CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Building a Project Ontology with Extreme Collaboration and Virtual Design & Construction

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Abstract

This paper reports on a laboratory study that uses Virtual Design Construction (VDC) modeling and Extreme Collaboration (XC) for early phase building project design. The process creates a specific project ontology that forms the initial design of a building project. Our project ontology explicitly represents the functional requirements, designed forms, and predicted and observed behaviors of the product, organization and process of the project. With collateral drawings, models, analyses and explanations, it becomes the schematic and initial detailed design for the project. We observed a group of six designers (experienced graduate students) developing a first draft project proposal bid for a real project scenario. They created a high-level project model containing about 40 product, organization and process objects that represented their solution to the problem specification. They created and documented a design in one day at a level of detail that often takes engineers weeks to establish using traditional processes. For simplicity, we represented the evolving ontology in Excel and projected it and the corresponding product, organization and process models for all to see in the design meeting. While large generic building project ontologies exist, e.g., the Industry Foundation Classes, we find that our ontology is so simple that teams using any design tools and methods can use it today, and it is helpful. We interpret our results as early evidence that the *Tripod* engineering process of VDC, XC and use of a generic project ontology together enable a design team to build an ontology for a new project design very rapidly. It can then be used to support downstream detailed design and construction planning and also reuse in other engineering projects.

Keywords: Tripod engineering process model, POP ontology, VDC, virtual design and construction, XC, extreme collaboration

Alle guten Dinge sind drei

(All good things come in threes)

German proverb

1. Introduction

A 19th century civil engineer could grasp his discipline in its totality. Today, civil engineering has subdisciplines, each with a set of experts looking at the same problem with a different approach, and no individual can master all the details of a project. Specialization has both allowed us to push the frontier in many directions and has led us to the subdivision of design project into separate activities, each managed by one or more experts. The performance of a design project is, therefore, not only a function of the expertise of the individual experts, but also how well they work together. If each task is independent, or if the information flows only in one direction, the individual activities can be sequentially executed at the experts' own place of work. However, as the project's tasks get more interdependent, more interaction in terms of communication and coordination is required among the project team participants.

Depending on the type of task interdependence, synchronous or asynchronous communication will be more efficient [Thompson, 62] for project development. In particular, reciprocal dependent tasks require synchronous communication, i.e., face-to-face meetings. As the number of these tasks increases, more meetings are required to avoid misunderstandings and misconceptions that lead to rework. The NASA Jet Propulsion Laboratory pioneered Extreme Collaboration (XC) as a project development method to design projects very rapidly, in spite of the problem that many tasks are complex and have high reciprocal interdependence [Mark 2000]. XC gives a structured, fast and effective way to discuss, analyze, and explain highly interdependent tasks. The XC goal is to create and document a technical project solution for a particular problem specification quickly, normally in about a week rather than in the usual 6-12 months that is typical of engineering projects.According to Mark, XC diminishes rework by reducing misconceptions and misunderstanding caused by asynchronous communication difficulties. Everybody is available for providing data, analysis, decisions, explanation and suggestions. XC requires that work organized as synchronous meetings vs. distributed and asynchronous tasks.

The method of Virtual Design and Construction (VDC) is the use of multi-disciplinary performance models of design-construction projects, including the Product (i.e., facilities), Work Processes, Organization of the design - construction - operation team, and Economic Impact (i.e., model of both cost and value of capital investments) in order to support business objectives. The Virtual Design and Construction (VDC) approach defines Project models as the composition of related models of Product, Organization and Process (POP). We suggest that developing and modeling the Product, Organization and Process consistently and in parallel is valuable for successful project development [Kunz & Levitt 2002]. The VDC development process incrementally creates and integrates POP project models at increasing levels of detail: after creating an initial model at a coarse level of detail, designers analyze the model for cost, schedule and functional risks; and then elaborate selected segments of the model to elucidate and eventually mitigate potential risks to project success.

We did a design charrette as an experiment that links VDC and XC to create a project POP model. Specifically, in a one-day experiment, we created a Level-1 POP model of about 10 objects of each type, for a total of about 25 objects in the project ontology. In our short one-day exercise, we did some analysis and discussion of the Level-1 model and then elaborated each of the POP models until we had a total of about 40 objects. In general, a Level-2 VDC model has about 100 objects.

One of the charrette engineers had responsibility to create, describe and explain the POP ontology. The design team visually presented its different models in a multidisplay interactive room. Participants had high-level engineering experience and moderate experience working together as a team. In addition to the six modelers and a facilitator in the charrette, a group of project managers from different companies and countries acted as guest-participants, questioning the project and the process as the exercise proceeded.

The XC meeting uses a number (six in our case) of co-located cross-functional engineers, each equipped with computer-based modeling and analysis tools that are networked together. Design session participants defined their designs, discussed and negotiated design implications, and identified dependencies among design parameters by explicitly describing the POP model.

Our experiment, like the NASA XC process, includes group project development and requires a special display and computational support environment to allow participants to easily share data and knowledge as well as to brainstorm and decide.

The NASA XC team uses a generic project ontology for space mission design. It has about 2200 attributes and describes the design attributes of a number of different engineering subsystems such as structures, propulsion, etc. The design task is to instantiate that generic ontology to support the functional requirements of each particular mission. Analogously, we propose a project ontology for building design and construction. It explicitly represents the Product, Organization and Process of the project [Gruber 92]. Instead of providing a detailed ontology that covers the entire engineering domain, we propose a method for extending it through use. summarizes the use of XC by NASA and our use of it in this experiment.

Table 1: this table compares some of the details of the mature NASA/JPL extreme collaboration process for space missions and those of the new CIFE process for building project design development. Many details are different, but the kind of deliverables, methods, organization design and speed of operation are very similar. NASA/JPL has developed hundreds of successful projects using the XC method over the past decade.

	NASA/JPL	**CIFE**
Domain	Space exploration missions	Building design and construction
Number of positions in the XC design session with computer modeling systems that contribute to the project ontology	~20, each an engineering specialty, e.g., structures, propulsion.	6 [architecture, organization model, process model, 4D construction animation, systems]

Computer models for each engineering position	Yes, to do calculations and visualization (specialty-built)	Same, except commercial (MS Word, MS Excel, MS Project, Autodesk ADT, CommonPoint 4D, ePM SimVision)
Project ontology to represent evolving design and final deliverable	Yes	Same
Generic ontology components	Cumulative generic design after many design sessions, generally including intended functions, designed forms and predicted behaviors of each product aspect, organization and process	Formally defined intended functions, designed forms and predicted plus observed behaviors of the product, organization and process
Owner of project ontology	Systems engineer, who populated and explained the Excel model	Same
Size of final design ontology	About 2000 object – attribute – value assignments	About 200 object – attribute – value assignments
Environment for storing and manipulating the project ontology	Excel	Same
Method for positions to communicate with systems engineer who owns shared ontology		Verbal discussion
Length of XC session	Three working days over one calendar week	One day
Deliverable of the XC session	Project model, PowerPoint summary for each position and overall project with notes, showing design objectives, choices, predicted outcomes, multiple visualizations	Same, although significantly less extensive
Next step after completion of XC design	Detailed design	Same
Use of "sidebar" small conversations among some design session participants	Frequent, both requested by facilitator and spontaneous	Same

This paper shows how an ontology based on VDC principles supports extreme collaboration. We claim, based on the results of this experiment and our previous related experiences, that using VDC, EC and a POP ontology together may facilitate faster, better and potentially safer and less expensive project development.

This paper starts presenting the Tripod model followed by a discussion on its three components: POP ontology, VDC and XC respectively. In the case study section, we discuss our initial experiment in which a team of six graduate students developed a POP ontology at the schematic level plus some detail for a specific project in a 6-hour project design session.

2. VDC Tripod engineering approach: Combining VDC, POP & XC for successful project development

Our approach to project engineering uses a VDC development "tripod" that includes use of:

- Product, Organization and Process ontology to represent in the computer the major aspects of the design that can be controlled and delivered by managers;
- Extreme Collaboration (XC) to develop or at least to start the project design very rapidly using a co-located cross-functional design team that has excellent engineering modeling skills, tools and methods and that populates an initial generic project model;
- Virtual Design and Construction (VDC) design development method by which the design team creates the design incrementally and manages the construction by constantly considering the POP project model.

Generally there are three different types of agents (or groups of agents) involved in the project development process:

- Product designers: responsible for developing the artifact description, for example architects, structural engineers, as well as client representatives;
- Organization designers: responsible for developing the organization structure for carrying on the activities' plan, typically an executive and managing project manager as well as managers of major product and process teams;
- Process designers: responsible for developing the activities' plan to build the artifact, including design and construction managers, contractors.

Project design groups share information and interact using meetings or through other informal means according to the process plan designed by the organization designers. They work in parallel and generally make assumptions about the work of others, which they try to confirm.

In the standard approach, each design team may have a different representation for the artifact product, organization and process. They exchange information on a project, manually and also possibly electronically. Careful Engineering and coordination is required to link the different design views consistently.

Our design process model includes a common generic POP representation shared and understood by the design team. POP designers analyze the POP context, generate POP alternative design changes, predict possible POP consequences, and share (publish) changed information to the group. A POP ontology provides a unified model that designers elaborate and refine as they build a project representation.

Designers must work together to resolve issues and to build the mapping among P, O and P representations. As a group, POP designers request and provide DEEPAND (Garcia et al. 2003) information, i.e.,

- Description of POP artifact information
- Evaluation of POP artifact information
- Explanation of POP artifact information
- Prediction of POP artifact information
- Alternative Generation of POP artifact information
- Negotiation of POP artifact information
- Decision of POP artifact information

In the VDC approach, designers develop the P, O and P models concurrently; i.e., they consider a component product, the related design and construction activities and the parties responsible for doing the work.

The Extreme Collaboration environment is the social method to build the POP representation quickly, allowing the VDC approach to be actually carried out.

3. POP Project Ontology

There are many definitions for the term ontology varying from Aristotle: "the science that studies the being while being" to the practical: "definition of concepts with agreed and accepted semantic meaning in a domain and the relation between concepts" (Costello 2003) and "specification of a conceptualization" (Gruber 1993). We assume that the project ontology is computer-based.

An ontology can be informal, semiformal or formal depending on the desired use, such as communication among agents, interoperability among systems, and systems respectively. However, it must represent an agreement by the community that will share it on the selection of the concepts that represent a domain, their meaning, and the relations between them. Large ontology efforts include CYC (Lenat and Guha 1990) for defining commonsense knowledge in the world and the IFC (IAI 2001) for defining the building domain. They bring the potential benefits of saving time and sharing common sense knowledge in a community. However, large shared ontology is not now used commonly in practice.

We propose an engineering project ontology that initially contains only basic constructs and that uses the structured incremental elaboration method of Virtual Design and Construction to expand its structure and to populate it with details as a design emerges. It explicitly represents the Product, Organization and Process of the project.

The constructs related to Product refer to the physical and abstract concepts that describe the artifact itself, such as the columns and electrical system of a building. The constructs related to Organization refer to the agency and agents responsible for design and construction of the artifact. The constructs related to Process refer to the design and construction activities that will be carried by the organization to build the artifact.

Figure 1 illustrates the high-level description of the POP ontology. In the POP ontology, a project is an official (currently accepted) alternative project design selected by an authority (individual or group organization) among a set of possible alternatives according to a set of constraints and criteria.

A project alternative is the specification of an alternative Product model that will be executed by an alternative Organization using alternative Process.

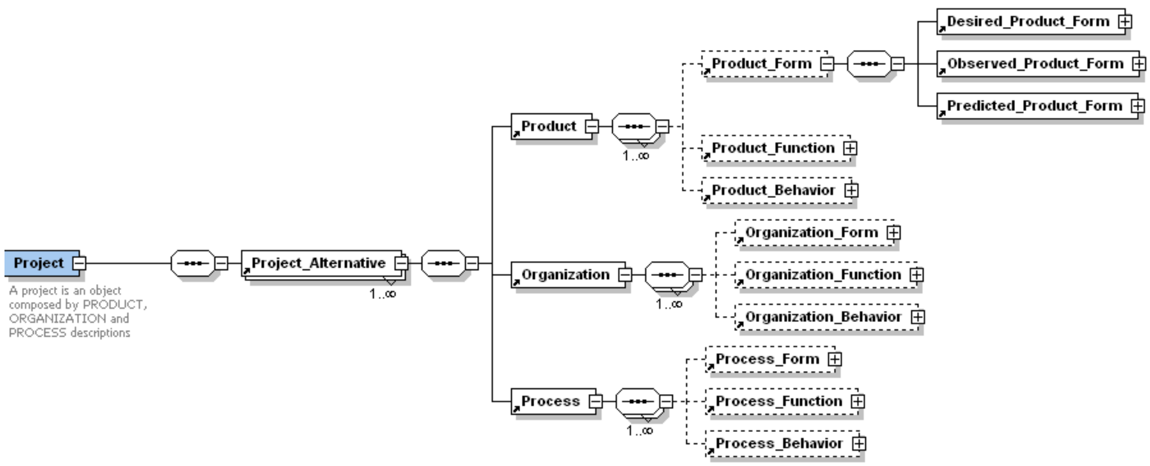

Figure 1: POP ontology high-level concepts: `Project` is an agreed project alternative among many. A `project alternative` is a complete or incomplete definition of its `Product`, `Organization` and `Process` models. The product, organization and process each have designed forms, intended functions and behaviors that are predicted, observed or desired.

3.1. Representing Product

POP constructs have three views: Function Form, and Behavior [Gero, 1990; Sasajima et al, 1995; Clayton, 1996]. Product form concepts describe the physical artifact, such as columns and beams, as well as the higher level abstract components related to it, such as the electrical or structural systems. Product function concepts represent the purposes of the artifacts or components, such as to support loads. Product behavior concepts represent the way form achieves its function. For example, predicted cost and schedule are behaviors, given the product, organization and process design, as is the predicted deflection of a beam. Any of these behavioral parameters can (in principle if not in fact) have a predicted value, a measured value and possibly a method to predict them.

Although Form, Function and Behavior is an established conceptualization in engineering domain, there can be a great deal of discussion when classifying the function and behavior of a concept. Let us consider a simple example of design a rectangular equipment room. Given the room length and width, the area is a predicted behavior of the room. The room may also have a functionally required area and an actual area, and in fact all three may be different. For example, suppose the owner wants a classroom and suggests a *Desired Area* of 400 sq ft. However, during the design phase the classroom dimensions were chosen to be 20 x 19, so the *predicted* area was 380 sq ft. Some changes occurred during construction and the classroom was built with different dimensions than specified. The *observed* area was 390 sq ft. We explicitly represent functions, forms and different kinds of behaviors to allow designers, owners and inspectors to represent their perspectives explicitly.

A desired generic concept can have constraints that restrict the space of possible values for instances of the concept. For example, the fire code may specify a minimum height for rooms. A desired concept must include a criterion to specify when the desired concept is satisfied. The desire can be described as a constraint over the possible alternative solutions of the object (component or higher level component).

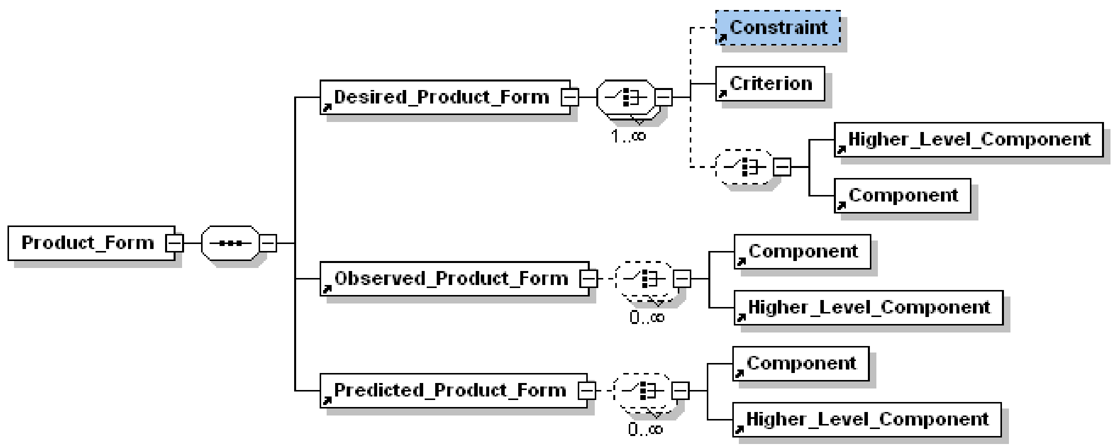

Figure 2: `Product Form` generic specification. Product forms, which are designed, include examples such as spaces and walls, can have desired, observed and predicted attribute values. `Higher_Level_Components` are systems, such as an electrical system.

3.2. Representing Organization

Generally, groups of people with different specializations do the planned work of a project. These people may coordinate; depending on the type of dependencies between the activities they perform.

Again, function, form and behavior play an important role in specifying the organization concept, as illustrated in Figure 3. Organization forms concern the groups that do work, with attributes such as size and skill. Organization function concerns the role of the organization when carrying out activities to achieve a designed artifact. Organization behaviors concern the ways organization interacts with each other, such as time spent doing direct, coordination and rework.

Organization form, function and behavior are qualified as desired, predicted and observed in the same way as Products.

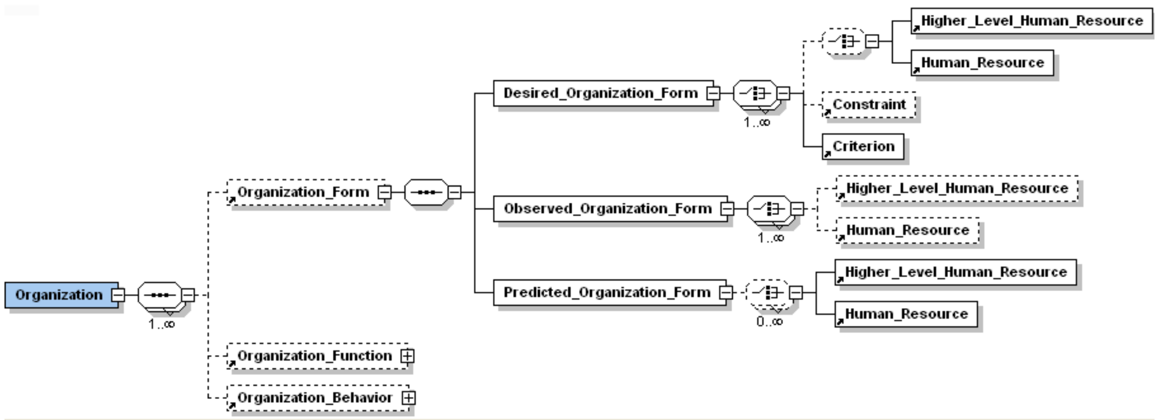

Figure 3: Project Organization generic specification. Designed organizational elements, such as design and construction teams, can have desired, observed and predicted attribute values. "Higher_Level_Human_Resources" are groups, such as a design team, and "Human_Resources" are individuals.

3.3. Representing Process

Process concerns the method to design and construct an artifact. To define process we need to define the activities, at micro and macro levels, and milestones (Process Form). Activities may have relationships such as temporal precedence or pre-conditions (Process Function), and schedule and delivery dates (Process Behavior). Desired, Observed and Predicted concepts apply to Process Form, Function and Behavior, as indicated in Figures 4 and 5.

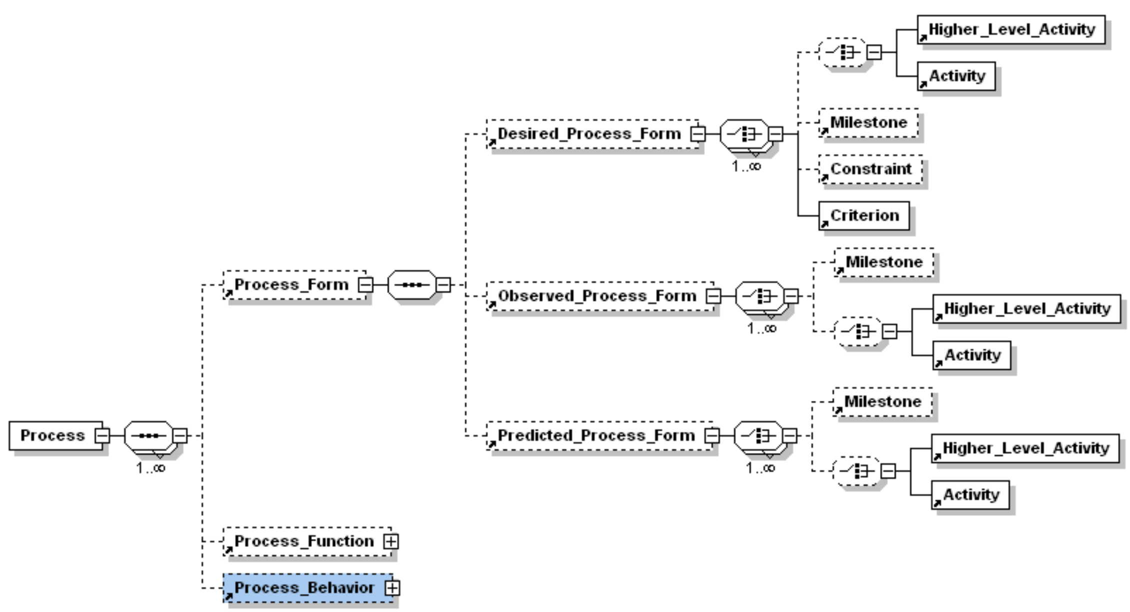

Figure 4: Project Process generic specification. Designed process elements, such as design and construction tasks, can have desired, observed and predicted attribute values. "Higher_Level_Activities" are networks of activities, i.e., detailed work methods, while "Activity" is an individual activity or task.

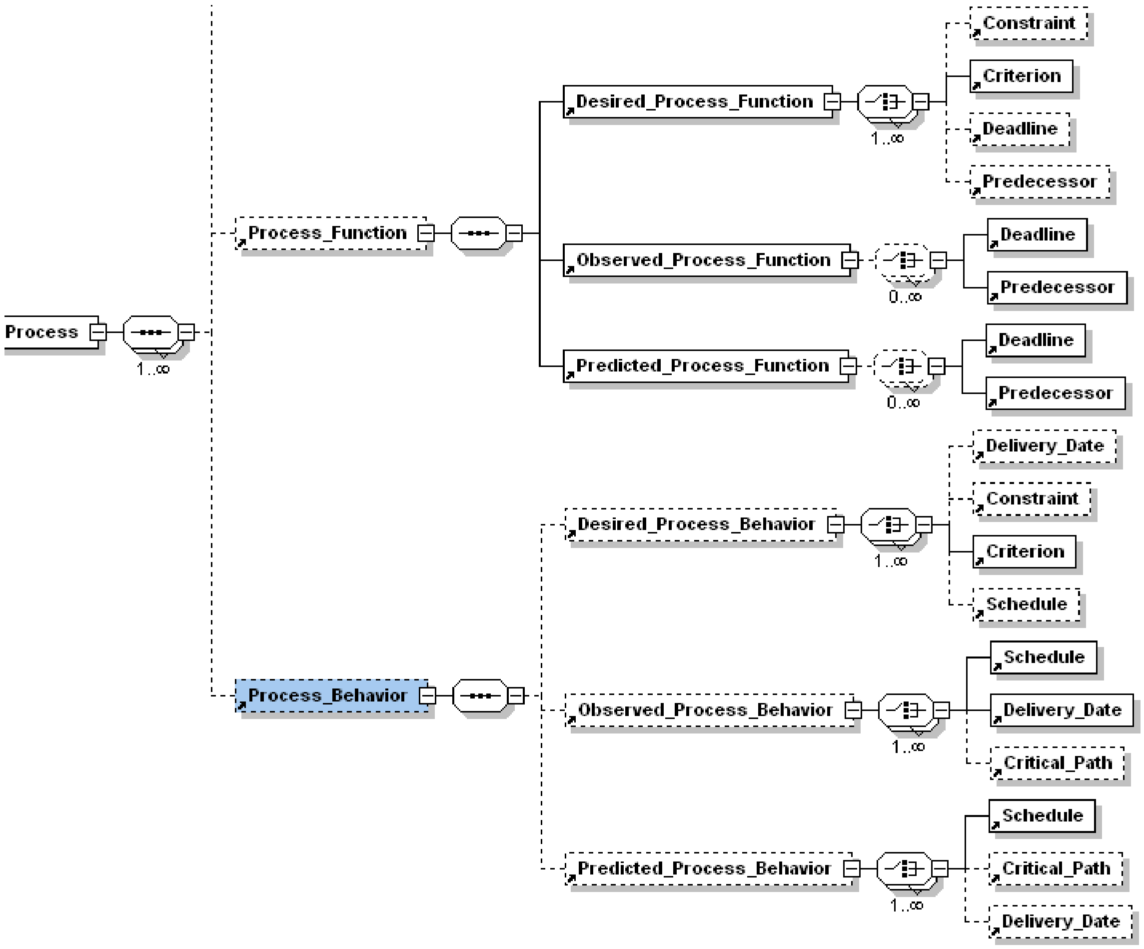

Figure 5: Project Process Conceptualization continued.

3.4. POP Ontology Model

Table 2 illustrates a series of examples to clarify our distinction between Product, Process and Organization, Form, Function and Behavior, and Desired, Predicted and Observed.

Table 2: The VDC POP ontology represents statements about architectural and engineering in an object-oriented way as the values of parameters of defined conceptual objects. This table shows some examples of the mapping of statements to the values of attributes of the Function, Form, Behavior objects defined in our Project Ontology of Product, Organization and Process objects. In the first example, the statement is mapped to the specific object Beam1, which is a subclass of the general object "Product". The statement refers to the object attribute Desired_Form_Parameter_Length. The attribute value is 100 ft.

World	*Representation*
Beam length must be = 100 ft (functional requirement for an attribute of a product component)	Beam1.Desired_Length = 100 ft
Calculated room area = 100 sq ft (Calculated behavior of a an attribute of a product component)	Beam1.Predicted_Length = 100 ft
Construction must finish by October, 1, 2004 (Functional requirement for an attribute of a process concept)	Activity271.Desired_Deadline = 10/01/2004
DPR was hired to build the electrical systems (Observed value of an attribute of an organizational concept)	Organization1.Observed_Responsible = DPR

4. Virtual Design and Construction approach to Project Development

Engineering projects generally start with a set of needs specified by an owner. From this functional specification, project designers create a conceptual solution that they further detail into a product specification (Product Model). A product model only becomes reality through construction. Consequently, a construction plan (Process Model) is a requirement of a successful project. Companies must be hired and organized (Organization Model) to develop both product and process plans as well as to actually carry out the plans to reach the product.

Implicitly or explicitly, every engineering project develops product, organization and process models. Since they are highly dependent on each other, developing them in parallel without adequate coordination can promote misconceptions and, therefore, a great deal of rework. The building development process today has large amounts of parallel design phase activity to create these models, and the coordination and inevitable rework contribute to making them slow in the eyes of owners.

To improve quality and reduce rework, the Virtual Design and Construction (VDC) project methodology [Kunz 2003] claims that designers should aggregate these three views of the project, not dissociate them as is common in practice. The VDC method tightly links the representation and development Project, Organization and Process models. For example when a designer proposes a component (product), the VDC process triggers the designer to think of the associated activities (process) and the potential work force to carry on these tasks (organization). In addition to developing the project the POP ontology concurrently, VDC approach emphasizes the importance of using models from the very beginning and throughout the project development: “Model early and model often.”

At the Center for Integrated Facility Engineering (CIFE) at Stanford University, there is an integrated computational and visualization environment called the CIFE iRoom [Johanson et al. 2002; Kunz et al. 2002]. This integrated environment passes messages from one application to others. Exactly as at the NASA XC facility, the CIFE iRoom has three large display screens to show project models, as illustrated in Figure 6.

Figure 6: Multi-display CIFE iRoom environment: in Extreme Collaboration, participants can project their models for all participants to see. Underlying application integration “glue” allows applications to share data and control.

The CIFE iRoom design tools include the Autodesk Architectural Desktop (ADT), CommonPoint 4D as the product and construction process 4D simulator, MSProject as process model tool, and SimVision [Levitt and Kunz 2002] to model and simulate processes and organizations. The shared visualizations of the P, O and P models allow all designers to see the impact of their design choices on their own and on related disciplines, as well as give the opportunity for all designers to review the design choices of other disciplines.

The POP model serves as a neutral information repository for XC participants, and we can display it on a screen in the iRoom. Designers use their specialized applications to create their own models, and they store those models in application-specific databases. They report the objects and attributes that they want to share in the shared project ontology. Thus, the shared object ontology identifies some assumptions about the objects, normally including their functional purposes, and some shared design form and important behavior attributes, at least the name and a cross-reference to the internal names in the individual applications.

Furthermore, capturing, representing and sharing the desired, predicted and observed project information allows the project team to check how the evolving design satisfies specifications, predict potential conflicts as well as learn from successful and not successful cases.

5. Extreme Collaboration Environment

Extreme Collaboration (EC) is a working environment, pioneered at the NASA Jet Propulsion Laboratory, in which collocated experts work simultaneously in design "sessions" while using excellent modeling, simulation, visualization and analysis tools to document and facilitate collaboration (Mark 2000). Since the design emerges during the XC session, the XC team can elaborate the structure of the project ontology as well as instantiate its values.

Mark (2000) refers to extreme collaboration as design activity that takes place within a "war-room" setting, in which the participants are working within a social environment that maximizes communication and information flow. Two of the most important characteristics are the collocation of team members and the deployment of information technologies.

In a traditional design process designers attend regular meetings to review each part of the project, which they develop and analyze in a stand-alone mode. In extreme collaboration, designers work physically together, i.e., at the same place, as long as they have to finish the task. The collocation facilitates communication in several ways. First, team members can break out and start an instantaneous meeting as soon as a planned or unplanned issue arises. Team organization, therefore, emerges and changes dynamically as the project proceeds. Second, team members can *eavesdrop* on the surrounding communication. They can become involved to prevent other team members from making uninformed decisions or immediately adapt their work to incorporate an unexpected result.

Another characteristic of extreme collaboration is the use of various types of information technologies to support the communication among the team members. The applications include graphical modeling systems, numerical simulations and analyses, linked spreadsheets, networked support, electronic whiteboards and a generic common product model. In addition, the team members also rely on traditional low-tech tools such as face-to-face conversation, whiteboards and flip charts. The instantaneous information sharing and excellent modeling, visualization and simulation tools also allow the team members to perform on the spot analyses and simulations to investigate how a change affects all the interlinked activities.

The next section of this paper discusses our experiment that investigated how a POP ontology implemented in VDC could support extreme collaboration in a civil engineering project.

6. The Template-Hospital *Charrette* Project

The Template-Hospital Charrette project was a group exercise presented at the end of the one-week 2003 CIFE summer workshop. Kaiser Permanente is a Health Maintenance Organization that is constructing a series of around 20 hospitals in a 13-year period. They will share the same core design, with nuances to comply with topographic and other site differences. The high-level architectural program for the template hospital served as the initial project specification. The objective of the charrette experiment was to show to an audience of about 20 project managers from different companies around the world the nature, feasibility and potential benefits and costs of using the Tripod engineering process.

6.1. Participants: the project team

Table 3 shows the CIFE design team for this experiment.

Table 3: CIFE Extreme Collaboration design team member task assignments

Task	*Tool*	*Role*
Create POP ontology for the specific project	MSExcel	VDC Project Coordinator (coordinator)
Make explicit business objectives	MSWord	Owner's Representative (representative)
Product Model (3D)	ADT (Autodesk)	Architect
Product Model	4D CAD (CommonPoint Technologies)	Architect
Organization Model	SimVision (ePM)	Project Manager (PM)
Process Model	MSProject	Project Manager (PM)

6.2. Method: the tripod experiment

The experiment was built in an XC environment since the team would remain collocated during the entire exercise. In that sense, the audience could estimate the degree of help (or harm) from XC.

The exercise facilitator introduced the participants and the project problem to the audience. In addition to presenting the problem and the team to the audience, he presented the objectives of the exercise, i.e., it was a live demonstration to show the feasibility of the engineering tripod approach as well as to stimulate people to consider potential benefits of using VDC, XC and a shared project ontology.

From the beginning the facilitator emphasized the VDC approach; i.e., to build the POP project model incrementally and to consider the product, organization and process concurrently. Team members contributed to the discussion either voluntarily, triggered by some displayed information, or as a response to an explicit request from the facilitator or another team member. As illustrated in Figure 1 and Table 3, the VDC ontology has a very simple representation. We showed it on an iRoom display and manually created and integrated it.

The discussions generated in the XC charrette reflected two rounds of the design activity: an initial conceptual design (VDC modeling Level 1), in which the team was concerned to find a sound solution, and some preliminary detailed design, in which the team discussed problems in specific components and activities (Level 2). These two discussions were documented, as illustrated in Table 4, and represent the objects in the evolving specific project ontology.

Table 4: Project POP ontology after first discussions. Each POP object explicitly represnets the relationships with other POP objects, e.g., procdess activities have a responsible organizational actor and act on one or more physical product objects. The POP model contains some details about each object. The appalication-specific P,O and P models contain a great deal more information.

	Product	Organization	Process
Functional requirements	**Generic physical components**	**Organization**	
	Budget	Completion date	Completion date
	Number of beds	Budget	Safety
Designed forms, Level 1	**Generic physical components**	**Organization actors**	**Process activities**
1	Site preparations	Owner	Start the construction
2	Ambulatory Surgical Center	Community	Construct Site preparations
3	Nursing Unit Floor	GC / CM	Construct Ambulatory Surgical Center
4	Parking Structure	Architect	Construct Nursing Unit Floor
5	Utility Room	Sub contractors	Construct Parking Structure
6	Ancillary Block	Sub consultants	Construct Utility Room
7	Medical Office Building		Construct Ancillary Block
8	Central Utility Plant		Construct Medical Office Building
9	Loading Dock		Construct Central Utility Plant
10	Landscaping and paving		Construct Loading Dock
			Construct Landscaping and paving
			Turnover
Predicted behaviors			
		Greatest predicted actor backlog	

Each of the participants described POP data, proposed POP design changes, evaluated suggestions, explained decisions and propositions, predicted impacts on individual tasks due to other's design changes, negotiated changes and finally committed to an integrated solution.

Although the exercise accomplished the expected goals, product, organization and process models stayed on a high level of abstraction. We ended up with 10 to 15 high-level objects that represented the Product, Organization and Process.

6.3. Experiment Results

In a 6-hour time frame a group of six graduate students generated a conceptual design for an actual engineering project. They developed a product (3D drawings), an organization and process models, as illustrated in Figures 7 - 9 respectively, an integrated project ontology, and a set of PowerPoint slides that documented the architectural program, the POP design response, and some of the important predictions.

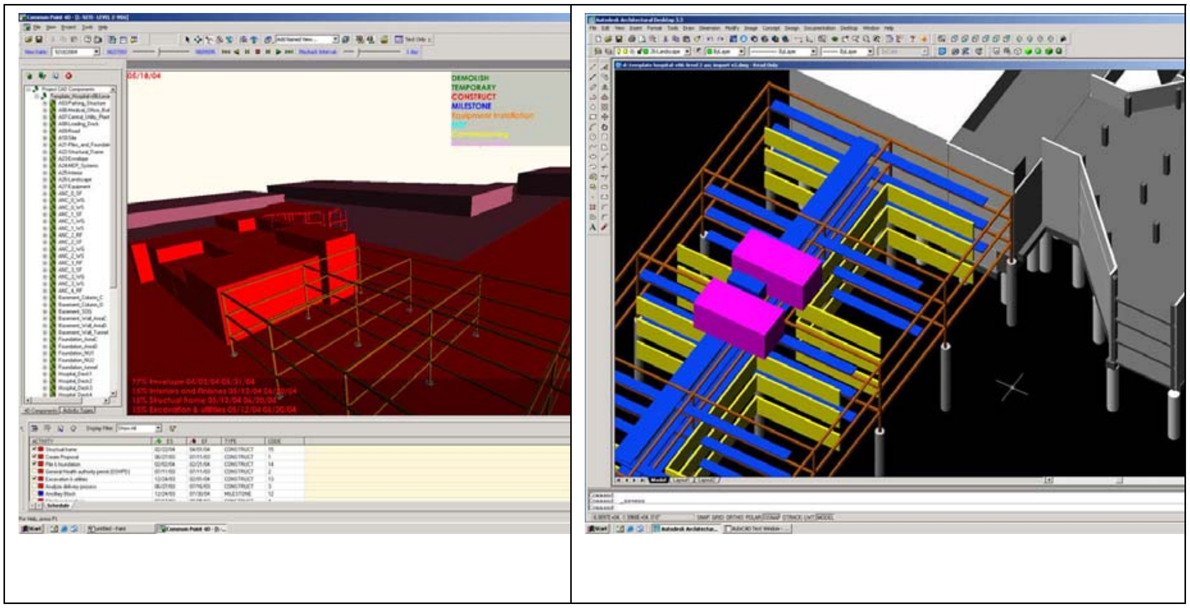

Figure 7: Kaiser template hospital product model (left) as it existed at the initial (Level-1 VDC model) abstract level of detail, and (right) in a more detailed version (Level-2). The left image is a snapshot from a 4D animation, which shows the construction of building components over time. The 4D snapshot shows major building components at a moment during the construction, and the animation shows the constructed sequence occurring over time.

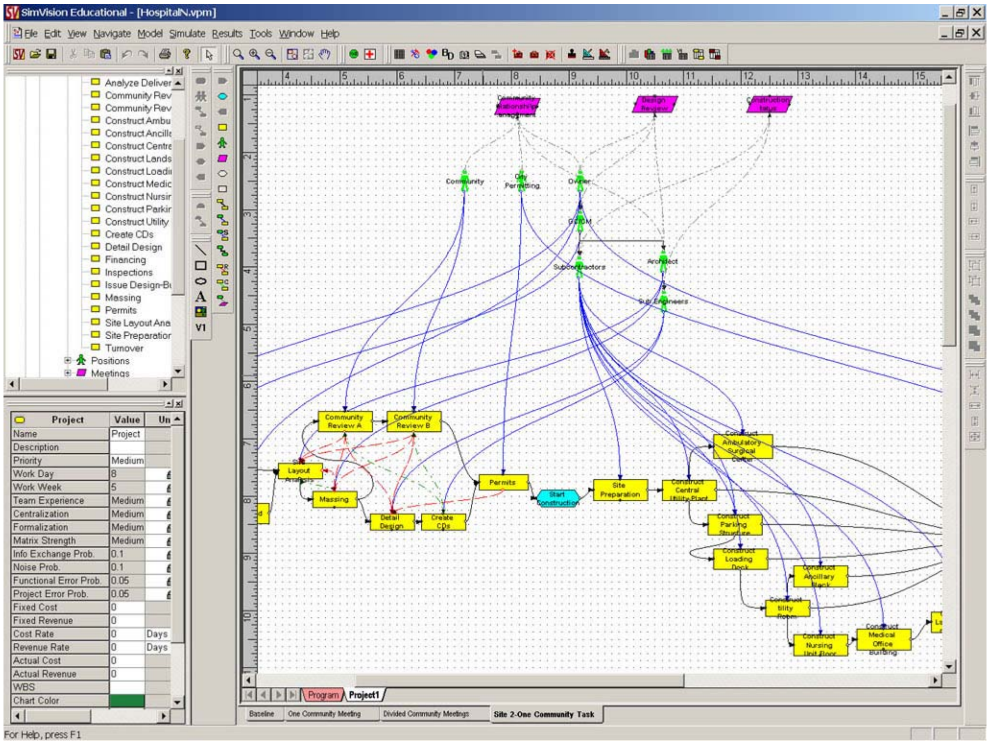

Figure 8: Kaiser template hospital solution: Organization Model. The process activities (rectangles) describe the design and construction of the component objects of the product model.

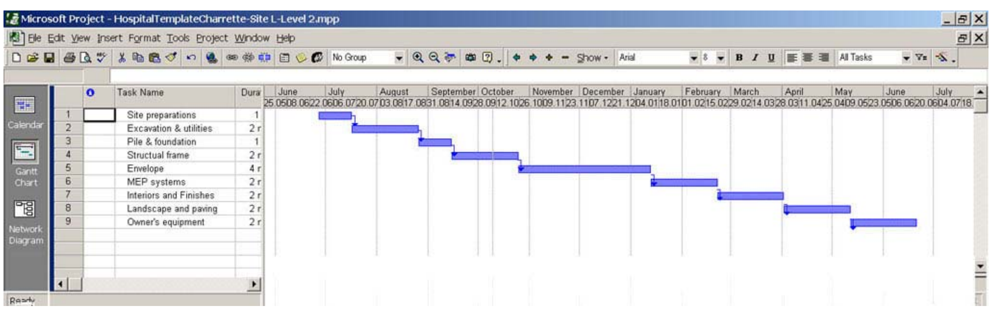

Figure 9: Kaiser hospital template project: process schedule, predicted by simulation of the organization and process model shown in Figure 8.

During the experiment, participants proposed incremental additions to the POP ontology, allowing design team members to discuss and agree to proposed changes. Since the initial representation was not completely instantiated, the group had the chance to negotiate and adopt not only project engineering terminology, but also the representation technology.

The XC drastically changed the task event allocation from a usual project review meeting. Normally, the decision events (Decide-type) are rare (less than 5%) either because people spend most of meeting-time understanding the context, and/or because participants delegate decision-making to others. As illustrated in Figure 10, decision-making events were about 21% in the XC session, probably because the group's goal was to come up with solution during the meeting, the XC environment facilitated rapid decision-making; the ontology allowed everyone to view proposed decisions; and the iRoom made the designs public for all to see.

Usual Project Meeting	*Tripod Engineering Process Meeting*

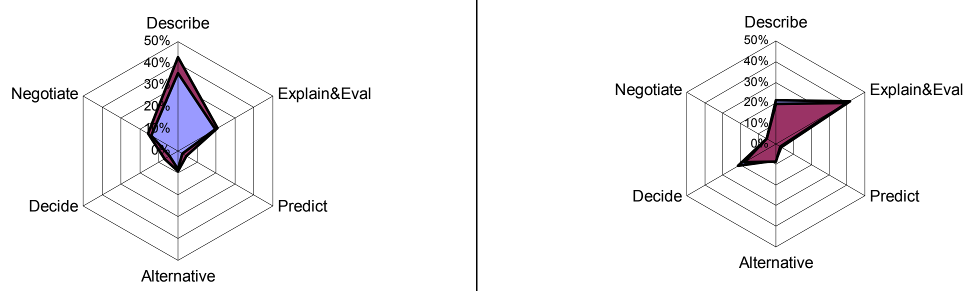

Figure 10: A usual project design meeting (Left, from [Garcia et al. 2003]) compared to the Kaiser charrette design meeting exercise (right). The dark areas show the fraction of inquires during the design session that were of each DEEPAND type. The lighter colored area shows the fraction of those inquiries that received a response that was both timely and of satisfactory quality to serve the intent of the questioner.

Another expected result was the decrease on the amount of Negotiate-type of events, from the usual 15% to less than 5%. As expected, the XC environment let people perceive needs and volunteer information and predictions before being requested, almost if everybody knew what to do without need for explicit task division.

Another interesting finding, although unexpected, was that the Predict-type events were the same 2% to 3% in normal practice and in the XC experiment. We expected an increase of Predict-events since they occurred during the XC meeting. As we analyzed the transcripts, we noticed that although working as a group during the meeting, participants foresaw information needs before being requested, ran their analysis/modeling tools and brought results either as a *Describe-event* or as a *formulate Alternative-event*. They did prediction on their own initiative, without an initiating social event to request it.

In our experiment, there was only minor rework due to misunderstandings. The misunderstandings occurred just before lunchtime.

More explanation and evaluation events occurred (about 40%) during the design exercise than the usual 20%. When further analyzed, we judged that a great deal of the explanative events were an expected side effect of the VDC approach, i.e., each participant sought at least a minimum understanding of the others' design issues and choices.

The presence of the audience strongly influenced the process. One significant impact was the constant need to show information to the audience. Despite this extra need, Describe-type events were drastically diminished from the usual 40 to 50% to a modest value of 22%.

After the experiment we asked both the audience and the design team to answer a survey. Our goal was to measure:

1) Usefulness of the experiment; i.e., in what degree the experiment was useful to understand the Tripod approach from both perspectives: designers and audience;
2) Soundness of the experiment; i.e., in what degree both participants and audience believe the experiment was valid to show the feasibility of POP ontology, VDC approach and XC work environment
3) Maturity of the Tripod approach; i.e., in what degree they believe they can input this new engineering process and technology into their companies

The feedback of the audience was highly polarized, either very positive or very negative. Probably this reflects the individual interests to modeling tools and methods on detail level. If you are not interested in details, you may get bored looking at people using the tools. On the other hand, if you are, then the process can be interesting, even regardless of the final results.

7. Discussion

The Kaiser charrette exercise was an experiment to show the feasibility of the Tripod engineering process approach. While most in the audience reported that the tripod approach does not seem mature enough to justify a drastic change in their company's way of doing business today, some reported that they would try parts of it. Some of the parts of the tripod approach are in use in some segments of industry today, i.e., multi-display working environments like the iRoom, extreme collaboration, modeling tools. We focused this paper on the ontology because we found that the small size and simple (Excel) implementation are usable and useful today.

The use of an ontology, natural for an engineering team and audience, helped fast understanding by design session participants and observers. We believe that the iRoom technology speeded up understanding by allowing information to be presented and discussed in an integrated view. For example, when discussing a set of activities (process model) presented in a screen, the related components (product model) could be presented in a second screen, and the responsible players (organization model) in a third screen. This holistic view of the project suggested by the VDC approach supported by the POP ontology allows information always to be presented in its proper context, speeding up understanding. The holistic perspective also appeared to diminish rework below that seen in normal design processes.

Modeling, especially in the beginning, contains periods where the visual results develop too slowly to keep up the interest of the audience, which forced the team to consider not only the optimal process, but also how to provide results in a constant stream. This meant that the process was not just testing extreme collaboration and VDC method, but also the presentation skills of the team in front of a demanding audience.

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