eighteen engineers, a customer and a facilitator work together to design space missions. In one week, they do the schematic and initial detailed design of the vehicles to execute those missions, and for each, a set of subsystems including telemetry and ground support, supporting systems such as project management plan, cost estimations and schedules. The Laboratory has used this extreme collaboration for hundreds of designs over nearly a decade.

1.2. Theoretical frame to describe Example-1

Theoretically, extreme collaboration includes a number of factors. To the Civil Engineering observer, it is striking that response latency – the time between the initiation of an inquiry of another design member and the response to that inquiry – is just a few seconds. The best

Architecture-Engineering-Construction (AEC) design projects normally achieve a response latency of a few days. To exploit this three order of magnitude reduction in latency, the team changed the design process from a series of related tasks done by largely independent parties over a period of months to a set of meetings of an experienced cross-functional team done over a few days within one calendar week. The extreme collaboration method includes a clearly defined generic product model built with well-defined conceptual content and vocabulary and containing some 2000 parameters, about 1500-1600 of which apply to any particular design. The team has highly developed modeling and analysis tools for each of the engineering disciplines (called "positions" in the design room), which are linked to the shared product model and that populate the shared model. The model represents the scientific and economic functions specified by the project customer, the designed forms and the predicted behaviors created by the design team. The model and the modeling tools explicitly describe the product (the spacecraft and its systems); the organization doing the work; and the design, manufacturing and operations processes. The design task is complicated, but not novel to the participants. Individual design tasks (vehicle design, propulsion design, etc.) have reciprocal interdependencies [Thompson 67] that are well understood by the team (which has considerable experience working together), but that nevertheless demand regular face-to-face interaction to resolve.

The meeting room has three projectors, each of which can project the screen display of the workstation of any selected position. Normally, one screen shows a 3D model of the vehicle, a second shows a portion of the shared project model, and a third shows changing views of the project design. The meetings have a facilitator, who generally guides the engineers working at the different positions. While the design session progresses under the guidance of the facilitator, the engineers often spontaneously form small "sidebar" meetings within the big meeting to discuss and resolve shared issues. The productivity is dramatic: within a few weeks, the team creates, documents, presents and delivers the multi-disciplinary schematic and initial detailed design of a space mission. The local market validates the effectiveness of the process: Internal and external customers have bought hundreds of these designs over nearly a decade, although customers have alternative ways to obtain designs.

1.3. Example-2: a hospital design-construction project

Our own work concerns developing the theory of Virtual Design and Construction and teaching it to Civil Engineers in the university. *We define Virtual Design and Construction (VDC) as the use of multi-disciplinary performance models of design-construction projects, including the Product (i.e., facilities), Design-construction-operation Organization, Work Process, and Total Economic Impact (i.e., the combination of both cost and value of capital investments) to all stakeholders (i.e., explicitly considering the politics of cost and benefit imbalances among stakeholders—a messy problem that most engineers would rather ignore).*

During this past year, a general contracting company offered an innovative project for the VDC student team. The four-person Stanford class team met with company representative to discuss the VDC process and to set the scope for the project. The project focused on a "template" hospital project being developed for a major health care provider.

The project aims to build a set of hospitals over the next decade using a single innovative template design. Therefore, the critical engineering problem the Stanford team focused on was the use of VDC tools to remove some of the uncertainty in the project schedule duration and to identify ways to improve the overall schedule for the template hospital.

Figure 1 – *3-D Product Model*

At the mini-internship project-scoping meeting, the team met with the contractor project manager and a team of five other stakeholders. The team decided to focus on schedule issues associated with the initial construction phases to compare alternative building methods. The team built 3-D product models (Figure 1) to represent key construction activities in these phases. The team then imported the process model into an organization model (Figure 2) to simulate and predict schedule length and schedule growth for the alternative construction methods.

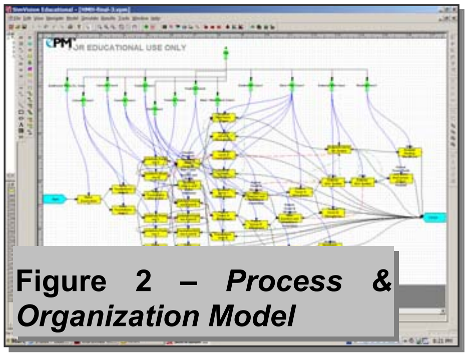

Figure 2 – Process & Organization Model

Finally, the team built 4-D production models (Figure 3) combining the product and process models for the various construction alternatives. The VDC models that the team created provided an integrated view and enabled the team to identify risk areas and relative durations for the proposed construction alternatives. The mini-internship team met with the contractor to discuss the VDC modeling results. The stakeholder team found significant value in the VDC models that enabled them to simulate the project "virtually" to predict schedule risks and durations for construction alternatives before construction begins.

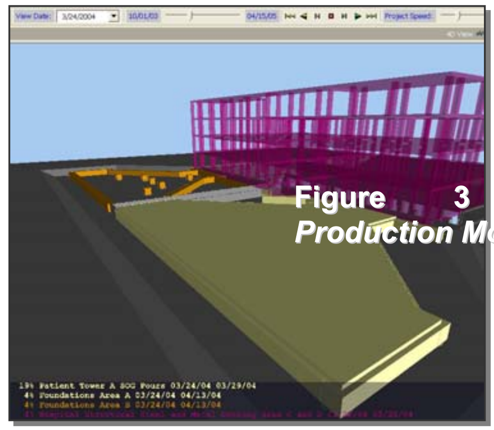

Figure 3 – 4-D Production Model

1.4. Theoretical and pedagogical frame to describe Example-2

Pedagogically, most VDC students started the ten-week VDC class knowing of neither the theoretical vocabulary of VDC nor any of the computer tools. Using lectures, class discussions and laboratory sessions, the first five weeks gave them novice capabilities in each. The class had a project, such as the one reported in this section, in which students met with corporate sponsors, built and analyzed models of the product, organization and process, and repeatedly presented their models and analysis to the class in the CIFE iRoom [Johanson 02, http://www.stanford.edu/group/CIFE/IROOM/] and in homework submissions. They then spent four days in a design charrette over Spring break working with the partner sponsoring companies.

The charrettes enabled participating companies to propose an engineering problem that could benefit from analysis with 3D, 4D, and other virtual design and construction technologies. A group of Stanford students worked on the problem with VDC tools as their project during the winter-quarter VDC class. The group then visited a site of the member company for four days over spring beak. The visiting student team explained its use of VDC methods and its approach, then worked collaboratively with company engineers to develop a second approach. Finally, the group and the company engineer discussed their use of VDC methods on the company problem. The four student teams were invited to present their work to a total of over two hundred fifty representatives in the four sponsoring companies.

1.5. Relationships of the two examples

Theoretically, VDC includes a number of factors. The rationale for building the VDC model is the observation that a contractor surely cannot build a project in practice if it cannot build a model in the computer, and the converse observation that if it is comparatively easy to build a complete project model, which we find that it is, the actual design-construction might learn something useful, which again we find that it normally does.

The JPL design meeting room and the CIFE VDC class use similar interactive multi-screen meeting rooms, which appear to be useful may be critical parts of the extreme collaboration method that both projects used. The JPL space mission project meeting room has about two dozen computer workstations, each networked together. The room then has three projectors to show the screens of selected computer workstations. Meeting participants view all three displays simultaneously. The CIFE version, developed independently based on initial work of the Stanford Computer Science Department, again has three screens with projectors connected to separate workstations [Johanson 02]. We call the CIFE facility an "interactive room" or iRoom, because it has touch-screen display panels and, like the JPL room, designers and engineers interact with project models in the display environment (http://www.stanford.edu/group/CIFE/IROOM/). Both the JPL and the CIFE rooms have networked workstations and the ability to create and display a shared project model. We characterize the iRoom as providing "view" and "glue" – view in the sense of multiple simultaneous views of an integrated project model, and glue in the sense that the parts have software linkages to allow data sharing and certain cross reference capabilities.

VDC, by definition and practice, models the design of the Product, the Organization and the Process (as in Figures 1 and 2 above) and uses these models for direct description (as in Figs 1-3), simulation (Figures 2, 3) and animation (Figure 3). The models create an explicit multi-disciplinary model of the project, which is descriptive and normally has a visual interface. The model represents the intended function, designed forms and predicted and observed behaviors of the project. The models support description, evaluation, explanation, prediction, analysis and negotiation for multiple stakeholders. We model and analyze the total economic impact, including both predicted costs and value, of technology investment. We do all of the modeling and the management of the actual design-construction process using explicit and measurable business objectives, considering the product, the design-construction process and the small number of factors that individual project managers can control.

Although there are differences in the product being designed (space mission vs. hospitals), there are great similarities between the JPL and Stanford examples.

- **VDC examples**: The definition of VDC applies well to both, which we quote at the beginning of this section. The differences in product, organizations and processes suggest the generality of the VDC perspective.
- **Task properties:** both tasks involve multi-disciplinary engineering design and analysis, significant but not novel complexity, reciprocal relationships among tasks (i.e., requiring close collaboration to resolve issues), significant requirement for coordination and rework, existence of initial functional requirements and a theory and practice of engineering design that normally can address those requirements effectively.
- **Team composition:** Teams had participants whose skills included all the cross-functional skills necessary to do the intended work at the intended level of detail, but not all the work that eventually needed to be done. The team members had high team experience, i.e., had shared vocabulary in detail and understood a shared method of operation.
- **Short schedule:** Cross-functional design teams worked quickly – about a month with a budget of about 500 total hours for the JPL case; about a month with slightly over 100 total hours for the Stanford case.

- **Intense collaboration:** Teams did most of their substantive work in intensive meetings over a only few days (three at JPL, four for Stanford). Teams were fully available for design meetings and attended; they were at least 50% available during the remainder of the design activity.
- **Short latency:** both teams did their important work in team meetings in which response latency was seconds.
- **Work scope:** Teams started only with a general specification and created approximately 50% detailed designs.
- **Multi-display iRoom:** Both teams used a multi-display iRoom and produced a documented design as a deliverable.
- **Good software:** Both teams had appropriate modeling, analysis and visualization tools that the responsible parties could use well; in neither case were tools highly sophisticated.
- **Visual representations of models:** both teams created and presented visual models of most of the disciplinary views of their designs, including 3D product models, and other visualizations as appropriate. Some of the visualizations were static; some were animated (spacecraft trajectory at JPL; 4D construction for Stanford teams).
- **Symbolic models:** the fundamental deliverables of both teams were documented descriptive computer-based models of the product, organization and processes (in an Excel spreadsheet at JPL, in native software applications for the Stanford teams).

2. Context for management and leadership education for Civil Engineers

We define sustainability as follows:

> *Sustainability is the ability of developers, users, communities and societies to continue engaging in current behaviors and practices, given predicted rates of change in the demographics, economic and social costs of resources, objectives of developers, the community and society, and the carrying capacities of ecosystems.*

With this definition, assuming that Civil Engineers will have leadership roles in advancing our world toward sustainability of the natural and built environment, it is understandable why management and leadership education for Civil Engineers is difficult. The current practice of employing relatively high-energy intensity materials and processes for construction and operation of built structures is not sustainably scalable if applied worldwide for the next few decades. The current practice of intense, and predominantly single, use of water in agriculture, industry and housing in California may not be sustainably scalable even in California, even for the next few decades. "Water wars" have been part of California history for two centuries. Some already say that "energy wars" have become too common.

The social, scientific, and engineering definitions of sustainability are all subject to interpretation and ambiguity. Sustainability ultimately must be understood at multiple levels: at the molecular level of physical, chemical and biological mechanisms and the micro-level of social mechanisms; at the meso-economic and organizational level of resource-constrained project design; and at the macro-economic and political levels of the region, nation and world. At the mechanism, project and Political-Ecological-Social and Technology (PEST) levels, the factors of sustainability are inherently multi-disciplinary and political, involving many stakeholders with different values. Finally, the interactions between the mechanism, project and macro levels are unclear and subject to interpretation for scientist, engineer and policy-maker alike.

Engineers have used virtual methods to design structural systems, such as bridges, for decades. The good news is that modern virtual modeling, simulation and visualization methods now allow engineering of the product, organization and the process that together create the structures of the built environment. Thus, we can engineer the product, organization and the process just as we engineer bridges. We can now build on scientific theories, systematic implementations of those theories in the computer, and formal repeatable testing of our processes and organizations as well as our products.

One of the realities of sustainability is that it is both a multi-dimensional and a time-varying issue. We look at sustainability as a problem of Pareto optimization. In principle, we (scientists, engineers and policy-makers) can identify a set of factors, quantify their significance at a moment in time, somehow attend successfully to the most significant, and watch sadly as some new factor emerges as the most important one.

Our goal for Management and Leadership Education of Civil Engineers is to teach them to see sustainability as a Pareto optimization problem. They need to learn to identify the factors that define broad geographic and long term sustainability, quantify their significance to a broad set of stakeholders, and make progress with the most important factors, without making others significantly worse. Thus, our objective is to teach the process of developing the structures of the built environment in such a way that our students can evolve the way they apply these methods as they advance through their careers and as there is evolution in the political, engineering, social and technical milieu in which they work.

3. Dialectics

Design inherently involves tradeoffs among mutually contradictory factors, at least among scope, cost, schedule and quality; and often designers choose to consider these factors at multiple levels of detail. Design of structures for the built environment requires such tradeoffs, as does design of a curriculum for leadership and management. When there are many factors to consider in a decision, we think it a service to students and ourselves to recognize some of the dialectics and to use the contradictions among factors to help elucidate and teach respect for the factors themselves. This section introduces some of the dialectics that we try to respect, keep explicit and simultaneous in our work, learning from the contradictions and not dismissing the methods that produce the perspectives that contradict our own.

- *Studio vs. real-world laboratory experience:* Architecture traditionally teaches design using classroom laboratory “studio” experiences. Students are asked to design a realistic project, but in the pure studio, they do work at a jobsite. Another option is to ask students to do projects in the messy, confusing, and time-pressured real world. Each has pedagogical advantages and limits. We find that the studio teaches students methods and approaches, internships and field experience teach reality. Professional mentoring in a studio experience brings some reality but retains more control over the process and the environment than the field experience allows. We find that the best students have both kinds of experience; they need to experience both the independent freedom of the studio and the messy reality of the real world.
- *Hand-sketched graphic vs. virtual or physical models:* Designers often sketch; they often build physical models, in clay or cardboard or other media. We encourage out students to develop some understanding both of how to understand and how to create sketches and physical models. Our judgment is that the computer-based virtual model, analysis and visualization should be the major focus of our teaching of both theory and practice as this is the theoretical framework that is both most difficult to get in practice (i.e., highest differentiated value-adding role for the university) and the most relevant method for many future professional designers.

- *Method of science vs. engineering vs. policy:* Sustainability is an issue at the levels of the broad political-economic-social-technological world, the project and the theoretical mechanisms of action. The public policy specialists, designers and engineers, and scientists are the principal creators of sustainability at these different levels, and all of them must work with the owners of and stakeholders in new projects. No one individual or discipline can function effectively without others. It is easy for an academic department or special interest group to dismiss any of these methods because it draws scarce resources and attention from a favored method. Civil Engineers need to understand that the scientist, engineer-designer and policy maker are all stakeholders in sustainable design. Our pedagogical approach is to attempt to bring all these methods under the umbrella of Civil Engineering, to teach all these methods, and to make the contradictions between their methods, findings and recommendations explicit for the students, each other and the world to see.

3.1. Curriculum in Virtual Design and Construction

What if you could design your next construction project – including the Product, Process and Organization – as engineers design bridges: in the computer? Do you want to visualize your project and make predictions before you spend significant amounts of effort, time or money?

The Stanford Virtual Design and Construction (VDC) curriculum, newly available both to matriculated and professional students, teaches the theory, methods and hands-on skills to do project design in this way, which is so familiar to design engineers of physical systems. The method uses the same process as the extreme collaboration method, applied to the AEC industry.

Virtual Design and Construction is the use of multidisciplinary performance models of design-construction projects, including the Product (i.e., facilities), Work Processes, and Organization of the project. You can now use VDC methods and tools to model the project design, construction, operation, and political, social and economic impact (i.e., model of both cost and value of capital investments to their multiple stakeholders) in order to support business objectives. The VDC certificate program includes an introductory Summer Program in VDC offered by Stanford's Center for Integrated Facility Engineering (CIFE), together with three integrated classes that introduce students to VDC theory and practice. Students will develop hands-on competence to model, visualize, describe, make predictions about and evaluate the product, process and organization designs of projects. Specifically, students will learn to use the following kinds of tools: 3D CAD, project process planning and cost estimation, organization analysis and 4D (3D plus time) animation.

The curriculum includes four classes, described below.

The objectives of this set of classes are to enable individual participants and project teams to:

- Understand *at a practical level, the theory behind virtual design and construction methods*
- Recognize *the capabilities, limits and potential of specific VDC technologies*
- Use *4D and other project visualization methods on their projects*
- Assess *the relative value and costs of technology investments*
- Evaluate *current VDC research for future AEC industry application*
- Set *specific measurable business and engineering objectives for using VDC*
- **Demonstrate** *the ability to apply the methods of VDC in their own practice*

Introduction to Virtual Design and Construction: principles of 4D and beyond – introduces emerging research and commercial developments that provide a new vision of design and construction integration. Intended for professionals, this class introduces integrated computer design and analysis tools that now have started to allow the unexpected: allowing designers and constructors to be able to cross-reference functional, architectural, plumbing, electrical, mechanical, personnel and financial concerns before breaking ground. Participants learn how virtual design and construction technology can save you time and money: by anticipating design risks, avoiding scheduling nightmares and by averting construction problems before they arise.

Techniques of Project Planning and Control – Intended for matriculated students and professionals, this class introduces fundamental concepts of project planning and control, current and future project information management technologies, and project planning and control systems at the firm and project levels. Topics include cost estimating at the conceptual, schematic, detailed and bid stages; measurement and pricing of work; specific techniques including CPM, PERT, Line of Balance; resource allocation and project control; supply chain models; treatment of uncertainty. The class emphasizes the integration of project planning and control methods and tools in the context of integrated Virtual Design and Construction models. See http://www.stanford.edu/class/cee241/.

Organization design for Projects and Companies – Intended for matriculated students and professionals, this class introduces the theory of organization behavior and its application in Civil Engineering. Topics include contingency theory of organization design for projects and companies, computer-based organization modeling and analysis tools, and case studies that focus on facility design and construction organizations. Concepts are applicable to project-focused teams and companies in many industries. The class discusses integration of organization modeling and analysis methods and tools in the context of integrated Virtual Design and Construction models. Groups of twelve students practice running problem-focused meetings. There is one case study per week outside class.

Virtual Design and Construction – Intended for matriculated students and professionals, this small laboratory class explores use of virtual (computer-based) models in building design and construction. The class introduces the theory and methods of VDC. It includes a laboratory experience to teach the tools. Assignments and a class project help students learn to integrate the description, prediction with and explanation of different models. Successful class participation may allow students the opportunity for a 4-day mini-internship at an AEC company over Spring break. See http://www.stanford.edu/class/cee143/.

4. Research and pedagogical goals

We can identify a set of research and pedagogical goals related to the topic of management and leadership education for civil engineers, and teaching virtual design and construction for sustainability.

We can identify specific research goals for the public policy, design and scientific communities with a stake in sustainability:

- **Performance-based design criteria for sustainable engineering:** because the factors of good design, construction, operations and sustainability vary by project, region, and time, it is valuable to set appropriate measurable objectives for facility development and sustainability, and to create public econometric models that relate the multiple conflicting objectives, e.g., between social desirability of specific outcomes, cost and time both to implement interventions to the design process and to experience benefits of improved cost, duration, functional quality for users and sustainability.

- **Practical methods of analysis for designers to consider project performance:** individual designers need analytical methods, which can be validated by trustable independent bodies, to use to predict project performance behavior, including design-construction duration, design-construction and lifecycle dollar and social costs, quality, risk and sustainability of alternative designs. In addition, they need procedural methods to manage the multiple conflicting goals of projects.
- **Novel mechanisms to improve sustainability:** new chemical and molecular mechanisms are needed to improve usage of the many types of energy and materials found in Civil Engineering projects.

4.1. Measures of pedagogical success

For both our matriculated university students (undergraduate and master's level) and professional students, we have a clear set of measures of success:

- *Demonstrated ability to apply product, organization and process modeling and analysis methods on a real project:* We want students to demonstrate their ability to use the major VDC modeling, analysis and visualization methods effectively and quickly on a real project.
- *Understanding of the theoretical vocabulary of VDC:* We describe models of products, organizations and processes using a specific theoretical frame of reference. This vocabulary includes concepts such as project, product, organization and process models; sustainability; mechanism; project scope, time and cost; unit and take-off based cost estimation; micro-behavior; function, form and behavior; stakeholder; predicted and measured performance; description, analysis, prediction, evaluation, explanation, negotiation; total economic impact; business, process and controllable objectives; plan and schedule; object; activity; validation methods; Level of Detail; VDC; Levels of VDC, etc. We expect that students will be able to define these concepts precisely, identify their occurrence in traditional and VDC visualizations of project designs, and understand their importance to the practice, science and policy of VDC.
- *Ability to use specific VDC tools:* While the lifetime of any version of any particular software tool is typically less than a year, we want students to able to create level-1 (coarse) and level-2 (first level of elaboration of detail) of products, organizations and processes, using a 3D CAD, organization and process modeling software tool.
- *Ability to present an integrated VDC design in a multi-screen visualization environment:* We expect that students should be able to both create individual models and relate them to an overall design, and explain individual models and an overall design using a multi-disciplinary visual presentation environment (we currently use the CIFE iRoom:).

4.2. Changing Elements of Sustainability

The most critical elements of sustainability, under the broad definition of sustainability that we are using, will change over time. In the last ten years the issues broadly viewed as being the most critical to sustainability of economic development of all kinds have been limiting energy use, water use and greenhouse emissions to globally sustainable levels. More recently security against terrorist attacks has emerged as a leading political and economic sustainability issue for the design of facilities like airports and government buildings.

So Civil Engineers need to learn to think globally about sustainability, considering multiple intellectual disciplines and to master problem formulation and analysis approaches that can be used to address a broad set of political, economic, social sustainability issues—in addition to the technological ones. Without political, economic and social sustainability, the creations of civil engineers will fall into disuse, or worse, become hazardous to their occupants and stakeholders. We believe that the broader definition of sustainability we have outlined, together with the pedagogical approach of extreme collaboration that we have described will empower civil engineers of this millennium to assume leadership positions in creating a sustainable built environment for humanity on spaceship earth.

5. References

Mark, Gloria: "Extreme collaboration", CACM 45(6): 89-93 (2002).

Johanson, Brad, Armando Fox, Terry Winograd, "The Interactive Workspaces Project: Experiences with Ubiquitous Computing Rooms", *IEEE Pervasive Computing Magazine 1(2), April-June 2002.*

Thompson, James: *Organizations in Action*. New York: McGraw Hill, (1967).