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A Proposed Trajectory of Validation Experiments for Computational Emulation Models of Organizations[1]

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Abstract

Validation of complex simulation models, with multiple inputs and feedback loops, is a challenging, multi-faceted problem. It has received considerable attention in the Computational Organizational Science (COS) literature. The COS literature typically calls for extensive validation and discusses some guidelines for when certain techniques are appropriate. However, reports of rigorous external model validations are limited. In this paper, we use an organizational design and analysis tool, called the Virtual Team Alliance (VTA), to illustrate that one needs to perform a series of validation steps in a predefined sequence to accomplish a comprehensive, credible validation of a computational organizational simulation model. The purpose of the VTA model is to provide managers with a tool that they can use to test "virtual prototypes" of project organizations and predict outcomes prior to actual implementation—it can therefore be described as an "emulation" system. The ultimate external validation of VTA is whether or not it is useful to managers for this purpose. VTA is useful if the model forecasts problems that will occur without organizational change, managers redesign the organization based on the model's problem predictions and suggested remediations, and the organizational risks, which the model predicted are thereby reduced. To reach this kind of ultimate external validation of usefulness, VTA has to go through a "trajectory" of different validation methods. The primary contribution of this paper is the development of an innovative validation trajectory strategy for complex computational emulation models. We present a validation trajectory that includes (1) computational synthetic experiments, (2) retrospective validation and comparison with manager's "what-if" predictions, (3) contemporaneous validation, and (4) prospective validation with intervention. We discuss in some detail how we applied VTA to two portions of an ongoing aerospace project. The VTA model made predictions about severe bottlenecks and potential quality problems for one sub-team within the two project teams but no problems for the other sub-team. These predictions were subsequently confirmed. The results of our experiments agreed with those of extant, qualitative organizational theory.

Key Words and Phrases: Contingency Theory, Computational Organizational Simulation Models, Information Processing, Intervention, Organizational Design, Validation.

1. Introduction

Computational Organizational Science (COS) has come of age, enabled by ubiquitous, low-cost desktop computers and modeling techniques from artificial intelligence. The

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COS community has produced several lucid models that have provided valuable insights into organizational phenomena (e.g., Cohen *et al.*, 1972; Huberman and Hogg, 1995; Hyatt *et al.*, 1997; Carley and Lin, 1995; Oralkan, 1996; Masuch and LaPotin; 1989; Zeggelink *et al.*, 1996). However, the implications of these findings for practice have been limited because the models have been intentionally simple and abstract, and used primarily for generating new theory fragments.

The Virtual Design Team (VDT) (Cohen, 1992; Christiansen, 1993; Jin and Levitt, 1996) showed that computational organizational models could provide accurate predictions for routine, fast-paced project organizations in which all participants were assumed to have congruent goals. Building off the VDT, the Virtual Team Alliance (VTA) model extended the existing VDT information-processing model to incorporate characteristics of semi-routine, fast-paced projects, and the notion that project participants could have incongruent goals (Thomsen *et al.*, 1998b). The purpose of the VTA model is to provide practitioners with a modern approach to organizational engineering of fast-paced, semi-routine project organizations. By running suites of simulations to analyze the effects of different model input variables, VTA can provide managers with predicted outcomes prior to actual implementation.

Validation of full-fledged, complex computational organizational models such as VTA, with multiple inputs and feedback loops, is a challenging problem that has received considerable attention in the COS literature (e.g., Baligh *et al.*, 1994; Burton and Obel, 1995; Carley, 1997). Typically, researchers call for validation, provide useful taxonomies of computational models, and elucidate the relative benefits and drawbacks of different validation approaches. In this paper, we focus on validation of emulation models (also referred to as wind tunnel or computational organizational engineering models). Since the ultimate purpose of emulation models is to provide detailed and explicit advice to practitioners on organizational design issues, emulation models require extensive real-world validation (Carley, 1997). Following Law and Kelton (1991), we argue that validation of emulation models is not a binary issue—i.e., valid or not valid—but a matter of degree. A validation strategy encompassing multiple validation methods is necessary to give emulation models as much credibility as possible. We present an innovative emulation model validation strategy and discuss how we validated the VTA model during a three-year period using this strategy.

In the following sections of the paper, we first briefly describe the overall functionality of the VTA model to illustrate that it is a complex model and therefore that validation is a non-trivial activity. Section 3 presents four validation steps for emulation models and summarizes how we performed them on the VTA model. Having provided an overview of the validation strategy, sections 4, 5, and 6 provide a detailed illustration of how we performed contemporaneous validation. Section 4 describes two portions of a real-world launch vehicle development project that we used as a test case. Based on organizational theory and our case project managers' challenges, section 5 develops detailed hypotheses that guide a set of "virtual experiments" carried out on the model of the case study with the VTA framework, as described in section 6. We conclude our paper with a summary of our practical and theoretical contributions to COS, our validation strategy's limitations, and suggestions for future work.

2. The Virtual Team Alliance (VTA) Model

In a companion paper, "The Virtual Team Alliance (VTA): Extending Galbraith's Information-processing Model to Account for Goal Incongruency" (Thomsen *et al.*, 1998b), we describe in detail the workings of the VTA model and their internal validation. This section provides the reader with an overview of that only.

VTA extends existing contingency theory (Thompson, 1967) and Galbraith's information-processing theory (Galbraith, 1973, 1977). Galbraith and other contingency theorists focus on organizational behavior at the level of the entire organization and do not concern themselves with the internal dynamics of the organization. We have extended contingency theory to develop a micro-contingency model of goal incongruency and organizational behavior within a broader information-processing framework. This model uses actors and the relationships between pairs of actors as the fundamental units of analysis.

Within the larger framework provided by Galbraith's information-processing model, VTA incorporates and operationalizes qualitative organizational theories that describe behavior at the level of individual actors and relationships. These theories cover the behavior of actors embedded in vertical dyadic relationships in the organizational hierarchy as well as the behavior of peer actors working on interdependent tasks. We depict organizational actors as relatively simple, goal-oriented, information processors and communicators with finite or "boundedly rational" capacity (March and Simon, 1993). Their work is choreographed by

- relatively abstract, flexible, sequentially and reciprocally interdependent information-processing activities assigned to them (Thompson, 1967), and
- organizational structures that handle exceptions from pre-planned activities reactively in the spirit of Galbraith (1973, 1977) and that proactively monitor the behavior of subordinates (Ouchi, 1979; Eisenhardt, 1985).

Exceptions are unexpected results that occur (1) during the process of product development, which overwhelm the cognitive capacity of the responsible team member (Galbraith, 1977) or (2) when an actor makes a decision about an engineering process that deviates from the usual process. We distinguish between three types of exceptions: technical errors, productive non-conformances, and counterproductive non-conformances. Technical errors are always detrimental to the product quality or successful completion of the desired objective and must be corrected to ensure the reliability and functionality of the product. Productive non-conformances are beneficial non-conformances that represent acceptable technical solutions that are superior to those anticipated by the manager or the project plan, i.e., they achieve a more desirable trade-off among project goals in terms of cost and duration. Counterproductive non-conformances represent alternative satisfactory technical solutions that are inferior to those anticipated by the manager or the project plan in terms of cost and duration.

There are two communication processes modeled and simulated in the VTA model: exception generation and information exchange. We also modeled two kinds of decision-making: attention allocation and whether or not to do rework when an exception is detected. We model seven "canonical" micro-interaction processes between actors using these two communication and decision-making processes: three interaction processes for vertical relationships—monitoring, selective delegation of authority, and exception generation—and four for lateral relationships—steamrolling, politicking, searching for alternatives, and clarification of goals. Steamrolling and politicking entail more counterproductive non-conformances, whereas searching for alternatives and goal clarification entail more productive non-conformances. The relative proportion of steamrolling and politicking behavior to searching for alternatives and goal clarification will be greater at higher levels of goal incongruency than at lower levels (Pfeffer, 1981). As more "productive" ideas are generated, problem-solving quality increases, and as more "counterproductive" ideas are generated, problem-solving quality decreases.

The total information-processing capacity of an organization is given by the aggregate information-processing capacities of its actors, mediated by the efficiency of the communication network that connects the actors together. The total information-processing "load" on the organization is derived from the project requirements, which must be met.

In this information-processing view, organizational performance emerges as a product of the fit between the load on the organization and the organization's capacity to handle that load (Tushman and Nadler, 1978). Specifically, VTA produces two measures of efficiency—project duration and total salary cost—and three measures of work process quality: problem-solving quality, coordination quality, and decision-making quality. In addition to providing a project manager with measures to support complex organizational design decisions involving trade-offs between cost, duration, and work process quality, VTA predicts risks that might adversely affect project performance. Users can identify and test feasible and useful interventions to mitigate the risks that have been identified.

3. Testing and Validation of Emulation Models

In this section, we first distinguish between testing and validation. We argue that an emulation model can be divided into three components and that each component needs validation. The section then presents four validation methods that comprise a comprehensive and credible validation strategy of emulation models. We conclude this section arguing that our validation strategy can be conceptualized as a "trajectory" in two-dimensional space spanned by "emulation model components" and "validity types."

3.1 Testing versus Validation

We use the following definitions to distinguish between testing and validation. Testing, often referred to as "internal validation," is the process of establishing that the computer implementation of the model is error-free and that the computer implementation is a correct representation of the logical behavior of the conceptual model built by the analyst. Testing is not concerned with the process of establishing whether the conceptual model is a reasonable representation of the phenomena of interest. The latter process is validation (Cohen, 1995). In this paper, we focus on discussing validation methods for emulation models.

3.2 Emulation Model Components and Their Validation

In constructing computational organizational models, researchers must balance between simplicity and veridicality (Burton and Obel, 1995). The balance point depends on the purpose of the model. The higher the asserted veridicality, the greater the need for in-depth and higher levels of validation (Carley, 1997).

In order to discuss validation, we define an emulation model as consisting of three major parts. All three parts must be validated through rigorous, clearly defined procedures.

(1) An *input model* describes the organization in question through established variables. It is impossible and unattractive to represent the real world in its entirety. Based on the questions one wants to investigate, one extracts and simplifies the most important aspects of reality. The problem being investigated suggests a sufficient, but not comprehensive, representation of the real world for the phenomena being studied.

(2) A *reasoning model* includes the simulation. The parameter representation of the input model is linked to reasoning or behavior in the simulation model. The behavior in the simulation model is, of course, less complex than the real world. It is created at level which is neither so complex that the model becomes ponderous and inefficient, nor so abstract and simplistic that the model produces no practical insights.

(3) An *output model* provides the results of the simulation. The simulation model behavior determines the emergent output. The difference between the actual project outcome and the simulated project outcome is a measure of how accurate the computational model is in running simulations and making performance predictions.

Emulation models typically represent micro-organizational attributes in some detail (e.g., activity uncertainty in VTA). In all modeling enterprises, it is imperative that precautions are taken to ensure that any given model remains undistorted by inter-rater biases or variations in procedure on the part of the modeler. Input data are subject to strong biases that reflect the personal background of the modeler. For example, the modeler may lack sufficient domain-specific expertise to correctly identify and interpret all relevant data pertaining to the organization and its work processes. Whenever possible, we attempted to derive input data using a formalized methodology, e.g., activity complexity, activity interdependence strength, and goal incongruency in VTA (Thomsen *et al.*, 1998a). The methodology nevertheless requires some skill and judgement. In this case, the methodology for generating input itself requires validation. We employed the kind of inter-rater validity checks used by social scientists who design and test survey instruments to ensure that the input data is valid (e.g., Babbie, 1995).

For semi-routine, fast-paced project organizations, behavioral micro-processes are relatively well understood, but the complexity of their interaction overwhelms closed-form mathematical solution approaches. Indeed, emulation models are necessitated by the inability of the human mind to extrapolate from understanding of canonical micro-processes to predictions regarding the emergent effects of these processes in a non-linear, complex web of relationships. The approach in VTA was to use, as far as possible, widely accepted or canonical micro-behaviors of actors (monitoring, selective delegation of authority, exception generation, searching for alternatives, goal clarification, steamrolling, and politicking). We relied on economic agency theories about supervisor-subordinate behavior and social psychological theories about peer-to-peer behavior (Thomsen *et al.*, 1998b). When theories were lacking, we gathered our own empirical data to validate the behavior we chose to implement.

If the input data is inter-rater validated, and canonical micro-behaviors are validated in the extant literature or through new observations, then we are ready to compare the emergent behavior of the model against qualitative predictions from macro-organizational theory and real-world data. This is an extremely challenging task that requires a variety of validation methods. We used (1) computational synthetic experiments, (2) retrospective validation and comparison with manager's "what-if" predictions, (3) contemporaneous validation, and (4) prospective validation with interventions.

The next sub-section summarizes these approaches, and section 4, 5, and 6 provide a detailed description of how we conducted contemporaneous validation on a project that developed a new launch vehicle for bringing satellites into space.

3.3 Validation Methods

A number of valuable validation methods has been proposed in the COS literature, such as grounding, calibrating, verification, and harmonization (e.g., Carley, 1997). Based on the emulation model purposes, we supplement these validation methods with four methods that we think are necessary to move emulation models from being useful to researchers to being useful in the realm of practitioners as well.

3.3.1 Computational Synthetic Experiments

We applied VTA to a number of small synthetic test cases—"toy" organizations—simple enough models that they could be analyzed manually. Based on the actor and activity micro-behavioral assumptions, we could adjust the model until its micro- and macro-predictions were consistent with our expectations. This method has the advantage of being relatively easy to perform, but is limited in that it does not necessarily relate to realistic large-scale test cases. The purpose is first to calibrate the micro-behavior of the model for the toy problem against the micro-theoretical predictions. Second, we want to validate the emergent macro-behavior of the model according to the predictions of established organizational macro-theory, and to understand which model variables were dominant and how they interacted (Thomsen *et al.*, 1998b).

3.3.2 Retrospective Validation and Comparison with Manager's "What-if" Predictions

We calibrated the internal variables of VTA against past data from a completed project. After adjusting VTA calibration parameters to reflect past project outcome data, we were able to reproduce the actual project outcomes. Then we applied VTA retrospectively to another completed real-world test case. We compared the simulated model predictions with the actual project outcome. Thereafter, we asked the project manager to make predictions about the effect of hypothetical changes to key input variables in the project's initial configuration (actor's skill set and goal incongruency between actors) on dependent measures of time, cost, and process quality. We compared our simulated model predictions with the project's actual outcome as well as with those of the manager's "what-if" scenarios. We ran t-tests on the data to show that the manager's prediction and the simulation results were statistically consistent.

Since VTA is an operationalization of qualitative organizational theory, the aggregate predictions of the model about the effect on a dependent variable (e.g., duration) caused by a change in a relevant input variable (e.g., actor-activity skill match) can be tested qualitatively against the predictions of the textual theory as well. VTA simulation results agreed qualitatively with this macro-organizational theory. This validation method has the advantage of relating to test cases of realistic scale, but it provides no evidence that the modeling method can be used in practice to support organizational design decisions. The ability to capture salient features of a realistic project and calibrate the values of model attributes demonstrates representational validity. Retrospective validation also provides insights into the cause-and-effect relationship between different calibration parameters and project performance (Thomsen *et al.*, 1998a).

3.3.3 Contemporaneous Validation

We applied our model to two on-going, real-world test cases and performed a series of experiments that produced forward predictions about the remaining project outcomes. These predictions agreed qualitatively with organizational theory. This method is more robust in that the researcher cannot "curve fit" calibration parameters to unknown future performance benchmarks. Rather, at the end of the project, we retrospectively compared the project's final results to the VTA's previously predicted results. Both VTA predictions about aggregate dependent variables (e.g., cost) and micro-dependent variables (e.g., actors' "in-tray depth") results agreed relatively closely with the actual project result. Thus, the study provided evidence not only about the representational validity of our model but also about its predictive power. From a managerial perspective, however, the value of contemporaneous modeling is limited, because it is more difficult to initiate interventions and mitigate risks in an ongoing project than to do this at the outset of a project. An application of the contemporaneous validation method is provided in section 4, 5, and 6.

3.3.4 Prospective Validation with Interventions

In the last of our case studies, we modeled the planned work process and organization and prospectively identified potential project performance problems. After considering our recommendations, the cooperating manager intervened in the engineering process to reduce some of the organizational risks that the model had predicted might adversely affect project performance. The manager had developed confidence in the validity of the VTA modeling approach and tools based on the accuracy of our predictions in the contemporaneous test case. In our subsequent observations of the project, the potential risks that our model initially identified as being likely to affect project performance adversely were avoided by this intervention. This prospective validation method has the advantage of providing representational validity and predictive power. Moreover, it demonstrates that our model could have significant value from a managerial perspective. We can thus claim that we have evidence of VTA's usefulness for practitioners (Thomsen *et al.*, 1998c).

3.4 Suggested Validation Trajectory for Emulation Models

To validate an emulation model against its ultimate purpose of providing practitioners with guidance in organizational design decisions, we used four validation methods. Even though the validation methods are autonomous, there is a conjunctive relationship among them. We argue that inter-rater validity checks on model inputs, computational synthetic experiments, retrospective validation and comparison with manager's "what-if" predictions, contemporaneous validation, and prospective validation with interventions are all essential building blocks in a comprehensive validation strategy for emulation models and have a logical sequence. That is, the input to emulation models has to be validated before the behavior within the model: "Garbage in leads to garbage out." The model behavior needs to be validated before the output can be validated: "Learn how to stand before walking." Finally, it is necessary to triangulate the resulting simulated outputs against predictions of macro-organizational theory and real-world data to make sure that the dynamics of the simulation model are valid—a "three-legged stool" validation approach.

Retrospective, contemporaneous and prospective validation form a hierarchy of stringency and difficulty in terms of external validation of the usefulness and credibility of emulation models. Prospective validation provides evidence that the model is useful for practitioners. Predictive power is a prerequisite for usefulness. Having predictive power guarantees representational validity. It is important to note that the validation strategy we have suggested here is a joint approach that simultaneously addresses the validity of the inner workings of the model and the results that it generates. An effective emulation model provides practitioners with measurable output predictions (e.g., project cost and duration). It also predicts factors or processes that contribute to potential performance problems and recommends possible corrective actions through virtual experiments. The internal workings of the emulation model must be rich, observable, and validated to represent relevant real-world organizational behavior.

Our validation strategy for the VTA model was to tackle the less challenging retrospective validation before contemporaneous validation and prospective validation. Contemporaneous validation and prospective validation requires that the practitioners have some confidence in the emulation model from previous validation efforts. If not, the practitioners will not be willing to base interventions on the emulation model's recommendations (Argyris, 1970; 1983).

Figure 1 depicts how we conducted the VTA validations and the validation trajectory strategy we propose for organizational emulation models.

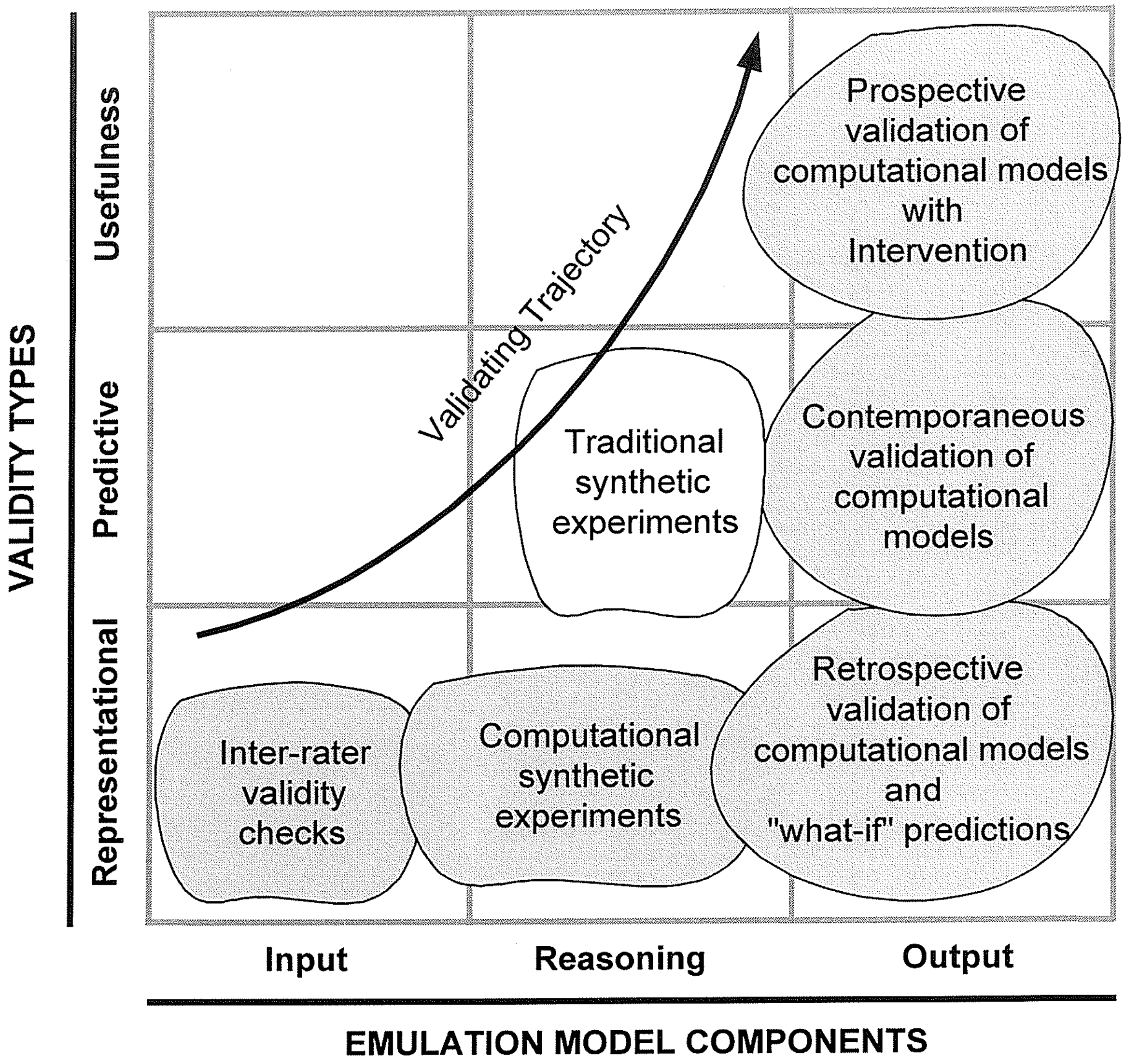

Figure 1: **Trajectory for Validating Emulation Models.** The figure depicts the validation strategy we performed during a three-year period on the VTA model. We propose that this strategy is broadly applicable for emulation models that aim at providing managers and researchers with capabilities to test virtual organization prototypes and run virtual organizational experiments. In addition to the trajectory of validation steps we performed for the VTA model, traditional Social Science, "synthetic experiments" involving groups of paid subjects might be valuable extensions to field observations or computational synthetic experiments in the course of validating areas of micro-behavior in emulation models that are not yet "canonical."

4. Launch Vehicle Development—A Case Study

This section first describes the research setting at our collaborating company, and reports on our case-study data collection approach. Following this, we describe organizational managerial challenges facing our collaborating partner and how the VTA emulation model was able to provide practical advice to our cooperating manager regarding his organizational challenges

4.1 Research Setting

We have taken our case study from a company within the aerospace industry that has traditionally developed launch vehicles for military applications. However, in light of the recent reductions in U.S. military spending and the company's entry into the commercial market, the main issue for the company today is to remain economically competitive by shrinking the time-to-market and cost of new products and by maintaining reliability. The introduction of the new launch vehicle program in 1993 marked a major milestone in the effort to build a commercially viable, versatile, and reliable spacecraft that could provide customers with quick access to space by minimizing preparation time before launch. The launch vehicle program is made up of various Product Development Teams (PDTs). We modeled two key PDTs, Avionics and Structures.

The first project team for which we created a model was the Avionics Product Development Team. The Avionics PDT was responsible for designing the electronic systems that supported such functions as guidance, telemetry, and destruct for the launch vehicle as well as for the various interconnections that link these functional systems to the rest of the vehicle and to each other. These systems were packaged in the form of flight boxes and were housed within the Equipment Section of the vehicle. The primary task of the Avionics PDT was to design and produce those flight boxes that were to be developed internally, to procure those flight boxes that were to be acquired externally, and to design and produce the cabling and interfaces. Cabling and interfaces were necessary to connect the flight boxes to each other and to other subsystems of the vehicle.

Avionics project participants were highly skilled specialists apportioned to the project by discipline-oriented home departments. They were divided into sub-teams according to function. The Avionics project manager was comfortable delegating authority and refrained from micro-management. Project participants responsible for activities were given great autonomy to come up with solutions to activity requirements. The development of new flight boxes is a highly complex process, requiring numerous iterations and extensive coordination. Product developers who used CAD systems for design tasks had to exchange information with all other sub-teams that interfaced with their particular flight box in order to produce a design that would meet shared requirements properly. For example, it was incumbent upon the designers of a flight box to communicate with the Cables sub-team in determining the type and location for all connections. Figure 2 shows our model of the Avionics PDT.

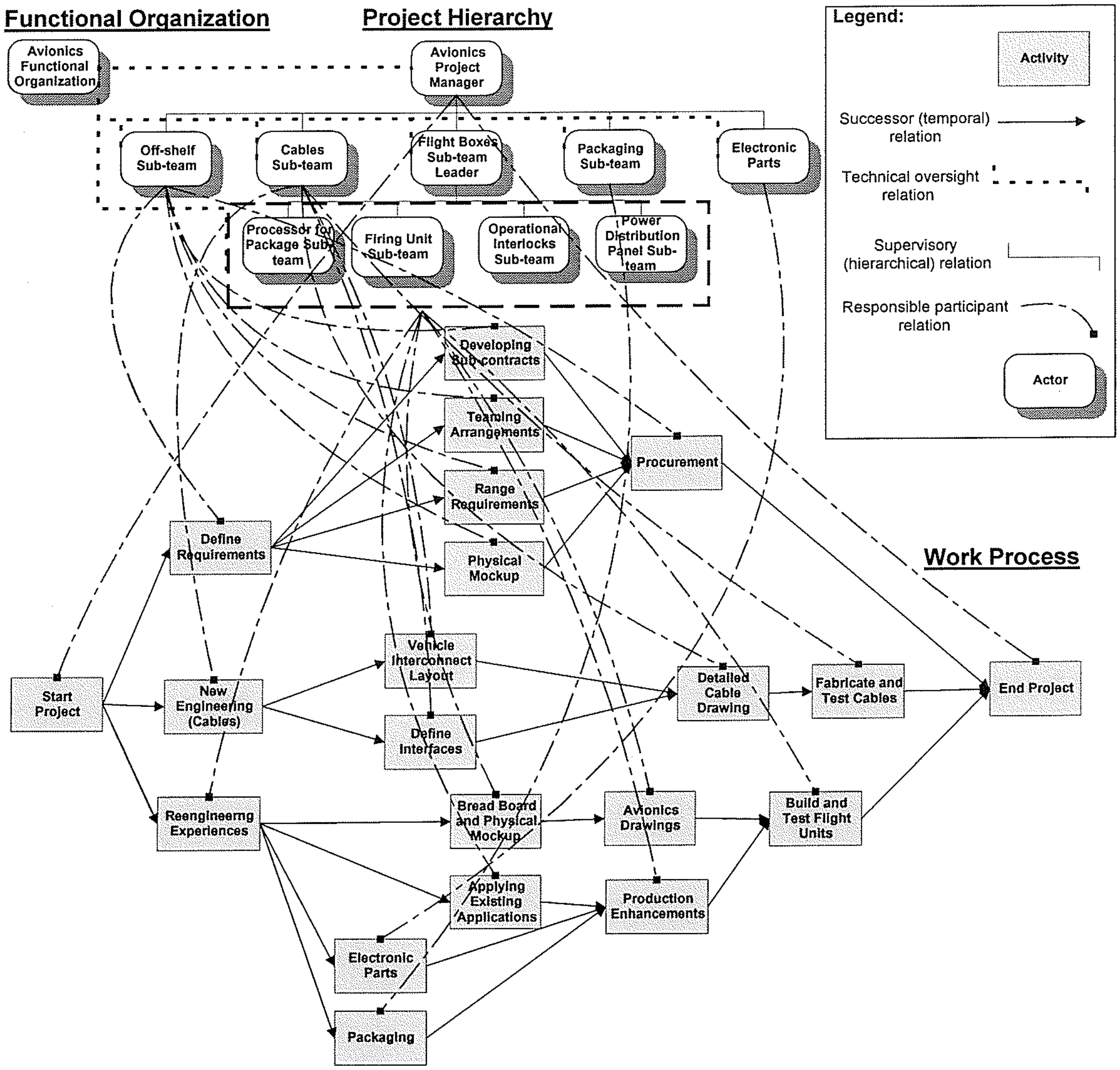

***Figure 2*: The Avionics Development Project Work Process and Organizational Hierarchy.** In our conceptual model, a project has two building blocks—the actors (embedded in an hierarchical organizational structure) and the activities (the Critical Path Model (CPM)). That is, each actor fills a position in the organizational hierarchy and works on one or more activities; the organizational structure and the interdependence between activities define relationships between actors. Avionics has a matrix structure in which subordinates report to two supervisors at the same time—one supervisor responsible for the project, and one responsible for a particular functional discipline. To incorporate this influence of functional managers in our model, we represent functional managers explicitly as actors.

The second project team for which we created a model was the Structures PDT. The Structures PDT was responsible for the development of the overall physical structure of the launch vehicle and the various structural components, which constitute the general framework for the vehicle.

The members of the Structures PDT were highly skilled professionals. The project manager served in a dual capacity as the Structures PDT leader and as the leader for the structural design functional group. The Structures project manager was not comfortable delegating authority and engaged in micro-management. The Structures PDT activities were highly specified and therefore gave very little flexibility to the responsible actors.

The Avionics and Structures PDTs differ considerably on a number of important dimensions. The Avionics PDT is characterized by high level of interdependence between activities, high activity flexibility, high level of goal incongruency, and a low preference for micro involvement by the Avionics project manager. Following March (1991), we refer to this as an "exploratory" project team. In contrast, the Structures PDT is characterized by a low level of interdependence between activities, a low level of activity flexibility, low level of goal incongruency, and a high preference for micro-involvement by the Structures project manager. We refer to this as an "exploitative" project team.

4.2 Data Collection

We obtained data on the organizations through semi-structured interviews with key project members, which we then used to construct the models in conjunction with continuous input from project participants. We conducted roughly forty interviews in the period from January 1995 to February 1997. Most interviews were tape-recorded and transcribed. We conducted interviews with project participants at all levels of the hierarchy, ranging from the vice-president responsible for the entire division (of which the launch vehicle program was but one element) down to individual project designers. Project team leaders were typically consulted on a bi-weekly basis to evaluate our results. When the input representation of the project was completed, our research to that point was presented in a technical report (Thomsen and Kwon, 1996) that received verification from the project managers. Later simulation results were also discussed with other project managers in order to validate the inputs and behavior of our model (Thomsen *et al.*, 1996). Before conducting virtual experiments, we asked managers for simple predictions, and examined whether our model generated results comparable to those predicted by the managers.

4.3 Managerial Organizational Challenges

Two main organizational challenges faced the Structures and Avionics development team project managers:

1. The launch vehicle program was assembled from multiple participating organizations, and consisted of multiple constituent sub-teams. The participants inevitably include members whose goals differ not only within the team, but also across teams. Project teams need to work unencumbered by close managerial scrutiny, highly formalized detailed plans, supervisory approvals and other "bureaucratic delays." Work autonomy or flexibility is needed to meet aggressive cost and duration goals. However, cost overruns and missed deadlines might be the result if there is too much goal incongruency between interdependent actors in the face of activity flexibility. The specific question that the project manager had to consider was the following: *What level of goal incongruency should I encourage so that: (1) task interdependencies can be worked out, (2) issues involving technical trade-offs between various perspectives can be resolved, and (3) solutions and approaches that build upon the diversity of relevant expertise and perspectives can all be determined?*
2. The earlier, military-related focus on product performance at virtually any price has been replaced by a focus on product cost-effectiveness and timeliness as the most important organizational goals for our cooperating aerospace company. These three drivers (cost, schedule, and quality) are not independent variables. Given the cost-schedule-quality priority for the launch vehicle, the design approach is very sensitive to cost, and must allow capability within cost and schedule to define the required quality. Quality requirements and cost-driven capabilities must find a middle ground where adequate quality can be achieved for a reasonable cost. However, most of the project participants have gone through extensive education and training in classified military product development projects, becoming steeped in the product performance *Weltanschauung* of such programs. The specific question that the project manager had to consider was the following: *Which participants do I allocate to activities to:*

(1) create a collaborative, innovative project environment, and (2) to increase the likelihood that the team will meet not only quality standards, but also tightened cost and duration goals?

Neither Critical Path Models (CPM) nor VDT can give practical answers to these questions. CPM (Moder *et al.*, 1983) project scheduling tools ignore coordination and rework, and VDT (Jin and Levitt, 1996) ignores goal incongruency between professionals from multiple disciplines. Our VTA model is an attempt to bridge this gap by providing a tool for developing theory and analysis tools to allow project managers to balance organizational design and management policies in such a way that optimum performance is achieved for a given level of goal incongruency.

5. Hypotheses

VTA can be thought of as a hypothesis-testing machine. Since we are focusing on validation in this paper and the managerial challenges are related to goal incongruency, this section will generate a number of hypotheses in regard to goal incongruency.

Deriving specific, testable and interesting hypotheses from organizational theory is not easy. Organizational science tends to be qualitative, descriptive and aggregate. Thus, even qualitative predictions may require interpretation and balance of conflicting theoretical arguments (Burton and Obel, 1995). The body of theoretical research described in a companion paper (Thomsen *et al.*, 1998b) supports the following hypotheses.

Hypothesis 1 (H1): ***Problem-solving quality****, the ratio between (productive non-conformances minus technical errors and counterproductive non-conformances) to (total number of exceptions), will peak at moderate levels of goal incongruency and drop at both lower and higher levels.*

Higher goal incongruency leads to more problem-solving communications. Because of the limited information-processing capacity of actors, a high number of communications will result in more non-attended communications (Simon, 1997). Non-attended communications are communications that are not processed because of negligence or overload on the part of the actor responsible for processing the communication. However, a very high level of goal incongruency may lead to a collapse in communication and ultimately to phenomena known as steamrolling and politicking (Pfeffer, 1981; Thomsen *et al.*, 1998b). Non-attended communications lead to breakdowns in coordination, since important requests for information may not be heeded, or vital information may not be received. Therefore, the more communications that are attended to, the lower the probability that misunderstandings or lack of information will degrade the coordination quality of the project.

Hypothesis 2 (H2): ***Coordination quality**, measured in terms of the number of attended communications divided by the total number of communications, will monotonically decrease with increasing goal incongruency in a relatively linear fashion.*

Typically, higher levels of goal incongruency cause more communications and more exceptions to be generated on the project. Because of limited information-processing capacity of supervisors, more default delegations will occur. Default delegations represent exceptions which are decided upon by an inappropriate actor due to the lack of timely decision-making about the exception by the appropriate actor. Each undetected exception represents a failure of the organizational members' ability to monitor their own behavior. A low proportion of detected exceptions to total exceptions indicates that the existing exception detection and handling system is flawed.

Hypothesis 3 (H3): ***Decision-making quality**, measured in terms of the ratio of the number of exceptions decided upon by the appropriate personnel in a timely manner to total number of exceptions, will monotonically decrease with increasing goal incongruency in a relatively linear fashion.*

Organizational theory qualitatively predicts that goal incongruency can increase the diversity of behavioral repertoires available to the project to meet the requirements imposed by the environment and will therefore improve project performance, e.g., reduce project duration and cost (Weick, 1979). At the same time, organizational theory indicates that too much goal incongruency can lead to time-consuming arguments and undermine project performance, i.e., increase project duration and cost (March and Simon, 1993).

Hypothesis 4 (H4): ***Project duration**, measured in terms of the total time required for the project to be completed successfully, will vary as a concave upwards U-shaped function with goal incongruency.*

*Hypothesis 5 (H5): **Project cost**, measured in terms of the total work volume generated by the project, will vary as a concave upwards U-shaped function with goal incongruency.*

Goal incongruency between two peer actors will have a direct effect on actor behaviors only if they are reciprocally interdependent (Thompson, 1967). If the work of one of two peer actors were completely independent of the work of the other, the actors' incongruent goals would be inconsequential. Two incongruent actors are more likely to desire different solutions if the solution space is large (i.e., high activity flexibility), since each actor has a greater probability of finding a solution which differentially meets his or her particular preferences.

Hypothesis 6 (H6): The effects of goal incongruency on all project performance indicators should increase with increasing levels of activity flexibility and interdependence between activities.

The next section presents and discusses a computational experiment that tests our hypotheses and provides the cooperating project managers with insights into their organizational challenges.

6. Computational Experiments and Results

The primary purpose of our experimentation program was to: (1) test our hypotheses (section 5) regarding the effect of goal incongruency between organizational actors on project team performance, (2) provide an illustration and evidence of how our model can be used to predict project schedule, process quality and cost risks, and (3) to provide the cooperating project management with guidance in relation to their managerial challenges.

Our simulation results from the Avionics and Structures models can be divided into two categories. The first set of results involves the straightforward predictions made by our model regarding the future behavior and performance of the actual project. The second set of results pertains to the data we obtained from a series of what-if experiments, in which our model predicted the likely performance of the project teams.

6.1 Model Predictions for the Project Teams: Initial Conditions

The dynamic VTA simulation of the information-processing behavior of our model for the Structures PDT did not predict any significant deviation from the original project plan or from the anticipated performance of the project. However, the model for the Avionics PDT predicted a severe risk of coordination bottlenecks within two of its subteams, the Cables Subteam (Figure 3) and the Flight Boxes Subteam, that represent risks of significant increasing time and cost for the project. Of the two cases, the overload on the Cables Subteam was greater.

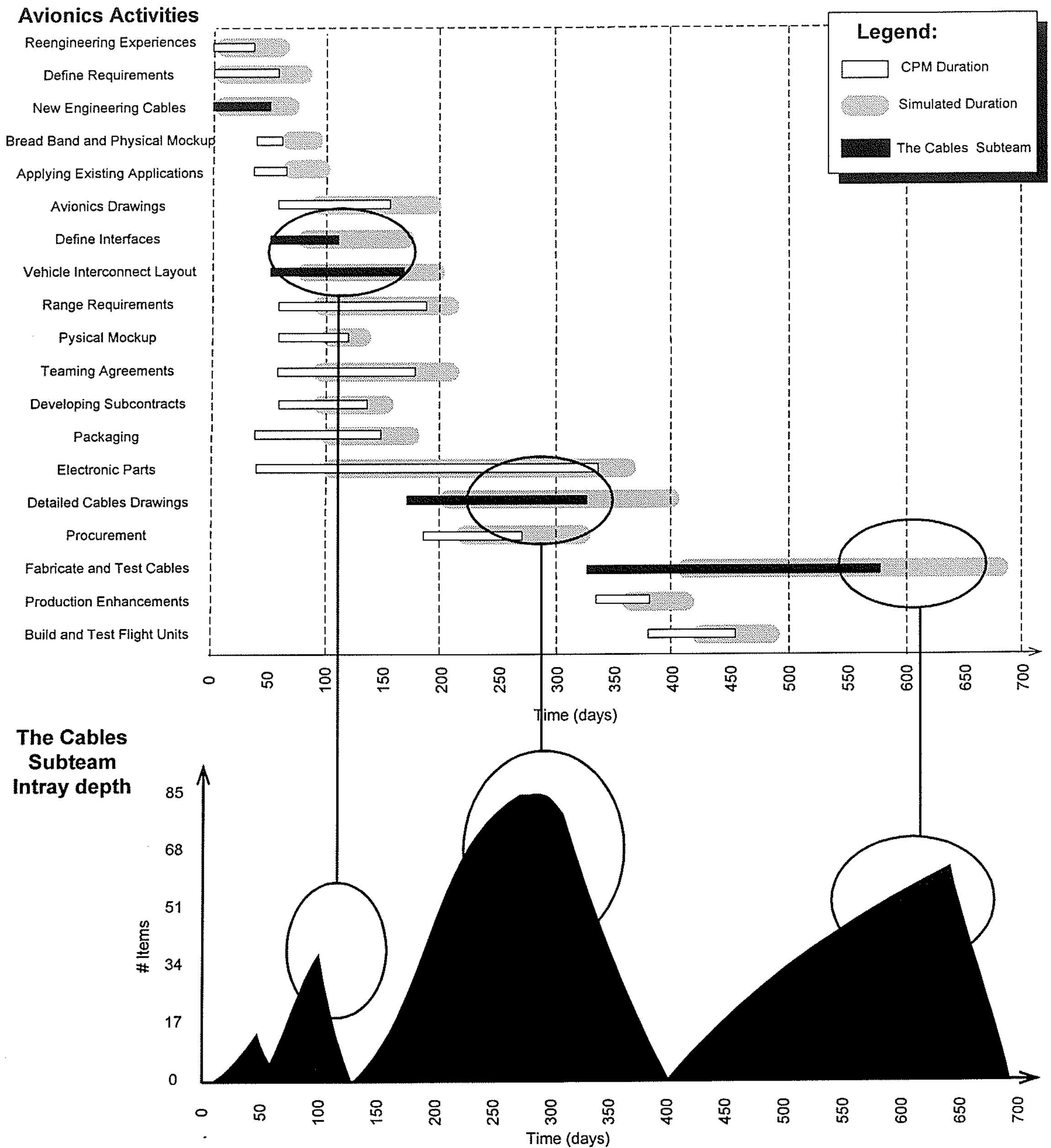

Figure 3: **Bottlenecks and Overloads in the Avionics PDT.** The top diagram is a Gantt chart of the Avionics PDT simulation. The thin black or white bars represent durations for each activity anticipated by the CPM, and the thicker, shaded bar overlaid on each thin bar represents the predicted duration in our simulation. We can see that the simulated activity durations by the Cables Subteam greatly exceeded the anticipated durations. The bottom diagram depicts the predicted in-tray depths for the Cables subteam. We can, again, see that the in-tray depth of the Cables Subteam was exceptionally large and that this subteam was greatly overloaded.

The manager for the launch vehicle program project considered our VTA analysis to be reasonable, and he felt that it predicted real risk to the cost, schedule and quality. Since the severe backlog occurred in an external team developing an outsourced component of the avionics package, there was a limited range of feasible interventions for this project at the time our study was performed.

In light of the managerial organizational challenges (section 4.3) and our simulation results, an appropriate managerial intervention could be to ensure that professional project engineers aligned their goals to those of the project and to each other. With lower goal incongruency, actors would need fewer communications to integrate their diverse perspectives and they could devote more attention to the primary work for which they were accountable. There are at least three ways to accomplish such an intervention:

- **Reduce use of outside subcontracts**: In the traditional procurement procedures of our cooperating partner, most parts were fabricated internally. However, substantially faster implementation than previously achieved with comparable military launch vehicles necessitated that parts were procured following an open bidding process. Such “make-or-buy” decisions had historically resulted in a “make” decision. Because of heightened cost pressures in our case study, much work was outsourced to external component suppliers whose goals were incongruent with those of the prime contractor. An option for the project manager could therefore be to reverse the “buy” decision and instead choose to “make.”
- **Increase micro-management**: The project manager had more relevant technical experience (he had 15 previous years experience as a rocket scientist) than any other member of the project staff. He could, therefore, also offer to help when needed with a telephone call or a visit to any project participant or participants who struggled to find a trade-off solution to a number of concurrent desired goals.
- **Introduce "inside" and "outside" incentives**: The project manager could attempt to incentivize "inside" project participants (from the same organization) to emphasize the manager’s goals through performance appraisals. Outside subcontractors' goals could be regulated through contractual arrangements—e.g., by use of incentives for critical performance metrics in vendor contracts.

In the next section, we demonstrate how our model can represent such goal-alignment interventions and can predict how project performance as well as work process quality might be affected.

6.2 Model Predictions for the Project Teams: Hypothetical Conditions

Prior to conducting the computational experiment (Figures 4 and 5), the project managers of the Avionics and the Structures PDTs independently qualitatively predicted the effects of a systematic variation of goal incongruency on their own project teams. Project duration was anticipated to increase monotonically with goal incongruency in a relatively linear fashion. Project costs were predicted to have a "U" shape in which cost initially decreased as goal incongruency increased from zero to moderate levels and then began to increase as goal incongruency continued to higher levels. In regard to work process quality measures, the Avionics and Structures project managers could not intuitively predict the emergent effects.

Moreover, in the predictions of the Avionics PDT project manager, the effects of goal incongruency on the various performance indicators were more exaggerated than they were in the predictions of the Structures PDT project manager. In other words, the slopes of the curves that the Avionics project manager predicted for his own team were greater than those predicted by the Structures project manager for the Structure PDT.

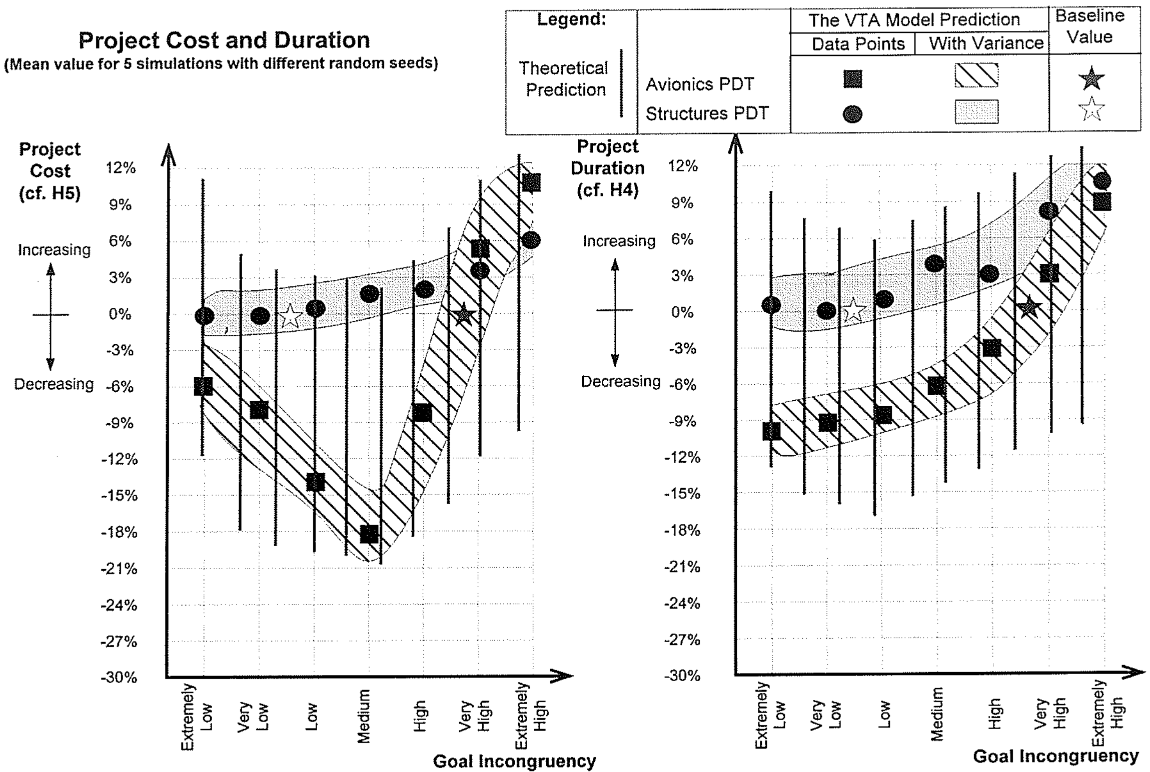

Figure 4: **Simulated Work Process Cost and Duration vs. Goal Incongruency for Avionics and Structures.** Both graphs show goal incongruency on the horizontal axis. The left graph shows project cost on the vertical axis, and the right graph project duration. We used the initial Structures and Avionics models as a baseline reference-point and changed all actor-actor goal matches to extremely low, very low, low, medium, high, very high, and extremely high. Simulation results agree qualitatively with organizational contingency theory. The results are statistically stable.

Cost was minimized at moderate to lower levels of goal incongruency both for Avionics and Structures in accordance with H5. Moreover, the fact that the graphs for the Avionics PDT are greater in amplitude and slope than the graphs for the Structures PDT indicates that the effect of goal incongruency on cost was greater for the Avionics PDT than for the Structures PDT, as hypothesized in H6. In the simulation, the intensified effect of goal incongruency in the Avionics PDT was due to the greater work process flexibility and interdependence between its members than present in the Structures PDT.

Duration was shortest at very low levels of goal incongruency and became progressively longer at higher levels of goal incongruency for Structures and Avionics—not as much U-shaped as H4 predicted, but the second derivative of the Structures and Avionics curves are clearly positive and we therefore conclude that results are consistent with H4. In addition, the fact that the graph for the Avionics PDT has more of a U-shape than the graph for the Structures PDT indicates that the effect of goal incongruency on duration was greater for the former PDT than for the latter, consistent with H6. Again, this intensified effect of goal incongruency can be attributed to the greater work process flexibility and interdependence in the Avionics PDT than in the Structures PDT.

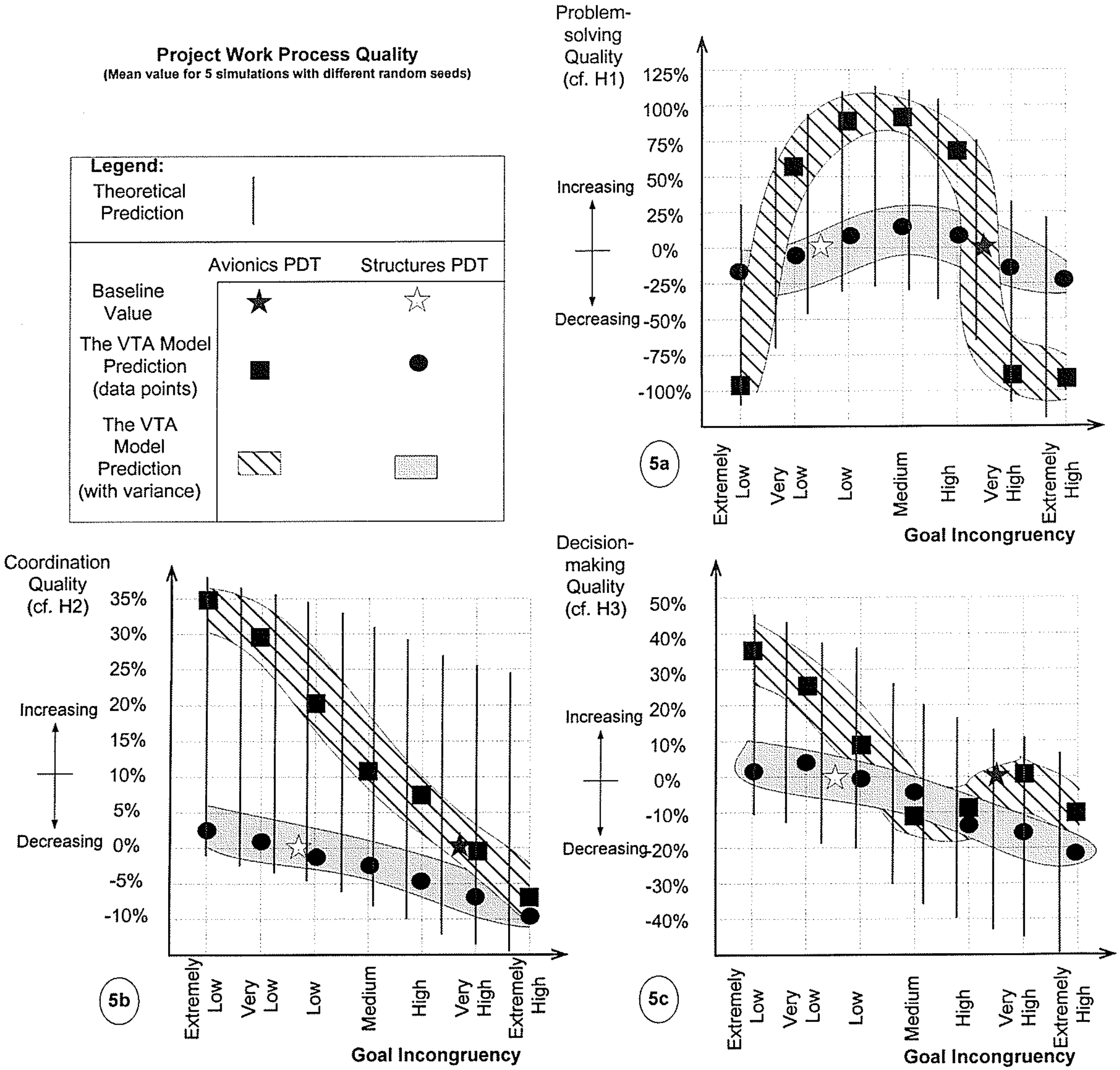

Figure 5: **Simulated Work Process Quality for Avionics and Structures.** The three graphs above show the levels of goal incongruency on the horizontal axis. Graph, 5a at top right, shows problem-solving quality on the vertical axis; graph 5b, at the bottom left, coordination quality; and graph 5c, at the bottom right, decision-making quality. We defined problem-solving quality, coordination quality, and decision-making quality in section 5. We used the actual Structures and Avionics models as a baseline reference-point and changed all actor-actor goal matches to extremely low, very low, low, medium, high, very high, and extremely high. Simulation results agree qualitatively with organizational contingency theory. The results are statistically stable.

The graphs for problem-solving quality for Avionics and Structures are, roughly, inverted U-shapes in which problem-solving quality is maximized at moderate levels of goal incongruency, as H1 predicts. At lower levels of goal incongruency, the productive non-conformances generated by searching for alternatives and goal clarifying outnumber the counterproductive non-conformances generated by steamrolling and politicking. However, at higher levels of goal incongruency, the latter two behaviors increase at a faster rate than the first two, until eventually more counterproductive non-conformances are generated. High levels of goal incongruency force actors to become overloaded by steamrolling and politicking communications. The increase in coordination volume forces actors to ignore exceptions as well as communications. The preponderance of missed exceptions and communications causes more exceptions to be generated later downstream, and, consequently, causes coordination and decision-making quality to decrease in agreement with H2 and H3. Again, the more pronounced effect of goal incongruency in the Avionics PDT than in the Structures can be attributed to the greater work process flexibility and interdependence of the Avionics PDT, as we expected from H6.

It is also clear that as goal incongruency increases, there is a distinct trade-off to be found between the five variables measuring project performance. Changing different parameters (e.g., goal incongruency) such that project performance will be maximized according to one indicator may negatively affect the other measures for project performance. Hence, before determining whether to promote or discourage goal incongruency within the team, a manager must first judge the relative importance of each performance indicator. Only then can our model of goal incongruency be applied to determine where on the performance curve the organization should be located and whether more or less goal incongruency is needed to achieve the desired performance. In providing a measure of the magnitudes of these trade-offs, our model suggests that the Avionics manager should nurture goal incongruency at a low-to-moderate level (he favored cost and duration above coordination and problem-solving quality). To change the level of goal incongruency, the Avionics manager could focus on selection of participants that were moderately goal congruent. Indeed, such an intervention would significantly reduce the Avionics backlog as well.

Because of a lack of sufficient prior experience with the modeling methodology, neither the investigators nor the project management intervened in the Avionics product development process based on our model predictions. The backlog and its impacts later materialized exactly when and where predicted, and had to be managed with a subsequent high impact on project cost and schedule. Moreover, during the demonstration launch, the launch vehicle veered off-course, and range control operators detonated the vehicle, along with its commercial payload. The subsequent analysis revealed two anomalies that caused loss of the demonstration launch vehicle:

- The first anomaly occurred 80 seconds after liftoff, when the vehicle suddenly pitched nose up. The pitch-up occurred because an electrical cable between the first-stage controller and the pitch actuator in the thrust vector control system experienced heating during flight in excess of its specifications.
- The second anomaly occurred 127 seconds after liftoff. The vehicle's inertial measurement unit (IMU), supplied by a subcontracting company, malfunctioned due to electrical arcing within the unit. The arcing was caused by exposing the high voltage circuits within the IMU to the low atmospheric pressure at high altitudes (LMMS Press Release, 1995).

The launch vehicle's instrumentation system provided extensive analog and digital data, enabling detailed analysis of the two anomalies. A company-led Failure Review Board was established to identify the cause of the loss of the vehicle and to recommend changes to eliminate the problems. The recommended changes to cables and flight-boxes were implemented, and the launch vehicle returned to flight successfully in 1997 (LMMS Press Release, 1997).

The VTA analysis predicted severe backlog problems in both the Cables and Flight-boxes subteams. The disastrous result of the first launch was caused by problems in the areas of responsibility of the Cables and Flight-boxes subteams. Our model results, therefore, provide ample evidence that product quality relates to process quality. The intuitive notion that the quality of an organization work processes affect ultimate product quality has also been demonstrated convincingly by several researchers in the facility engineering domain, most recently by Fergusson (1993). Hence models like VTA, which generate predictions of process quality, can provide indications of the levels of risk for product quality problems in particular subsystems.

7. Discussion

Since our long-range research goal is to provide project managers with a theory and tools to predict project behavior and performance through the development and analysis of a computational organizational model, it is extremely important that the model capture the key aspects of a project that determine project performance. The success of predicting emergent project behavior is fundamentally contingent on the accuracy and relevance of the rules of behavior that have been posited for the system at the micro-level. The assumptions regarding the nature of the constituent elements, as well as the rules that govern their interaction, determine the extent to which the emergent behavior generated by the simulation model will agree with both theory and real-world behavior. In order to ensure that our model captures the essentials of project behavior, extensive real-world validation is necessary.

The primary contribution of this paper is an innovative validation strategy. The validation strategy includes four validation methods:

- **Computational synthetic experiments:** We applied our model to a number of small synthetic test cases—"toy" organizations—simple enough models that their micro- and macro-behavior could be computed manually and compared to simulation predictions to test for internal representational validity (Thomsen *et al.*, 1998b).
- **Retrospective validation and comparison with manager's "what-if" predictions:** We applied our model retrospectively to a completed real-world test case and then compared the simulated model predictions with the project outcome and the manager's "what-if" predictions to test for external representational validity.
- **Contemporaneous validation:** We applied our model to an on-going real-world test case and performed a series of experiments that produced forward predictions about the remaining project outcome to test for predictive validity.
- **Prospective validation with interventions:** In our final case study, we modeled the planned work process and organization for a real project and prospectively identified potential project performance problems. These were then used to guide management interventions. This successful intervention demonstrated the model's representational validity, predictive power, and its usability by managers.

We proposed this multi-stage validation strategy for emulation models and discussed how we applied it on the VTA model. The VTA model did not remain static during our three-year-long validation period, but was extended somewhat for each of the validation steps. We conducted two contemporaneous validation test cases of VTA. We performed a three-way comparison between the predictions of the underlying organization theory, the computational model outputs, and field data for these two case studies. We conducted the virtual experiments contemporaneously with project execution. For one of these test cases, VTA correctly predicted the risk of backlog in the external team developing an outsourced component of the avionics package, as well as a serious quality problem and resulting delays. In the other contemporaneous test case, no problems were predicted and none occurred. From this small set of test cases, we have gained some confidence that the VTA model can effectively describe fast-paced project plans and support organizations; it can also predict project schedule, process quality and cost risks. Further, from our prospective validation test case, we conclude that VTA can enable managers to identify, choose, carry out and manage interventions to reduce predicted risks.

We cannot necessarily attribute the Avionics case study project performance problems to the risk we pinpointed. The project might have had the same problems had the manager intervened in the engineering process; other exogenous factors might have contributed more significantly to the outcome than the factors represented in our model. However, since we modeled two radically different teams, the "exploitative" Structures team and the "explorative" Avionics team, and our model predicted outcomes consistent with the actual outcomes in both of these teams, we are encouraged about the generality and validity of our model.

Our two case study observations do not make up the usual statistical sampling approach according to which we can do large scale hypothesis testing and ANOVA testing. But there is a good deal to learn in this sequence of "sample of one" observations (March *et al.*, 1991). We have applied our model to a series of case studies (Thomsen *et al.*, 1998a, 1998c). VTA can be viewed as an organizational inference model when applied to a series of test cases. A series of test cases create a “web of inferences.” A web of inferences provides a framework and logic for learning from multiple samples of one.

Statistical evidence of predictive validity and efficacy of our model will come only from a series of intervention studies done concurrently with similar studies done without intervention. Nevertheless, our model has gained credibility, if not from statistical validity, then from the fact that it prospectively produced an outcome that was consistent with the end results of two different project teams that we observed.

In addition to performing more intervention studies using the VTA model, we also propose to do cross-model validation, i.e., "docking" (Axtell *et al.*, 1996), between VTA and OrgCon (Burton and Obel, 1995). OrgCon is a heuristic implementation of macro-contingency theory. Both OrgCon and VTA are based on organizational contingency theory and an information-processing perspective of work, so they have essentially the same theoretical platform. It would, therefore, be theoretically sound as well as interesting to judge the degree to which the two models correspond in their recommended interventions for a particular organization. This form of cross-model validation on common data will help to advance the field of COS toward a true science.

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