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Object-Oriented Enterprise Modeling and Simulation of AEC Projects

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Abstract: *In this paper we describe an object-oriented framework for developing enterprise models of Architecture, Engineering, Construction projects, and a methodology for formalizing these models such that they can be used for discrete event simulation of information processing and coordination in project execution. The simulation results can be used to predict the probable effects of carrying out proposed changes in planning and managing projects.*

In our enterprise modeling framework we represent engineering design projects in terms of deliverables (*requirements and solutions*), *plans* (*activities and process relations*), *and organization* (*participants and organizational relations*). *The resulting project model is the starting point for identifying coordination requirements between project team participants. Our methodology uses matrix techniques derived from qualtiy function deployment* (*QFD*) *to identify interactions between project requirements and solutions and calculate measures of product* complexity. *We then describe information flow between project activities in a similar matrix and calculate measures of process* uncertainty. *Finally, we identify the responsibilities of project team members and use a matrix to point out organizational* interdependencies.

We apply our framework and methodology to model and simulate engineering design for a major extension of an electrical power substation. Our simulation results demonstrate how project performance is contingent on the fit between the project policies and the objectives and preferences of the project team.

1 INTRODUCTION

Our *motivation* for modeling and analyzing Architecture, Engineering, Construction projects is an increasing demand for effective and efficient project management. Projects in the AEC industry are becoming ever more difficult to manage, with demanding customers, tight budgets and schedules, complex technology, and project teams that work concurrently in different locations. Consequently, project managers need tools to help them make the right decisions during project planning and execution. However, such decision support tools must be based on true understanding of the decision situation, acquired by careful description and analysis. If we can develop models that *consistently* represent relevant aspects of the selected model domain and *correctly* recreate observed behavior in simulation, we believe that a combination of model building and simulation is a good way to create understanding.

We address this representational issue by defining *project enterprise* in terms of “an *organization*, carrying out some [set of] *process*(*es*) to create *products* which satisfy predefined *objectives*.[4] Based on this definition, we model the project team, plan, deliverables, and requirements. We take an information-processing view of project execution and define a methodology for explicating the associated *coordination*. This methodology uses matrices to identify and quantify dependencies between different parts of the requirements and deliverables, planned activities, and team members. The project model and associated dependencies can be input to the Virtual Design Team (VDT) discrete event simulator.[17] For a given project, the VDT simulation then produces measures

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of duration, cost, and quality. Thus the simulation results can be used for assessing the effect of deploying different project teams, executing different project plans, and managing different coordination policies.

The *objective* of this paper is to demonstrate how modeling and analysis can be used to understand project enterprise and how such understanding can be turned into performance predictions. Consequently, the paper focuses on giving an overview description of our framework. Further details can be found in the refs. 4 through 9, 17, 19, and 20. Also, the paper is descriptive, outlining an application to a project that had already finished when we modeled and simulated it. We believe that our framework and methodology may be used a priori to design better project configurations. However, we also feel that further calibration against real-world experience is required in order to calibrate our approach before we can apply it prescriptively with confidence.

In Section 2 we outline our framework for modeling project enterprise. Next, in Section 3 we describe our methodology for identifying coordination requirements. Then, in Section 4 we outline the VDT discrete event simulator and present a set of simulation results. All these sections are illustrated by a project to design a major extension of an electric power substation.

2 A FRAMEWORK FOR DESCRIBING PROJECT ENTERPRISE

Project enterprise consists of an assigned team working together for a planned period of time to deliver according to specification and satisfy stated requirements. In order to create a consistent model of project enterprise, we must therefore describe why we act (requirements), what is the result of action (deliverables), when and how we act (activities), and with whom we interact (team). Thus our OPPO model of project enterprise[4] represents projects in terms of objectives, product, process, and organization, as well as the various dependencies that exist within and among them. In the next subsection we outline an engineering design project in the electric power industry. Then, in the following subsections we describe the various dimensions of the OPPO model using this project as an example.

2.1 The Table Mountain Substation engineering design project

Engineering design in the electric power industry involves development of design drawings and procurement specifications for complex and costly installations. Typical design objects include components for voltage generation, transformation, and transmission, as well as systems for control and communication. The Table Mountain Substation (TMS) project was carried out to design and install a major extension to an existing electric power substation. The substation, which regulates a major part of the electric power to San Francisco, needed this extension in order to ensure reliable power supply in case of fluctuations in power supply (e.g., due to line breakage). Figure 1 shows an overview picture of the extension to the TMS.

The extension involved installation of a set of shunt capacitors, inductors, switches, and control circuitry. The project team thus included people from electrical, civil, and telecommunications engineering, as well as procurement and project management. The engineering part of the TMS project involved some 20,000 person-hours, carried out over 18 months by an engineering design team varying between 10 and 15 persons. We shall use the engineering design part of the TMS project throughout this paper as an example application to illustrate our framework and methodology.

2.2 Describing objectives and products

To represent project deliverables, we integrate the description of *objectives* and *products* using functional decomposition. Specifically, we use the FUTS technique,[29] which matches functional units (FU) with corresponding technical solutions (TS). In the present application of FUTS we view design as a two-step process. *Conceptual design* transforms operational and performance requirements (FU) to a corresponding functional description (TS). *Detailed engineering* then transforms this functional description (FU) to detailed solution specifications (TS) for construction or procurement. The deliverable from the detailed engineering part of the TMS project was therefore a set of detailed specifications (TS) corresponding to a high-level functional description (FU). This functional description was developed together with the client as part of the bidding process. Figure 2 shows the "requirements-solution breakdown structure" for the detailed engineering deliverable, with requirements and solutions objects and the relations between them.

In the FUTS technique, a specific top-level requirement is met by a corresponding top-level solution. This solution generates a set of lower-level requirements, which in turn are met by more detailed solutions—which in turn generate new detailed requirements and so on until a suitable level of detailing exists for describing procurable specifications. In our TMS example, the breakdown starts with the overall functionality to provide stable voltage supply, which is met by a solution to extend the substation with (a set of) mechanical switching capacitors. The extension generates requirements to support equipment, convert voltage, and control operations, for which specific types of engineering are required. The various engineering disciplines are faced with more detailed requirements—such as "stable support" for civil engineering. These requirements to the engineering disciplines are met by specific engineering solutions—such as "foundation" as a solution to the support requirement. This decomposition may

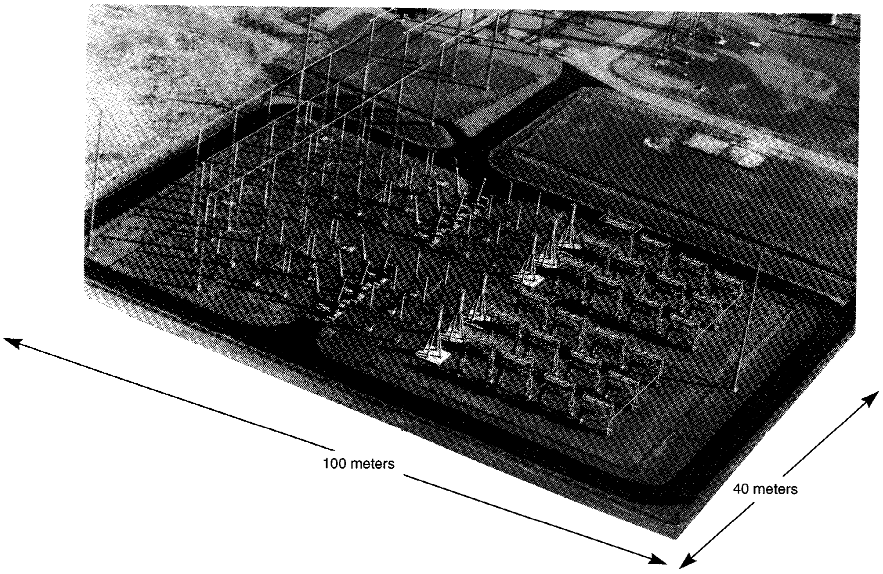


Fig. 1. The deliverable from Table Mountain Substation (TMS) project.

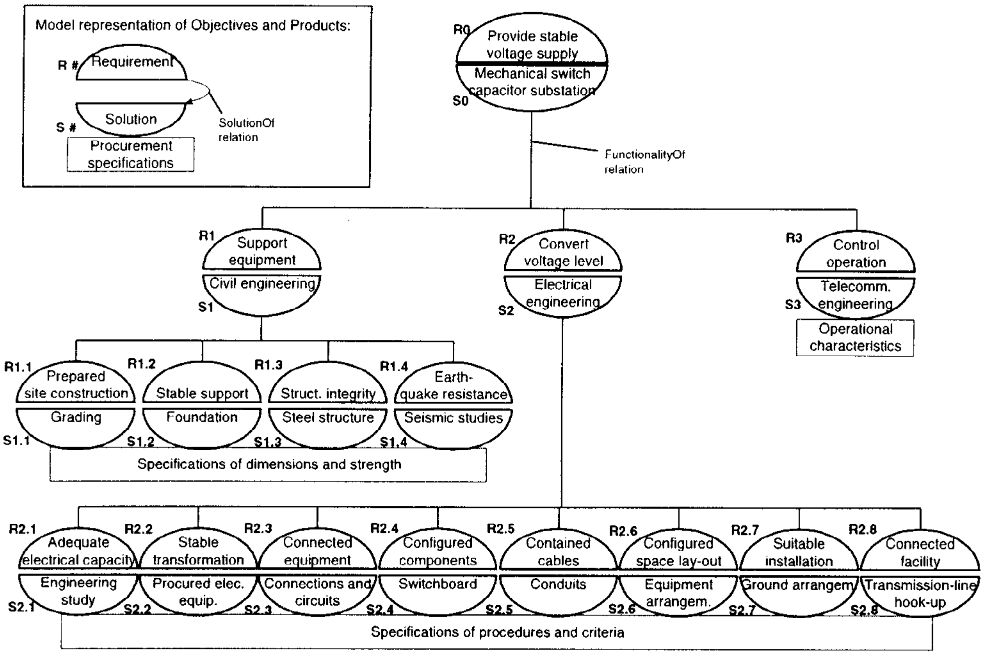


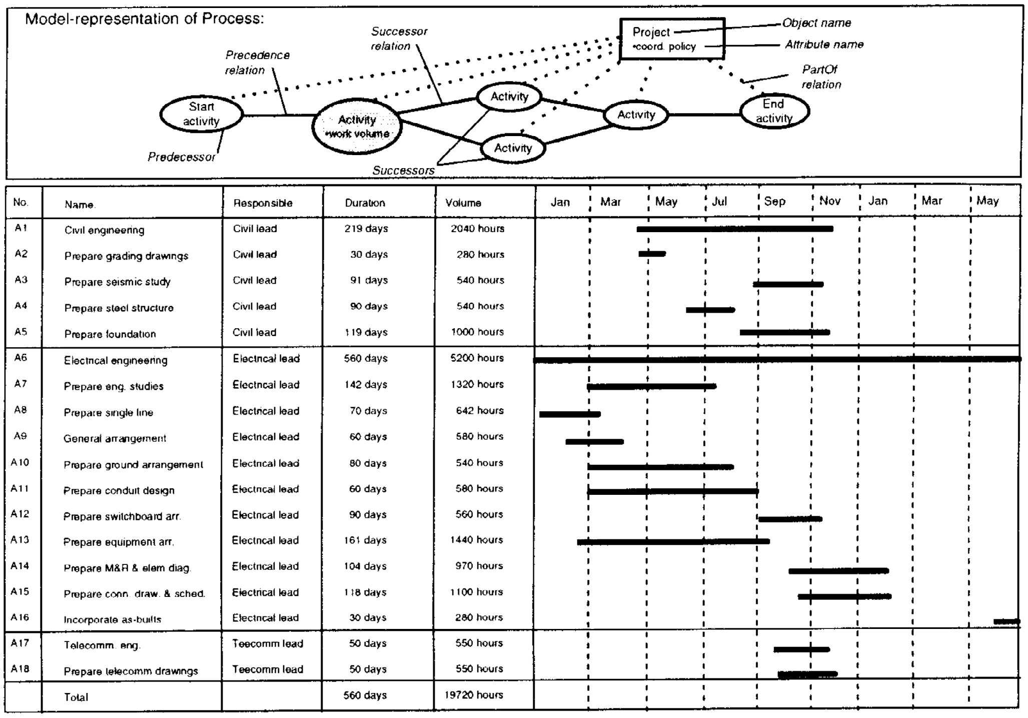
Fig. 2. The requirements-solution breakdown structure for the TMS project.

be continued until a suitable level of detail has been reached to specify characteristics for design and procurement.

In the present example we wish only to illustrate how we describe objectives and products and have (arbitrarily) terminated the breakdown at an artificially high level of detail. In the next section we shall use this description to identify product interactions and resulting needs for coordination. We point out that our representation of objectives and products relates required and realized characteristics of the project deliverables. The difference between them determines the *product performance* of the project enterprise.

2.3 Describing the process and organization

Describing the *process* dimension involves representing the activities in the project plan, as well as their work volume and precedence relations (the order in which they are planned to be executed). Figure 3 shows the project plan for the engi-



No.	Name	Responsible	Duration	Volume
A1	Civil engineering	Civil lead	219 days	2040 hours
A2	Prepare grading drawings	Civil lead	30 days	280 hours
A3	Prepare seismic study	Civil lead	91 days	540 hours
A4	Prepare steel structure	Civil lead	90 days	540 hours
A5	Prepare foundation	Civil lead	119 days	1000 hours
A6	Electrical engineering	Electrical lead	560 days	5200 hours
A7	Prepare eng. studies	Electrical lead	142 days	1320 hours
A8	Prepare single line	Electrical lead	70 days	642 hours
A9	General arrangement	Electrical lead	60 days	580 hours
A10	Prepare ground arrangement	Electrical lead	80 days	540 hours
A11	Prepare conduit design	Electrical lead	60 days	580 hours
A12	Prepare switchboard arr.	Electrical lead	90 days	560 hours
A13	Prepare equipment arr.	Electrical lead	161 days	1440 hours
A14	Prepare M&R & elem diag.	Electrical lead	104 days	970 hours
A15	Prepare conn. draw. & sched.	Electrical lead	118 days	1100 hours
A16	Incorporate as-builts	Electrical lead	30 days	280 hours
A17	Telecomm. eng.	Teecomm lead	50 days	550 hours
A18	Prepare telecomm drawings	Teecomm lead	50 days	550 hours
	Total		560 days	19720 hours

Fig. 3. Project plan for engineering design of the TMS project.

neering design phase of the TMS project, together with our model representation for describing processes.[23] The project plan for the TMS project was characterized by many concurrent activities, resulting in a number of dependencies between civil, electrical, and telecommunications engineering activities. Our process model is made up of activity objects and precedence relations. The work volume is represented as an attribute of each activity object. We also represent various coordination policies (for command, control, and communication) as attributes of an overall process object.

In the same manner that the difference between objectives and product deliverables defines product performance, the difference between the process plan and execution defines *process performance* in terms of duration and person-cost (efficiency).

Describing the *organization* involves modeling the various project team members (actors). We describe actors in terms of their craft, skill, and experience and the relations between them—including the formal hierarchy of command and control. We also represent the responsibility relations between actors and various activities for which actors are responsible and the communicational relations due to these dependencies.

Figure 4 illustrates the engineering design project team and their relations to other project participants. Note the two different organizational hierarchies, the functional and project lines of command and control. This is typical for project organizations and often is referred to as a *matrix structure*.[12] In our model of the TMS project we have not explicitly represented the functional hierarchy. However, we have included an important attribute of matrix organizations by describing it as a "weak" (i.e., functionally oriented) matrix.[12] This value is stored as an attribute in an overall organization object, to which all actors have a membership relation.

The difference between project policies—stored in the process object—and personal preferences of actors will determine how planned action is translated into actual behavior. This determines *organizational performance*, which influences and constrains process and product performance.

2.4 Summarizing the enterprise modeling framework

In Fig. 5 we illustrate how projects can be viewed in terms of our OPPO framework. Starting from a given set of objectives, project enterprise proceeds by (1) definition, (2) identification, and (3) assignment of a set of dependencies (*coordination requirements*) and subsequent (4) execution to handle these dependencies according to defined policies (*coordination mechanisms*). Project performance may be viewed as a result of the alignment between project coordination policies and the preferences of project team members and can be (5) assessed by comparing the realized and desired solutions. The project can then be (6) evaluated by comparing performance with the objectives.

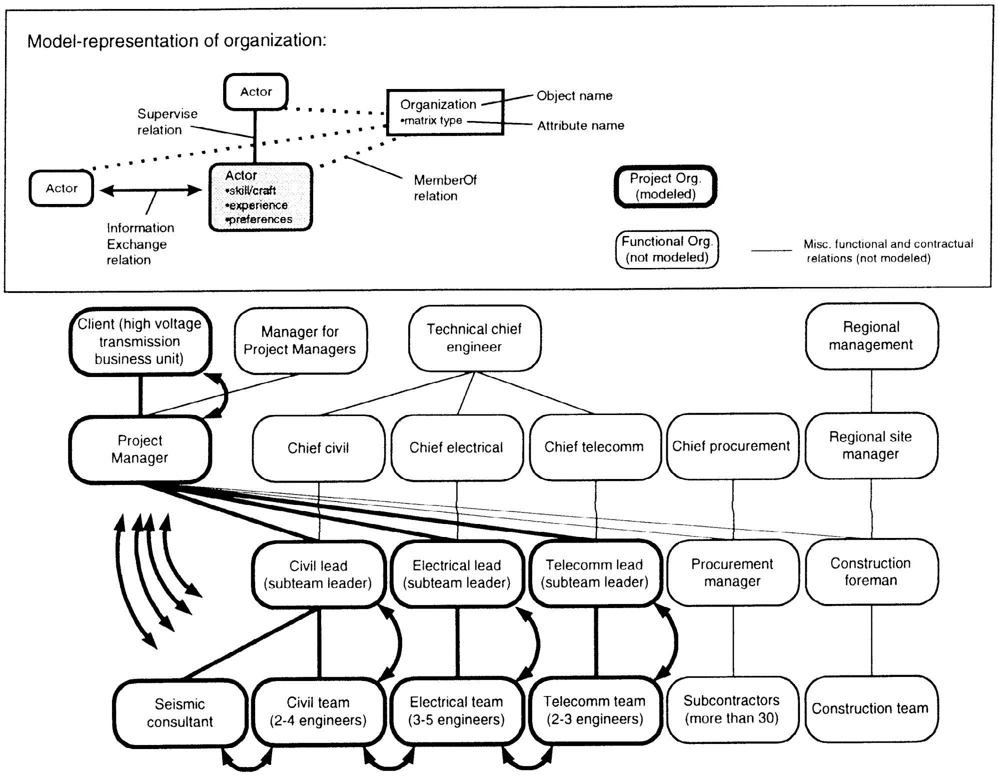


Fig. 4. The engineering design team organization for the TMS project.

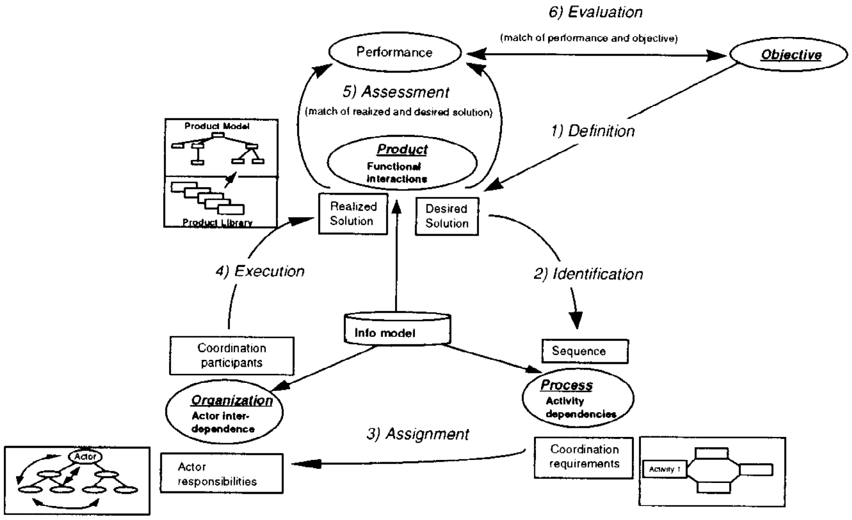


Fig. 5. An overview of the OPPO enterprise modeling framework.

The preceding modeling framework addresses definition and establishes a basis for identification and quantification of coordination requirements. In the following section we describe how our methodology is used to identify these requirements and assign them to actors in the project team. Then, in Section 4 we describe execution, assessment, and evaluation.

3 A METHODOLOGY FOR MODELING COORDINATION REQUIREMENTS IN PROJECTS

In this section we describe our methodology for identifying and quantifying coordination requirements, based on the project model resulting from the framework described in Section 2.

3.1 An information-processing view of coordination in engineering design

To describe coordination[21] in projects, we use an analogy between organizational and physical structures. Both physical and organizational structures may be thought of in terms of elements with given material properties connected by nodes in a given configuration. Both are subject to load from their environment, and for both the capacity to meet this load is determined by their material properties and configuration. And for physical as well as organizational structures, the match between required and realized behavior under load determines the performance of the structure.

We take an information-processing view of project execution in terms of a set of processors (actors) who work by processing information items in order to complete activities in the project plan. These actors are dependent on each other for producing, consuming, and sharing information to carry out their work. In addition to work arising from planned project activities, we model various coordination items arising due to these dependencies. We can then define *coordination load* among information processors in terms of the demand for their attention when processing information. The more coordination items due to causal and informational dependencies in their activities, the more coordination is to be attended and the higher is the load. Thus coordination load is a function of the requirements, selected solutions, project plan, and allocation of responsibility. Similarly, *organizational capability* is given by the sum of the *ability* of actors (craft, skill, and experience), the processing capacity of the team (manpower, structure, and tools), and the coordination capacity of the team. The latter is determined by project policies and actor preferences for handling coordination. For a given project enterprise, the match between coordination load due to project requirements and the team's capability to meet that load will determine performance.

Given the preceding *organizational mechanics*, our coordination load model attempts to define and operationalize measures that are important for determining the performance of real projects. Traditional project planning assumes an ideal situation where different parts of the project deliverable are uncoupled, such that an error in one part will not affect any other part. Another traditional assumption is that project activities are sequenced so that all necessary information is available when required. In reality, these assumptions are very seldom anywhere near the truth. Consequently, delays, cost overruns, and poor quality occur due to lack of information and error propagation. Experienced project managers account for this heuristically in their planning and scheduling. However, most project plans are still optimistic, leading to frequent disappointment.[18]

3.2 The house of complexity

To identify dependencies in the project deliverables, we describe the various interactions between project requirements and solutions in a quality function deployment (QFD) interdependence matrix.[1,11,16] In the QFD notation, any matrix element a_{ij} represents an interaction where solution j affects requirement i. That is, the solution needs to satisfy the requirement, and any change in requirement may necessitate a corresponding change in the solution. It follows that any error in the solution may imply that the requirement is not satisfied.

We can use the interaction matrix as a *house of complexity* to calculate project-specific measures of the complexity arising from coupling in the project task.[26] Using Herbert Simon's notion of complexity as "the number of constraints an actor must simultaneously keep in mind while carrying out a task,"[26] we count the number of interactions between requirements and solutions to get complexity measures. The more requirements a given solution must contribute to satisfying, the more complex is the solution. Thus *solution complexity* is a measure of the probability that actors producing the solution will make errors when carrying out their work.

Similarly, the number of solutions that contribute to a given requirement gives a measure of the complexity of the requirement. Even if all solutions contributing to satisfy a requirement are in order, the customer may still not be satisfied. We use the *requirement complexity* as a measure of the probability of failure to satisfy various requirements. Figure 6 shows the house of complexity for the TMS project.

In Fig. 6 we see how the solution Civil Engineering (S1) addresses the requirement for Supported Equipment (R1) and all its lower-level requirements (R1.1 through R1.4), as well as two lower- level requirements under electrical engineering (R2.6 and R2.7). The resulting number of interactions is 8 (out of a total of 15), and the normalized solution complexity is 0.53 (8/15). Conversely, the requirement for Supported Equipment (R1) is addressed by Civil Engineering (S1) and all its lower-level solutions (S1.1 through S1.4), as well as telecommunications engineering (S3). The resulting number of interactions is 6 (out of a total of 15), and normalized requirement complexity is therefore 0.4 (6/15).

In the matrix we have chosen the value 1 for all interactions. In the standard application of QFD to product design,[11] these interactions often have different weights depending on the relative strength of the interaction. We feel, however, that we do not yet have enough experience from application to projects that we can meaningfully derive such weights.

Shaded lines signify aggregate requirements and solutions

		S1 Civil engineering	S1.1 Grading	S1.2 Foundation	S1.3 Steel structure	S1.4 Seismic studies	S2. Electrical engineering	S2.1 Engineering study	S2.2 Procured elec. equipment	S2.3 Connections and circuits	S2.4 Switchboard	S2.5 Conduits	S2.6 Equipment arrangement	S2.7 Ground arrangement	S2.8 Transmission line hook-up	S3. Telecom engineering	Requirement complexity
R1.	**Supported equipment**	1	1	1	1	1										1	0.40
R1.1	Prepared site construction	1	1														0.13
R1.2	Stable support	1		1	1	1											0.27
R1.3	Structural integrity	1			1	1				1		1	1	1		1	0.53
R1.4	Earthquake resistance	1				1							1	1			0.27
R2.	**Suitable voltage level**	1			1		1	1	1	1	1		1	1		1	0.67
R2.1	Adequate electrical capacity				1		1	1	1	1	1		1	1	1	1	0.67
R2.2	Stable transformation				1		1	1	1	1	1		1	1		1	0.60
R2.3	Connected equipment						1			1	1	1	1	1		1	0.47
R2.4	Configured components						1			1	1	1	1	1		1	0.47
R2.5	Contained cables						1			1		1					0.20
R2.6	Configured space lay-out	1		1	1		1		1	1		1	1	1		1	0.67
R2.7	Suitable installation	1		1	1		1		1	1		1	1	1		1	0.67
R2.8	Connected facility														1		0.07
R3.	**Control operation**								1	1	1					1	0.27
	Solution complexity	0.53	0.13	0.27	0.53	0.27	0.53	0.20	0.40	0.67	0.40	0.40	0.60	0.60	0.13	0.67	

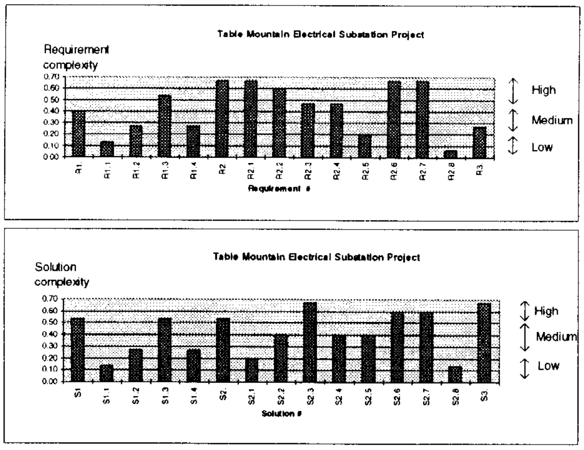


Fig. 6. The house of complexity for the TMS project.

3.3 The house of uncertainty

We next use the same type of interaction matrix to describe the production of and need for information for carrying out the various project activities. Employing the design structure matrices (DSM) technique,[13,15,27] we place the project activities both along the rows and columns of the interaction matrix. In the DSM notation, a_{ij} means that activity j produces information that is needed by activity i. If we order the DSM interaction matrix so that activities are listed according to their order of execution, we see that any a_{ij}, where j is larger than i (i.e., which lies to the right of the midline diagonal in the matrix), represents information that is not available when it is needed.

We use Galbraith's[14] notion of *uncertainty* as "a result of differences between the information which is needed to carry out a task and that which is available at the time the task is carried out." That is, uncertainty arises from lack of necessary information. The more information is needed but not available when carrying out an activity, the more uncertain is the activity. Thus we may sum all a_{ij}, where j is greater than i, to get a relative measure of uncertainty for the various activities.

Thus the DSM interaction matrix becomes a *house of uncertainty*, which can be used to derive the distribution of uncertainty of different activities. Assuming that uncertainty gives rise to the need for communication, we use this uncertainty distribution as an indication of the required communication intensity between actors who are responsible for various activities. Figure 7 shows the house of uncertainty for the TMS project.

In Fig. 7 we see how the Electrical Engineering activity (A6) requires information from a total of 9 out of a total of 18 activities (A8, A9, etc.) and thus has a relative uncertainty of 0.5 (9/18). Similarly, the Incorporate As-builts (procured equipment) activity (A16) in the engineering interacts with 10 other activities. However, all these activities are carried out before A16. Thus all required information is (at least in principle) available, and there is no uncertainty.

It is evident that the usefulness of DSM to derive uncertainty measures depends largely on the activity description. If the project plan describes activities at too high a level, the information flows that can be identified between activities most probably will not be meaningful in describing the real communication requirements of actors in the project team. From Fig. 3 we observe that Electrical Engineering (A6) is defined for the complete project duration. Consequently, it starts before all other activities, and any information needed for electrical engineering would seem to be produced by activities that start later. This would indicate a level of uncertainty that may not be consistent with the actual use of information during project execution.

The solution to this problem of representation would be to detail the electrical engineering activity. However, we chose to use the project plan shown, since this was used by the project manager during execution. During project execution, the indicated uncertainty actually was felt by the electrical engineering subteam and subteam leader, who had to constantly communicate both with other subteam leaders and with the project manager.

As noted by Gebala[15] and Eppinger,[13] the DSM technique may be used to optimize the sequencing of project activities by LU decomposing the activity plan as far as possible to get a process with minimal uncertainty. This would result in a DSM matrix where most of the matrix elements are located below the leading diagonal (representing information that is available when it is needed). So far our approach has been to describe projects where the scheduling has already been determined, and thus we have no experience in using matrix techniques prescriptively. In future work we plan to use DSM as a tool to prescribe and study project design.

3.4 The house of interdependence

Given the required communication intensity, we can relate the responsibility of actors for activities to the information they produce and consume when carrying out activities. This results in a *house of interdependence*, which illustrates which actors are responsible for producing information in given ac-

		A6	A8	A9	A13	A7	A10	A11	A1	A2	A4	A5	A3	A12	A17	A18	A14	A15	A16	Uncertainty
A6	Electrical engineering	0	1	1	1	1	1	1						1	1				1	0.50
A8	Prepare single line	1	0																	0.00
A9	General arrangement	1	1	0																0.00
A13	Prepare equipment arrangem.	1		1	0	1	1	1												0.17
A7	Prepare engineering studies	1	1	1	1	0	1	1												0.11
A10	Prepare ground arrangements	1		1	1	1	0				1									0.06
A11	Prepare conduit design	1		1	1	1		0			1				1					0.11
A1	Civil engineering	1		1					0	1	1	1	1							0.22
A2	Prepare grading drawings			1					1	0										0.00
A4	Prepare steel structure			1					1	1	0									0.00
A5	Prepare foundation			1					1	1	1	0	1							0.06
A3	Prepare seismic study								1		1	1	0							0.00
A12	Prepare switchboard arrangement	1	1		1	1	1							0	1					0.06
A17	Telecomm. engineering	1		1	1		1	1						1	0			1		0.06
A18	Prepare telecomm. drawings			1											1	0		1		0.06
A14	Prepare M&R & elem. drawings	1		1	1	1								1			0	1		0.06
A15	Prepare conn. draw. & sched.	1			1									1	1		1	0		0.00
A16	Incorporate as-builts	1		1	1	1	1	1	1					1	1		1		0	0.00

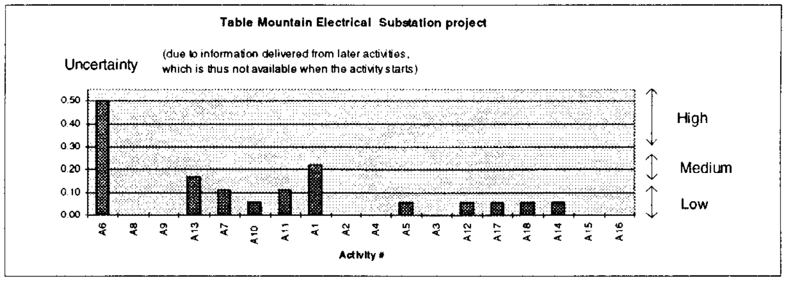


Fig. 7. The house of uncertainty for the TMS project.

tivities and which actors need the information produced by those activities.

The matrix illustrates the required participation in information exchange (the various communication events) during project execution. If we use James Thompson's typology of pooled, sequential, or reciprocal interdependence,[28] we can use the house of interdependence to identify the required frequency of communication between various pairs of actors during execution as follows:

> Actors who are responsible for activities that do not need to exchange information have *pooled interdependence* and need not communicate with each other while carrying out their activities.
>
> Actors who are responsible for activities where one activity needs information from a previous activity have *sequential interdependence* and need to communicate with moderate intensity while executing their activities.
>
> Actors who are responsible for activities where both activities need information from the other have *reciprocal interdependence* and need to communicate intensely while carrying out their activities.

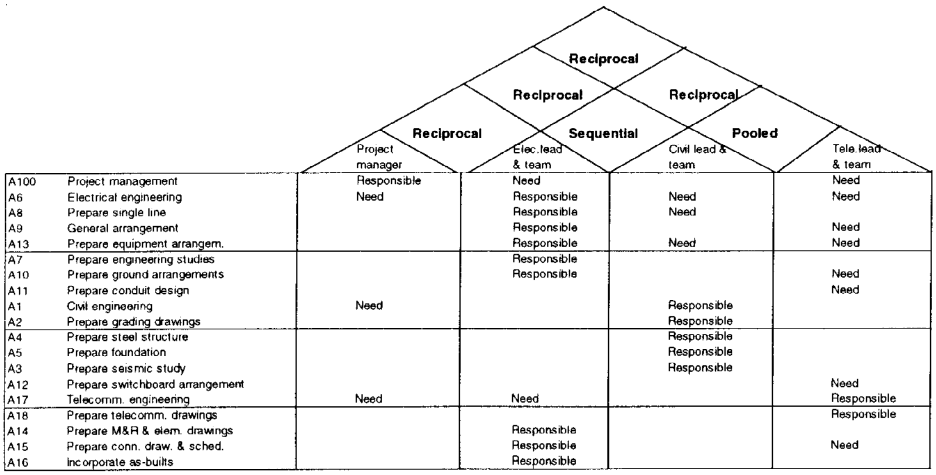
We use the triangular interrelationship matrix between actors, at the "roof of the house,"[16] to represent this *type of interdependence* between the different actors. Figure 8 shows the house of interdependence for the TMS project.

From Fig. 8 we see how the electrical and telecommunications leads are both responsible for activities from which the other needs information (e.g., electrical and telecommunications engineering, respectively). Thus they are reciprocally interdependent. The electrical lead is also responsible for the Single Line activity, from which the civil lead needs information for (at least some of) its activities—which start later. Thus they are sequentially interdependent. Since neither the civil nor telecommunications leads (and teams) are responsible for any activity for which the other needs information, they only have pooled interdependence.

3.5 Summarizing the load modeling methodology

Figure 9 summarizes the preceding methodology for defining and modeling the load distribution on project team members during project execution. We see how a structured breakdown of requirements and corresponding solutions, together with activity plans and organization charts for the project team, is used as input to a set of matrix tools for deriving the relative distributions of complexity and uncertainty for the various activities and interdependence between project team members (see ref. 8 for further details).

We use these measures to quantify (1) the relative probabilities that solutions generated by given activities will contain errors, (2) the relative probabilities that solutions will fail to satisfy given requirements, (3) the relative measures of uncertainty and associated communication frequency for activities, and (4) the required participation in communication by project team members. These measures are, in our view, important parts of a correct description of how execution of the project plan actually determines project performance. Our load modeling methodology describes the detailed *load distribution* on individual actors, as opposed to a traditional



		Project manager	Elec. lead & team	Civil lead & team	Tele. lead & team
A100	Project management	Responsible	Need		Need
A6	Electrical engineering	Need	Responsible	Need	Need
A8	Prepare single line		Responsible	Need	
A9	General arrangement		Responsible		Need
A13	Prepare equipment arrangem.		Responsible	Need	Need
A7	Prepare engineering studies		Responsible		
A10	Prepare ground arrangements		Responsible		Need
A11	Prepare conduit design				Need
A1	Civil engineering	Need		Responsible	
A2	Prepare grading drawings			Responsible	
A4	Prepare steel structure			Responsible	
A5	Prepare foundation			Responsible	
A3	Prepare seismic study			Responsible	
A12	Prepare switchboard arrangement				Need
A17	Telecomm. engineering	Need	Need		Responsible
A18	Prepare telecomm. drawings				Responsible
A14	Prepare M&R & elem. drawings		Responsible		
A15	Prepare conn. draw. & sched.		Responsible		Need
A16	Incorporate as-builts		Responsible		

Fig. 8. The house of interdependence for the TMS project.

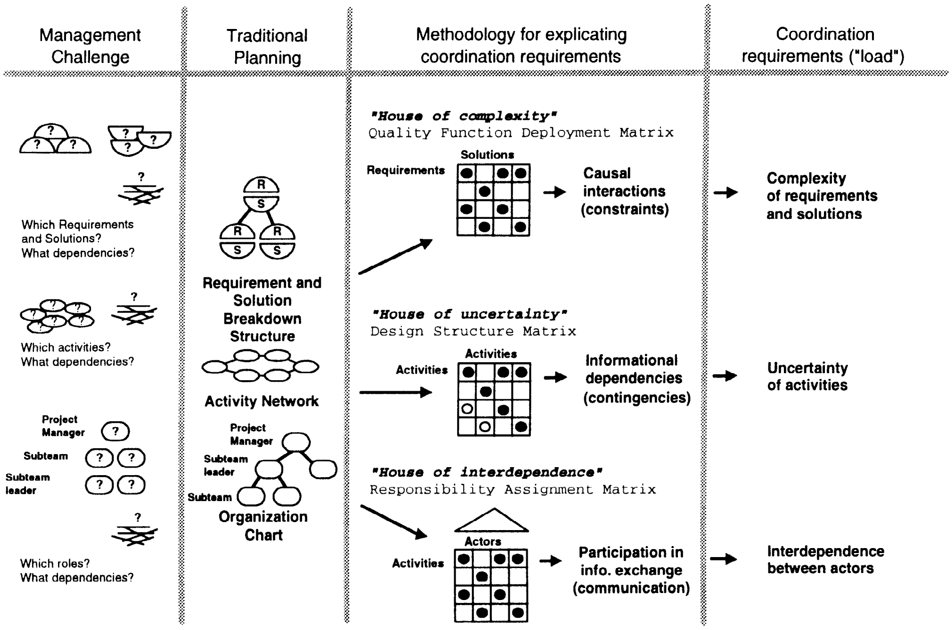


Fig. 9. An overview of the methodology for modeling coordination load.

description of coordination requirements as a "point load through the center of gravity." The traditional description involves statements such as "the complexity of the task was high,[24] without identifying which part of the organization is subjected to load.

It may be argued that our decoupling of complexity due to causal dependencies in the project deliverables and uncertainty due to informational dependencies is an oversimplification. In most projects, causality and information need are not independent. Typically, missing information leads to rework, and errors lead to the need for additional information. However, we view our "linearization" as an initial approach to describe project dependencies. Through using the simplified description on a number of real-world projects, we hope to develop the insight and understanding that are necessary for a better description of dependencies.

4 DISCRETE EVENT SIMULATION OF INFORMATION PROCESSING AND COORDINATION

This section outlines how the coordination load described in Section 3 may be used in simulation of information processing and coordination handling in this section and how simulation gives estimates of project performance that may be used to predict probable effects of proposed changes to project design.

4.1 The VDT discrete event simulator

The Virtual Design Team (VDT)[19] discrete event simulator is a result of an ongoing project at Stanford University[10,19] with the aim of using simulation to investigate various aspects of project team organization. VDT is implemented as an object-oriented discrete event simulator where each processor (actor) uses communication tools to carry out work and coordination generated by activities for which they are responsible.

Since VDT actors are modeled as boundedly rational,[25] they must engage in *coordination*—exception handling, rework, and communication—in addition to *working*—processing according to the project plan. This leads to a series of decision making events,[22] where actors must allocate their attention to requests for communication and handling of failures discovered during verification. VDT uses a set of stochastic (random number) process elements to model uncertainty in human decision making. The simulation continues until all work and coordination items are processed, giving predictions for project performance, in terms of the critical path duration, work volume (a substitute for project cost), and coordination performance (error handling and communication attendance).[8]

The input to VDT consists of a description of the coordination load, the capability of the project team, as well as policies and preferences for handling coordination. The load is described in terms of activities' work volume, failure probability, and communication intensity, as described in Sections 3.2 and 3.3. Organizational capability (processing speed) is determined by the capacity of the team (manpower, structure, and tools) and the ability of team members (skill, craft, and experience), as described in Section 3.1. The team's handling of coordination during simulation is determined by the match of policies (what should be done in given situations) and preferences (what is actually done in those same situations). This match defines the information-processing behavior of the various actors in terms of their decision making about attention allocation and participation.[22] Both project policies and preferences of actors are explicitly modeled[17] and may be altered between simulation to study the predicted effect on performance. Figure 10 gives an overview of input and output for the VDT using the IDEF-0 notation,[3] where *input* is transformed to *output* using *resources* and according to *control*.

Given the measures of the complexity of requirements and solutions described in Section 3.2, we must derive corresponding values for the complexity of the various activities. The higher the number of requirements a designer has to keep in mind when designing a given solution, the higher will be the chance that he or she will make errors while carrying out the activity to produce the solution. The solution-decision matrix[3] produces an *internal failure probability* for each activity, which is a measure of the chance of making mistakes (exceptions) while working. Such exceptions are typically discovered in self-checks or peer reviews. Similarly, the higher the number of solutions needed to satisfy a given requirement, the higher will be the chance that the requirement will not be satisfied—even if each individual solution may be according to specification. The requirements-access matrix[3] gives an *external failure probability*, which is a measure of the chance of nonconformance when carrying out work to satisfy customer requirements. Such nonconformances are typically discovered at project milestones or during client reviews. The uncertainty of activities will determine the frequency with which responsible actors will generate communication requests. The interdependence between actors will determine to whom these communication requests are sent.

Figure 11 illustrates how the coordination load for activities and actors is transformed to measures of failure probability and communication intensity for each activity and how these measures are used during simulation. The top part of the figure shows how complexity and uncertainty cause decision making about coordination. The bottom part of the figure shows how the outcome of this decision making determines project performance. The lower-left graph shows the simulated failure rate for activities as a function of complexity. The lower-right graph illustrates the number of requests for communication as a function of the uncertainty of activities for which the actors are responsible.

For a specific set of inputs, the VDT simulation will give the critical path duration, overall person-hours (project cost), and process measures of the quality of coordination. Specifically, verification quality is measured by the number of noncorrected exceptions. Likewise, communication quality is measured by the number of nonattended requests. Below we give examples of results from simulation of the TMS project in VDT, as obtained from the mean of a series of simulation runs with different random seeds for stochastic processes. The results show how a change in coordination policy (higher or lower value than the one used in the TMS project) is likely to affect duration, cost, and quality. The simulation predictions are compared with predictions from contingency theory[28] and predictions from the project manager (who planned and managed execution of the project).

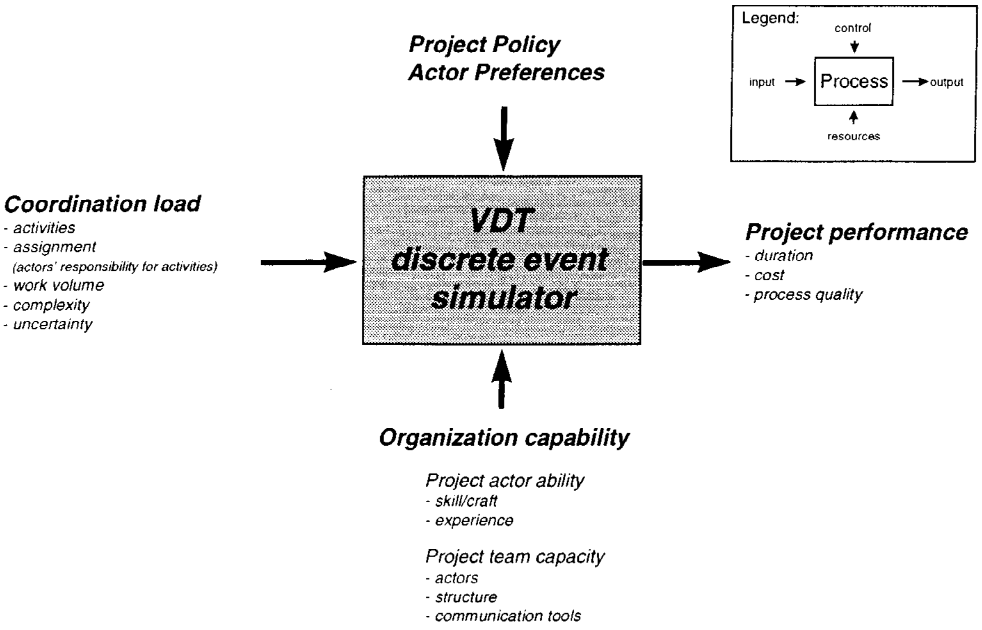


Fig. 10. Information flow for the VDT simulation.

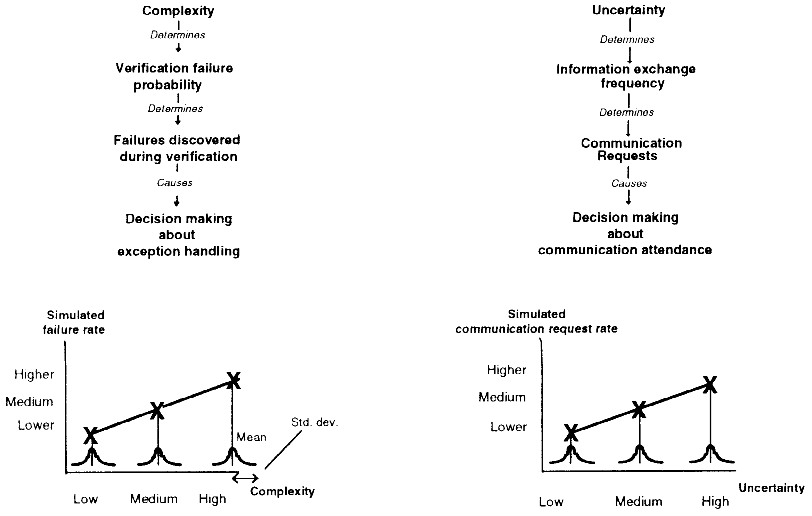


Fig. 11. The use of coordination load measures in the VDT simulation.

4.2 The effect of exception handling on performance

Figure 12 shows simulation results (from ref. 8) for duration, cost, and verification quality as a function of centralization in the TMS project compared with predictions from contingency theory[28] and the project manager of the project. Our use of the term *centralization*[24] relates to the probability for "how high up in the hierarchy" decisions about exception handling "must travel" before reaching an actor with authority to make a decision. Carrying out rework involves time and cost, while ignoring it lowers coordination quality. Thus project performance is influenced by rework decisions made by actors.

For *duration*, the expected behavior from contingency theory is based on the assumption that project managers have a global view of dependencies between different parts of the project and thus will tend to prefer rework, since they understand the potentially detrimental effect of ignoring failures in one activity on a number of dependent activities. Project team members often will engage in local suboptimization of performance by ignoring and quick-fixing failures. In addition to this, decisions from managers will be delayed by other

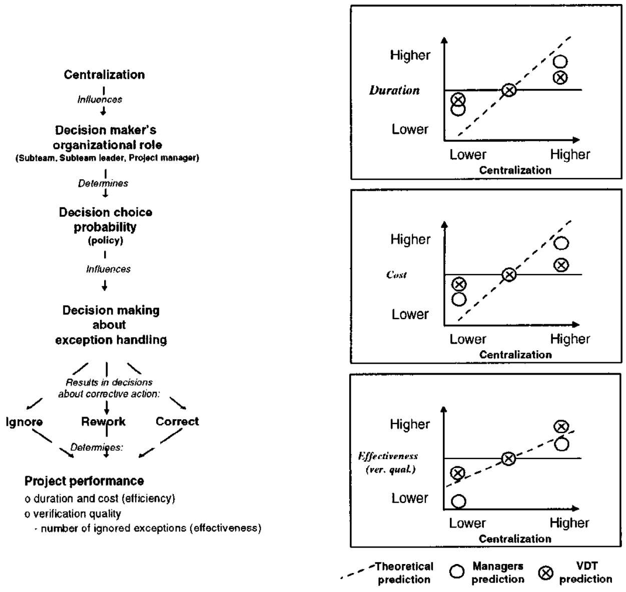


Fig. 12. Performance as a function of centralization in the TMS project.

items in their "in tray." The result is that "higher" centralization (more decisions made by high-level managers) tends to give more waiting time for rework decisions, as well as more rework. Both effects lead to longer duration. For *cost*, the contingency prediction is the same as for duration, based on the same assumption that managers favor rework, which increases the total volume of work carried out. *Verification quality* is given by the ratio of reworked exceptions to all exceptions. Higher quality means that more exceptions are reworked, and thus higher centralization gives higher verification quality. The simulation results are in good agreement with the predictions from the project manager—and consistent with contingency theory.

The simulation results illustrate that there is no universally "best" centralization policy for the TMS project. The most suitable policy depends on the degree to which efficiency or quality has the highest focus, in which case one should choose a decentralized or centralized policy, respectively. That is, the choice of coordination policy for exception handling is contingent on project objectives.

4.3 The effect of communication policy and preferences on performance

Figure 13 shows simulation results (from ref. 8) for communication quality as a function of formalization for the functionally oriented "weak" matrix team[12] of the TMS project compared with similar results for a project-oriented "strong" matrix team.[12] For both sets of results, the simulation predictions are compared with predictions from contingency theory[28] and from the project managers of the two projects. See ref. 7 for a discussion of the modeling and simulation of the "strong" matrix team.

Our use of the term *formalization*[24] relates to the fraction of communication that is handled by formal prescheduled meetings as opposed to informal information exchange. A formal communication policy mandates prescheduled project meetings with mandatory attendance by selected team members. An informal communication policy relies on frequent face-to-face communication between physically colocated project team members. Participation in communication involves time and cost, while lack of participation lowers coordination quality. Thus project performance is influenced by actors' decisions about communication attendance.

Actors' decisions on whether or not to attend are influenced by the match between communication policy (type of communication) and the communication preferences (culture) of the project team. For a "weak" matrix team,[12] the assumption is that lack of physical colocation and involvement in several simultaneous projects tends to distract team members, who thus prefer formal project meetings to structure their participation (higher performance for high formalization). For a "strong" matrix team,[12] focus and colocation ensure frequent and informal information exchange, and attempts to formalize the communication degrade motivation (higher performance for low formalization). In both cases, the simulation predictions compare well with the predictions from theory and from the project manager. The results illustrate how different cultures for handling project communication are likely to affect project performance.

We see from Fig. 13 that project performance is again contingent on situational factors. There is "no best way" to formalize communication. Lowering formalization, which is predicted to increase communication effectiveness of a "weak" matrix team, will decrease the effectiveness of a "strong" matrix team. Thus the choice of coordination policy for communication is contingent on the preferences (culture) of the project organization.

5 SUMMARY AND FUTURE RESEARCH DIRECTIONS

For both centralization and formalization, the model behavior reflects the contingent nature of project performance,[28] consistent with predictions based on theory and real-world experience. We claim that this is a result of a consistent representation and correct behavior of the model.

All simulation results give the order of magnitude of qualitative change as selected input variables are altered. Because of a set of stochastic element in the VDT model, several simulations are necessary to obtain statistically stable results. The simulation results are stable in the sense that changes in input variables give consistently larger changes in output variables

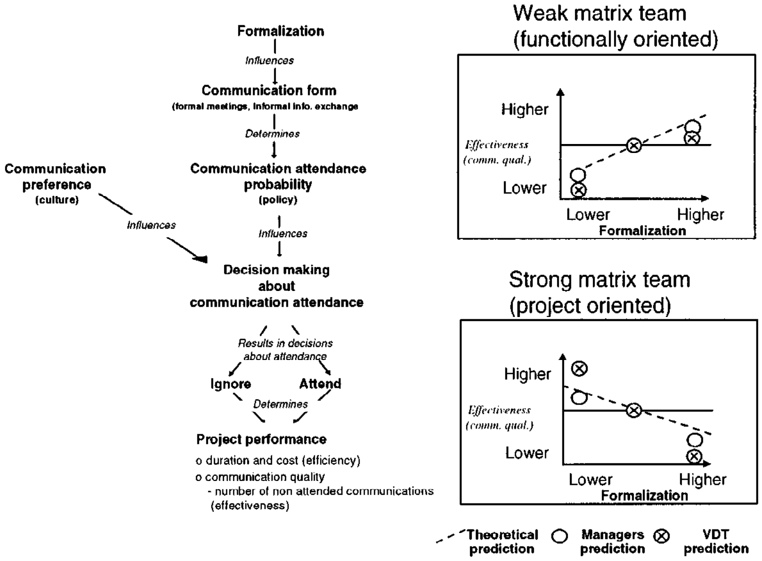


Fig. 13. Performance as a function of formalization for different projects.

than the standard deviation of the mean of those same output variables. We view this as an indication of consistent model behavior.

In Fig. 10 the policy and preferences for coordination are shown as control variables. That is, we vary policy and preference variables for a given coordination load and organizational capability and run series of simulations to obtain the resulting performance estimates. Given that our model behaves similarly correctly for these alternative aspects of project enterprise, we may use it to study the various tradeoffs between alternative ways to plan, man, and execute projects. An example is the tradeoff between duration and cost in adding extra personnel to given activities. Another example is the tradeoff between scheduled duration and the amount of generated rework (and thus actual duration) when the project plan mandates concurrent execution of activities.

Throughout this paper our style has been descriptive. We believe that our framework also can be used prescriptively for designing better project configurations. However, we feel that further calibration against real-world experiences is required to build up faith in our approach. After all, the only real differentiator between believing something you can check and something you cannot check is faith. We must therefore formally validate the various aspects of the framework, methodology, and simulation tool. We also must gain experience by modeling and analyzing projects in a number of different industries.

Further development of VDT takes place both at Stanford University in the United States[20] and at Det Norske Veritas Research in Norway. We are extending our representation of product requirements[5] and adding explicit representations of performance objectives.[9] As indicated in Fig. 5, this will allow us to include assessment of realized solutions and evaluation of project enterprise. We are also investigating how we can use our simulated predictions for coordination quality of process activities as an indication of expected problems with the solutions produced by these activities. This will allow us to extend modeling and simulation beyond engineering[5] to get input for predictions about product quality and maintenance planning requirements.

Also, we plan to study the *implementation* of proposed changes in different projects to understand how to best relate project models to actual project execution. We hope that in the future our framework and methodology will be used to build models that create insight and understanding for better project planning and that these models may be used to predict probable effects of proposed change. We can then use the model as a base for turning performance predictions into performance improvement.

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