Relationship between Project Interaction and Performance Indicators

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Abstract: Researchers and practicing engineers have recently paid considerable attention to alternative approaches to project integration, such as partnering, design-build, constructability, and combinations of these. Each approach may improve a project's integration by increasing the quality and/or quantity of interaction between designers and builders. It is generally accepted that project performance can be enhanced when interaction occurs on a regular basis, beginning early in the project, in an open and trusting environment. This paper presents a method for measuring a project's degree of interaction (DOI), and verifies the relationship between DOI and performance indicators such as cost growth, schedule growth, and number of modifications. The writers apply the analytic hierarchy process technique in weighting criteria for measuring DOI. Data were collected from 25 recently completed public-sector projects using traditional and alternative approaches. The projects with low DOI have a wide range of cost and schedule growth and number of modifications, while projects with high DOI tend to have better and more consistent performance indicators.

INTRODUCTION

Researchers and practicing engineers have recently paid considerable attention to alternative approaches to project integration, such as partnering, design-build, constructability, and combinations of these. Each of the approaches may improve a project's integration by increasing the quality and/or quantity of interaction between designers and builders. It is generally accepted that project performance can be enhanced when the interaction occurs on a regular basis, beginning at an early stage in the project, in an open and trusting environment.

This paper presents a method for measuring a project's degree of interaction (DOI), and verifies the relationship between DOI and performance indicators such as cost growth, schedule growth, and number of modifications. Data were collected from 25 public-sector projects using traditional and alternative approaches. These approaches include traditional design-bid-build, partnering, design-build, constructability, and combinations of these approaches. Rather than focus on these different approaches, the writers attempted to get at the issue of project integration itself. A method was developed to measure a project's DOI directly, using interaction time and the analytic hierarchy process technique to weight interaction in different phases. Each project's DOI score was compared and correlated with the performance indicators. The projects with low DOI have a wider range of cost and schedule growth and number of modifications. Projects with high DOI tend to have less variance, lower schedule growth, and fewer modifications.

BACKGROUND

Fragmentation of Project Delivery Process

Many years ago an architect or engineer could rightly be called a "master builder." The master builder designed virtually every aspect of a project, understood how it was built, and directly oversaw its construction. The project delivery process has become much more fragmented with the passage of time. The design and construction phases have been separated by traditional contracts, organizational structure, specialization, and a retreat from legal responsibility.

The traditional design-bid-build contracting method keeps designers and builders from interacting. Most engineers and architects could benefit from contractor input, but contractors are not usually involved in a project until bidding. They work from completed drawings and specifications without having any input to their contents (BR 1982).

Both private and public owners separate design and construction into different functions. Projects are typically transferred from the design organization to the construction organization with little interaction. Such separations exist both at the industry and project levels. These divisions have become so institutionalized that people from different organizations have lost some of their respect for and ability to work cooperatively with one another. Anyone who has worked in design or construction is aware of the negative attitudes engineers, architects, and contractors can have toward one another. These attitudes become part of the culture of many organizations and negatively influence communications among the different parties involved in a project.

Today architects and engineers rely on many consultants (structural, mechanical, electrical, etc.) and have backed away from their traditional responsibilities during construction. Contractors rely on a long list of subcontractors and may not even perform any work with their own forces. This division of responsibility creates significant gaps between individuals and organizations working on the same project. With the increase in the number of parties and gaps in responsibilities, litigation increases. This increase across the industry causes all players to attempt to limit their legal responsibility. Contracts are written seeking to insulate parties from lawsuits, but they contribute to the atmosphere of segregation. For example, parties may be reluctant to even be present for the discussion of project aspects for which they have no contractual responsibility.

Successful Projects

Planning, design, procurement, construction, operation, maintenance, and reuse or disposal are all phases in what should be a continuous process. Nevertheless, owners, designers, consultants, contractors, and subcontractors have chopped it into separate pieces. They each have their own project objectives and criteria for measuring success. Some criteria,

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which are common to all, include: being on time, being on budget, satisfying profit or fee goals, and having no legal claims. A recent study of 16 construction projects used these criteria to identify four critical factors of successful projects: (1) A cohesive team to plan, design, and construct the project; (2) contracts that encourage team behavior and allocate risk fairly; (3) experience in all project phases; and (4) designability, constructability, and operability information from and available to the project team in a timely manner (Sanvido et al. 1992).

Alternative Approaches

Partnering, design-build, and constructability are alternative approaches to project integration, each including some of the aforementioned critical success factors. Each of these approaches helps improve integration in a different way. Partnering attempts to change the nature of the often adversarial relationship between owners, contractors, architects, and other project team members by getting them to commit to common objectives, formalizing improved communication, and preventing disputes. Design-build combines the architecture/engineering (A/E) firm and contractor into one organization. This sets up an environment in which communication between them can begin early and should be more routine. Constructability can take a number of forms, but its aim is to get construction knowledge and experience into the early stages of planning and design.

Existing Research

Researchers have been examining alternatives to the traditional approach as opportunities to improve integration, especially since the Business Roundtable's (BR) landmark series of reports in 1982. Nam and Tatum (1992) use the term "integration" to mean "integration between design and construction." They have described four major means to increase construction integration: contractual, organizational, information, and noncontractual.

Each of the alternative approaches examined in this paper, partnering, design-build, and constructability, have been the subjects of academic study. The Weston and Gibson (1993) study of partnered versus traditional projects in the Corps of Engineers includes enough projects of both types to reach convincing conclusions about the increased success of partnered projects. Trade journals have described the strong growth of design-build in the industry, especially in the public sector (Edmunds 1992). This led Songer et al. (1994) to present a process model for public-sector design-build planning. Ndedugri and Turner (1994) report that the use of design-build is also increasing in the United Kingdom, with greater acceptance among construction professionals, but is still meeting considerable resistance. The Federal Construction Council's (FCC) Committee on Cost Engineering performed a subjective study of 27 design-build projects in federal agencies (FCC 1993). The seven agencies perceived the design-build projects as "somewhat better" than traditional projects in several respects, especially in saving time. The Construction Industry Institute (CII) has produced a great number of publications on constructability, with topics ranging from the value of constructability programs to how they can be implemented. Researchers working with CII, including O'Connor and Miller (1994), Russell and Gugel (1993), and Russell et al. (1994), have focused on convincing owners about the return on the investment of constructability programs, and on practical help for those trying to select and implement them. Russell et al. (1994) developed an equation for estimating the cost of implementing constructability.

Cohenca-Zall et al. (1994) use the term "degree of involvement" to describe the roles of various parties in construction planning and to emphasize the importance of meetings as a major means of planning during construction. Fergusson and Teicholz (1994) have developed an industrial-facility quality-measurement technique based on owner attitudes and validated it by correlation with plant production.

Although researchers have demonstrated that integration in terms of using computer technology may enhance integration and project performance (Teicholz and Fischer 1994), other approaches also offer promise for increasing integration in the industry. Among them, degree of interaction, including quality and quantity, may directly impact project integration and performance. The following sections describe research that demonstrates a relationship between increasing interaction among designers and builders and improvement in key project performance indicators.

PROJECT PERFORMANCE AND INTERACTION

It has long been believed that interaction among different parties in a construction project directly impacts the project's performance. There has been a lack of quantitative research to directly support or negate this belief. The writers developed a method to measure the degree of interaction and its impact on project performance.

Realizing that project integration is not directly measurable, we have chosen to use interaction as a quantifiable substitute. Degree of interaction is defined as: "The extent of interaction among designers, builders, and project-related personnel during a project's planning, conceptual design, detailed design, procurement, construction and start-up phases." Not only is interaction measurable, but its extent is essentially the opposite of the fragmentation in the aforementioned project delivery process. DOI is calculated for individual projects by adding weighted interaction for each project phase.

Project performance is measured by cost growth, schedule growth, and number of modifications. Data are collected from 25 recently completed construction projects, including traditional and alternative approaches. Project performance and DOI scores are analyzed by category. In a series of scatter diagrams, performance data are plotted against DOI data for each project to demonstrate a relationship between the two. The relationship is verified based on scatter diagrams and regression analysis. The relationship is further examined and verified by dividing the projects into those with high and low DOI scores.

Project Performance Indicators

The writers considered all directly measurable indicators, which might provide insight into how project performance has been affected. In addition to cost and schedule performance, other possible indicators included number of contract modifications, claims cost, value-engineering savings, and safety information. After collecting and examining project data, the researchers found the results for claims and value engineering to be inconclusive. The great majority of projects studied had no claims and no value-engineering savings, regardless of the approaches used. The results for safety were often unavailable and were inconclusive when available. Most projects studied had no lost-time accidents. The cost, schedule, and modifications data proved more useful. They provided measurable differences between projects and categories. In this study, cost growth (percent difference between original and actual cost), schedule growth, and the number of contract modifications are used to represent project performance. Although these are not comprehensive measures of project performance, they are certainly useful indicators, reflecting concerns from all parties involved, especially the owner's.

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This questionnaire attempts to measure the degree of integration in terms of **interaction between designers and builders**.

YOUR NAME:______________ PROJECT NAME:______________________

I. INSTRUCTIONS:

Interaction Phase: Enter data for each phase in which designers and builders had direct contact.

1) Number of Persons: How many persons were involved in each phase of interaction?

2) Job Titles: Give the job titles for each person involved in the interaction. Be specific (e.g., project architect, contractor's project manager, etc.).

3) Hours/Month: Approximately how many hours per month did each person spend in interaction?

4) Duration: How many months did interaction occur during this phase?

5) Misc. Cost: What miscellaneous costs were associated with interaction (e.g., telephone calls, travel, and office expenses)?

6) Interaction Type: Was the interaction by planned schedule or in reaction to problems?

Interaction Phase	1)Number of Persons	2) Job Titles	3) Hours/ Month	4) Duration (months)	5) Misc. Cost ($)	6) Interaction Type (problem or scheduled)
Planning						
Conceptual Design						
Detailed Design						
Procurement						
Construction						
Start-up						

II. CONTENT

Please describe the most common content of the interaction between designers and builders on this project:

III. REMARKS

Is there anything out of the ordinary we should know about this project?

THANK YOU FOR YOUR TIME AND COOPERATION IN FILLING OUT THIS QUESTIONNAIRE!

FIG. 1. Questionnaire for Measuring Project Interaction

TABLE 1. Weighting Factors for Relative Value of Interaction in Each Project Phase

Phases (1)	Weighting Factor (2)
Planning	0.35
Conceptual design	0.27
Detailed design	0.18
Procurement	0.11
Construction	0.07
Start-up	0.02

Degree of Interaction

Significant Parameters

Measuring DOI requires measuring both the quality and the quantity of interaction. The writers developed a questionnaire that includes both quality and quantity parameters. The questionnaire was designed to be brief and easy to fill out, while soliciting data that were quantifiable and objective. Following are the selected parameters and their definitions:

- Interaction phase: the project phase(s) in which designers and builders had direct contact.
- Number of persons: the number of persons who were involved in the interaction.
- Job titles: the job title for each person involved in the interaction.
- Hours/month: the approximate hours per month each person spent in interaction.
- Duration (months): how many months the interaction occurred during each phase.
- Interaction type: whether the interaction was by planned schedule or in reaction to problems.

The questionnaire also provided a blank space on the second page and asked the respondent to: (1) Describe the most common content of the interaction between designers and builders;

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TABLE 2. Example of DOI Score Calculation

Landing craft support center, phase III (1)	Weight factor (P_k) (2)	Number of persons (m_k) (3)	Interaction (h/month) (t_{ik}) (4)	Interaction duration (months) (D_{ik}) (5)	Construction duration (months) (CD) (6)	DOI score (7)
Conceptual design[a]	0.27	4	20	6	20	0.041
	0.27	2	10	6	20	0.010
Detailed design[b]	0.18	2	10	3	20	0.003
	0.18	3	25	3	20	0.013
Construction[c]	0.07	3	10	20	20	0.013
	0.07	3	5	20	20	0.007
	0.07	1	4	20	20	0.002
Start-up	0.02	12	10	2	20	0.002
Total score						0.090

[a]Subtotal = 0.051.
[b]Subtotal = 0.016.
[c]Subtotal = 0.021.

TABLE 3. Project List and Performance

Project category and number (1)	Project title (2)	Final cost ($,000) (3)	Final duration (days) (4)	Cost growth (%) (5)	Schedule growth (%) (6)	Number of modifications/million dollars (7)	Average cost and schedule growth (8)
	(*a*) Traditional						
T-1	Dormitory	5,516	531	5.07	20.65	4.71	12.86
T-2	Flight simulator facility	3,080	652	2.67	−9.44	19.48	−3.39
T-3	Alter electric substation	2,342	444	2.27	18.09	11.10	10.18
T-4	Add/alter field training	2,126	328	25.50	21.48	5.17	23.49
T-5	Shortfield assault strip	2,114	610	24.72	103.33	14.66	64.03
T-6	Flight simulator facility	1,817	554	8.54	60.12	24.22	34.33
T-7	Engine inspection	698	471	21.39	74.44	28.65	47.92
	Category average	2,528	517	12.88	41.24	15.43	27.06
	(*b*) Partnering						
P-1	Intelligence center	69,462	1,140	28.52	18.75	10.26	23.64
P-2	Explosives handling wharf	39,719	882	5.14	6.91	1.64	6.02
P-3	Replacement hospital	39,496	751	6.17	23.52	1.60	14.85
P-4	Drydock modernization	29,678	552	13.92	1.28	3.27	7.60
P-5	Audio visual center	19,663	540	7.72	0.00	5.19	3.86
P-6	Fleet headquarters	9,037	563	7.11	13.74	10.51	10.42
P-7	B-2 avionics facility	7,913	647	9.48	17.42	2.91	13.45
P-8	Urban training facility	7,515	460	14.42	−26.16	3.19	−5.87
P-9	Landing craft facility	6,370	601	2.91	11.30	3.77	7.10
	Category average	25,428	682	10.60	7.42	4.70	9.01
	(*c*) Design-build						
D-1	Health care facility	16,478	734	12.16	15.77	4.13	13.97
D-2	Student quarters	9,974	720	2.99	50.00	4.41	26.50
D-3	Dining facility	2,904	810	0.55	68.75	15.15	34.65
D-4	Child development center	967	626	−0.51	73.89	14.48	36.69
D-5	Child development center	848	568	18.44	33.65	9.43	26.04
	Category average	6,234	692	6.73	48.41	9.52	27.57
	(*d*) Combination (includes projects with constructability programs)						
C-1	Sparkman center	60,314	660	3.28	15.79	0.88	9.53
C-2	Propulsion training center	16,738	759	6.19	45.96	5.91	26.07
C-3	Add/alter hydrant system	15,438	610	6.49	−15.28	2.91	−4.39
C-4	Intermediate maintenance	10,294	605	17.51	−0.82	9.42	8.35
	Category average	25,696	659	8.37	11.41	4.78	9.89

and (2) state whether there was anything out of the ordinary one should know about the project. The questionnaire is shown in Fig. 1.

Objectivity of Parameters

The researchers considered how to evaluate data that was subjective and combine it with numerical data in producing a score. For example, the participation of various personnel in interaction could be weighted differently according to their management level. To minimize subjectivity and to simplify the process, the writers decided to begin measuring DOI using only the most objective data among the foregoing parameters. Therefore, we assume the interaction of all personnel is equally valuable, and that scheduled interaction is just as valuable as interaction resulting from problems. In future research based on this work, we plan to assign weights to these factors and examine their impact on the DOI and its relationship to project performance.

Measuring DOI

Principles in Counting Interaction Data

To maintain consistency, the researchers used the following principles in counting interaction data from the questionnaires:

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TABLE 4. Average Project Performance by Category

Categories (1)	Cost growth (%) (2)	P ($T \leq t$) two tail (3)	Schedule growth (%) (4)	P ($T \leq t$) two tail (5)	Number of modifications per million dollars (6)	P ($T \leq t$) two tail (7)	Average cost and schedule growth (8)	P ($T \leq t$) two tail (9)
Traditional	12.88	—	41.24	—	15.43	—	27.06	—
Partnering	10.60	0.641	7.42	0.067	4.70	0.022	9.01	0.092
Design-build	6.73	0.286	48.41	0.705	9.52	0.193	27.57	0.959
Combination	8.37	0.400	11.41	0.171	4.78	0.027	9.89	0.151

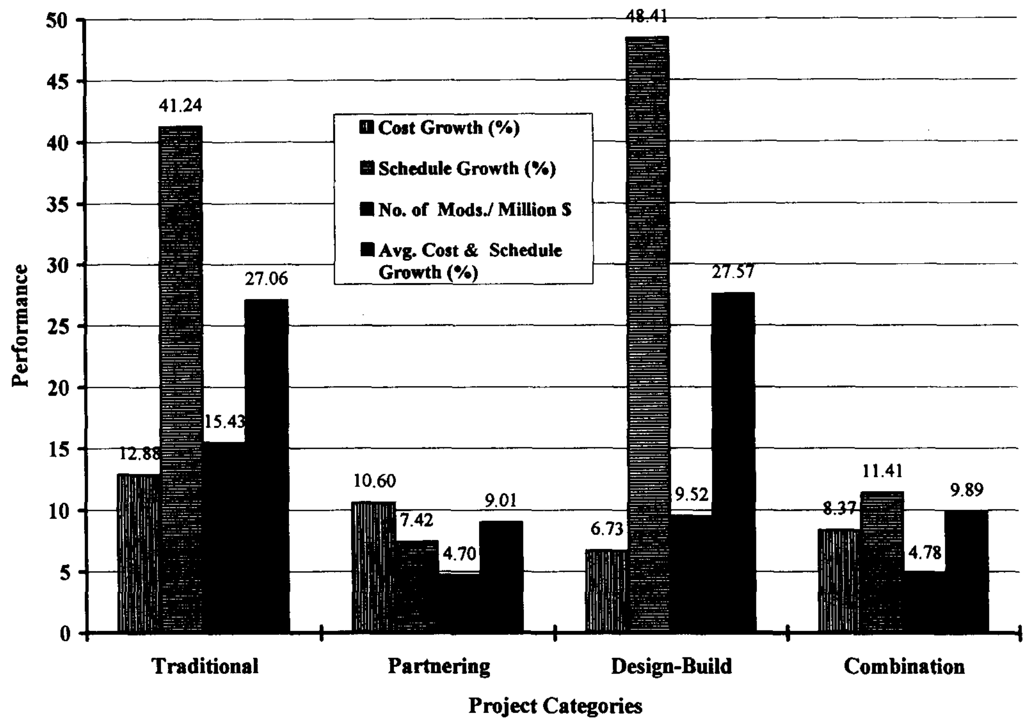

FIG. 2. Average Project Performance by Category

TABLE 5. Average DOI Score by Category

Categories (1)	Average DOI score (2)	P ($T \leq t$) two tail (3)
Traditional	0.031	—
Partnering	0.244	0.022
Design-build	0.177	0.310
Combination	0.436	0.125

1. When designers and builders interacted, we considered all of the participants, assuming they would also contribute to the interaction.
2. However, if designers and builders did not both participate, the interaction would be disregarded.
3. We included measurable results of interaction from the "content" and "remarks" sections of the questionnaire.

Weighting Factors for Each Phase

To measure DOI we divided each project into six phases: planning, conceptual design, detailed design, procurement, construction, and start-up. Researchers have long been aware that interaction early in the project has greater impact than in later phases (CII 1986). Therefore, it was necessary to assign weights to reflect the relative value of interaction in each phase. To do this as objectively as possible, we used the analytic hierarchy process, which is well-known as a decision-making technique. The analytic hierarchy process, which was developed by Saty (1980, 1982), organizes objective and subjective factors in a systematic manner, and provides a structured yet relatively simple solution to decision making (Skibniewski and Chao 1992). Using a predetermined scale, the writers made pairwise comparisons of the relative value of interaction in each phase. A computer program, developed by the second writer, was used to process the comparisons and calculate the weights. A more detailed description of this process is provided in Appendix I. The final weighting factors are listed in Table 1. These weighting factors, however, can be adjusted by decision makers based on their preferences.

Calculating DOI

The writers use a time-based method to combine the questionnaire results into a single DOI score for each project. DOI is calculated as the ratio between the weighted total man-hours spent on interaction and the construction duration. For each project phase, the weighting factor is multiplied by the man-hours of interaction. The products from each phase are summed and divided by construction duration, to give the DOI

$$\mathrm{DOI} = \frac{1}{CD} \times \sum_{k=1}^{n} P_k \times \left[\sum_{i=1}^{m_k} \left(\frac{t_{ik}}{160} \right) \times D_{ik} \right] \quad (1)$$

where DOI = degree of interaction based on man-hours; CD = construction duration in months; n = number of project phases (six in this paper); P_k = weighting factor for each interaction phase, where k = 1, 2, 3, . . . , n; m_k = number of persons participating in the interaction for each phase; t_{ik} = hours/month each person (i) spent in the interaction for each

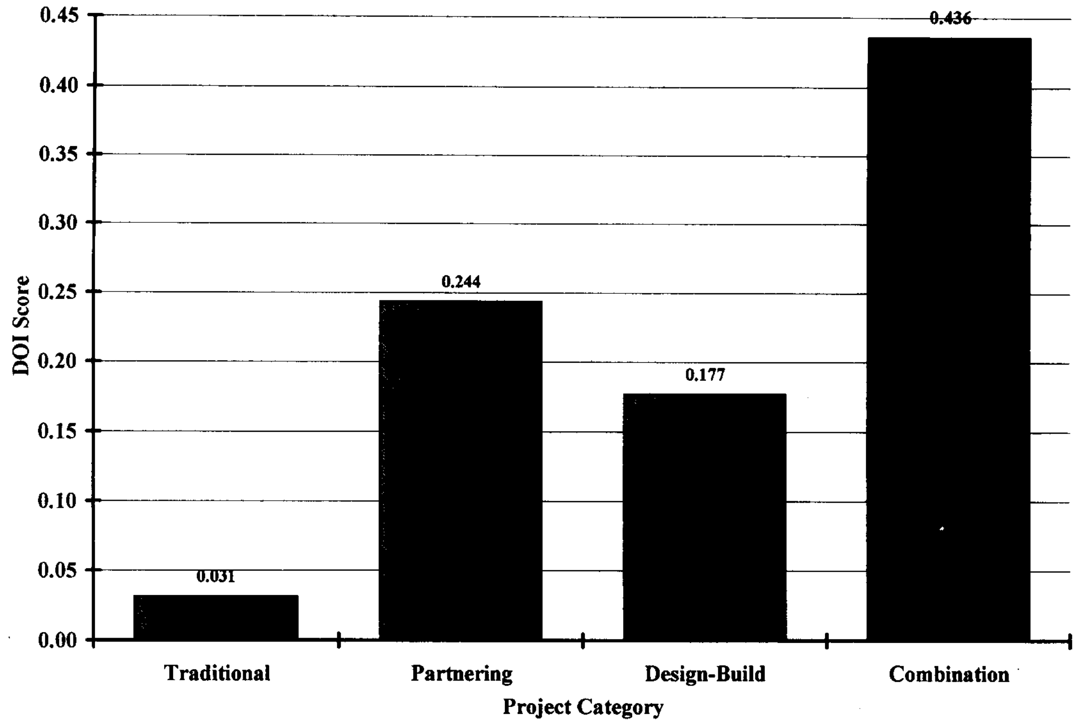

FIG. 3. Average DOI Score by Category

TABLE 6. Relationship Table

Project number (1)	DOI score (2)	Cost growth (3)	Schedule growth (4)	Number of modifications/ million dollars (5)	Average cost and schedule growth (6)
T-1	0.030	5.07	20.65	4.71	12.86
T-2	0.086	2.67	−9.44	19.48	−3.39
T-3	0.006	2.27	18.09	11.10	10.18
T-4	0.060	25.50	21.48	5.17	23.49
T-5	0.011	24.72	103.33	14.66	64.03
T-6	0.009	8.54	60.12	24.22	34.33
T-7	0.018	21.39	74.44	28.65	47.92
P-1	0.501	28.52	18.75	10.26	23.64
P-2	0.216	5.14	6.91	1.64	6.03
P-3	0.058	6.17	23.52	1.60	14.85
P-4	0.337	13.92	1.28	3.27	7.60
P-5	0.686	7.72	0.00	5.19	3.86
P-6	0.146	7.11	13.74	10.51	10.43
P-7	0.069	9.48	17.42	2.91	13.45
P-8	0.091	14.42	−26.16	3.19	−5.87
P-9	0.090	2.91	11.30	3.77	7.11
D-1	0.672	12.16	15.77	4.13	13.97
D-2	0.036	2.99	50.00	4.41	26.50
D-3	0.035	0.55	68.75	15.15	34.65
D-4	0.026	−0.51	73.89	14.48	36.69
D-5	0.116	18.44	33.65	9.43	26.05
C-1	0.990	3.28	15.79	0.88	9.54
C-2	0.354	6.19	45.96	5.91	26.08
C-3	0.278	6.49	−15.28	2.91	−4.40
C-4	0.120	17.51	−0.82	9.42	8.35

phase (k), where $i = 1, 2, 3, \ldots, m$; 160 = approximate work hours in a month; and D_{ik} = duration of each person's interaction in months, for each phase.

There are two reasons for using construction duration rather than total project duration. First, several project phases often include significant "dead time" while waiting for approval or funding, during which no work or interaction occurs. Furthermore, it is difficult to obtain total project duration because good records for all phases of projects spanning several years are often unavailable, while construction duration is always recorded. Therefore, we chose to use the project construction duration based on the assumption that it is proportional to the scale of the project and usually does not include significant dead time.

DOI scores were calculated by applying (1) to data from the questionnaires. An example for calculating a DOI score is shown in Table 2. Column 1 lists the project name and the phases for which interaction occurred. For each project phase with interaction, the weight factor (column 2), the number of persons (column 3), the interaction hours per month (column 4), and interaction duration (column 5) are multiplied. This product is then divided by 160 (approximate work hours in a month) and the construction duration (column 6). A subtotal is provided for each phase and the sum of the subtotals equals the total DOI score for the project.

Data Sources and Collection

This study required projects using each delivery approach from which to collect data on performance and degree of interaction. All projects in this study were selected using five basic criteria:

1. They are all military construction projects. This is primarily because of the availability of project records. Military construction projects have relatively more consistent contracting and management procedures. They also represent a wide variety of public-sector project types and locations. Of the 25 projects in this study, there are 20 different facility types, located in 11 states.
2. Each project is located in the continental United States to avoid distortions by overseas costs.
3. The minimum project value was set at $500,000 to ensure each project had a reasonable amount of management attention.
4. All projects were completed recently, having been funded in Fiscal Year (FY) 1988 or later.
5. No family housing projects are included in the study because of their different funding and contracting policies.

The 25 projects were chosen from a larger group of 119 projects, which were collected randomly to include projects of each category and all three military services. Questionnaires

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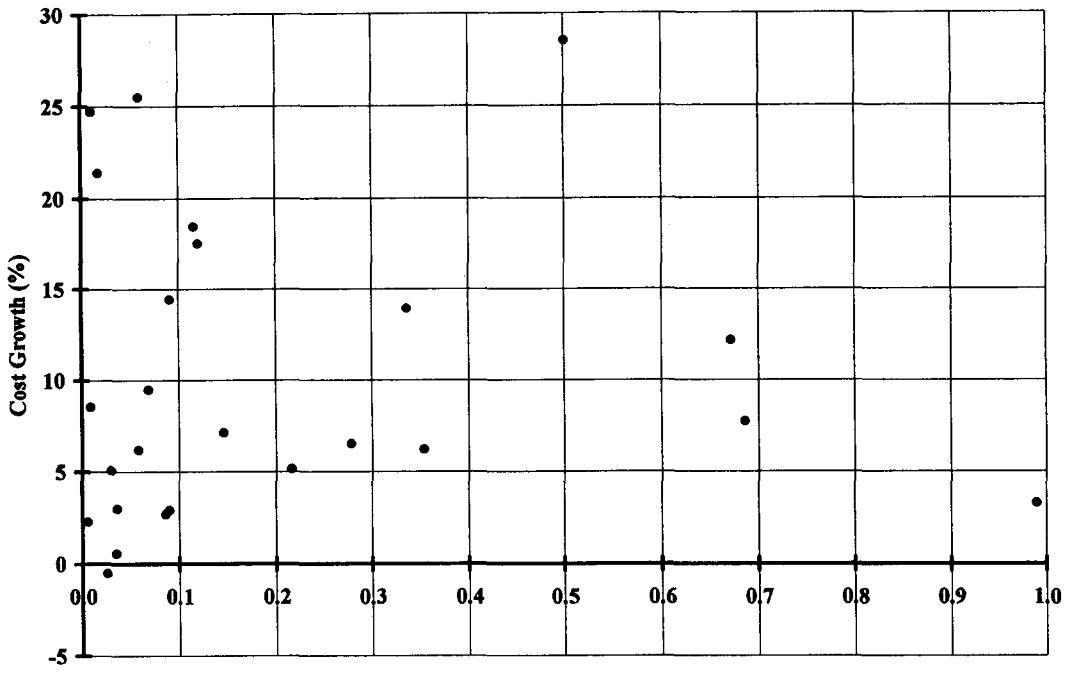

FIG. 4. Relationship between Cost Growth and DOI Score

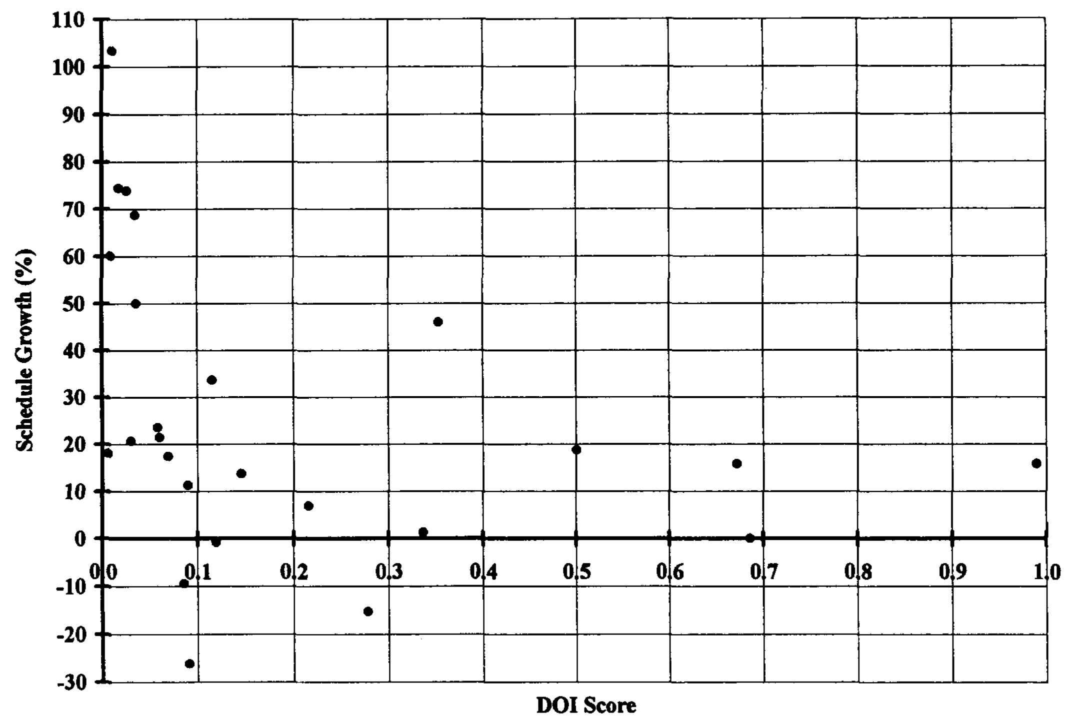

FIG. 5. Relationship between Schedule Growth and DOI Score

were sent to government project managers who were intimately familiar with each project. These project managers would have been present during any direct interaction between designers and builders. For some of the design-build projects, the project manager referred us to the design-build organization to complete the questionnaire since some designer-builder interaction was internal. The 25 projects ultimately chosen were those for which the project manager was still in place, remembered the project well enough to complete the questionnaire, and was willing to provide the information.

Both headquarters and project-level sources provided performance information on the 25 military construction projects. Information from both sources was cross-checked to ensure its accuracy. The data were gathered from July to December, 1994. Twenty respondents provided 25 usable questionnaires for this research. These projects include some projects from each of the alternative approaches. The researchers conducted telephone interviews with the respondents to clarify incomplete or unclear answers on the questionnaires.

RESULTS

Project Performance by Category

Table 3 lists each project, sorted by project type (traditional, partnering, design-build, or combination) and original cost.

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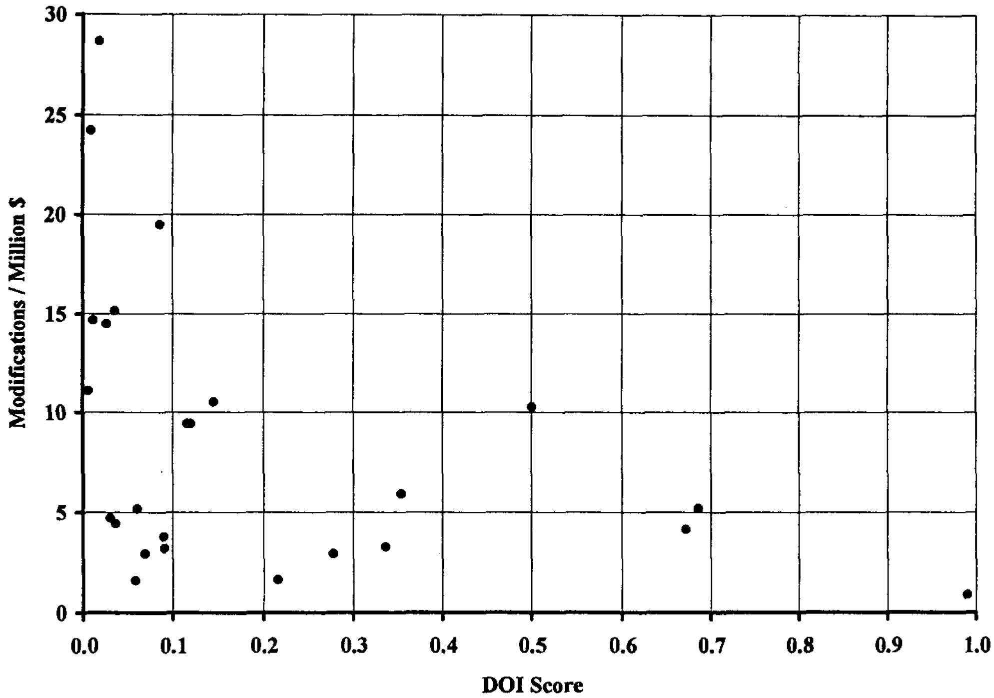

FIG. 6. Relationship between Number of Modifications/Million Dollars and DOI Score

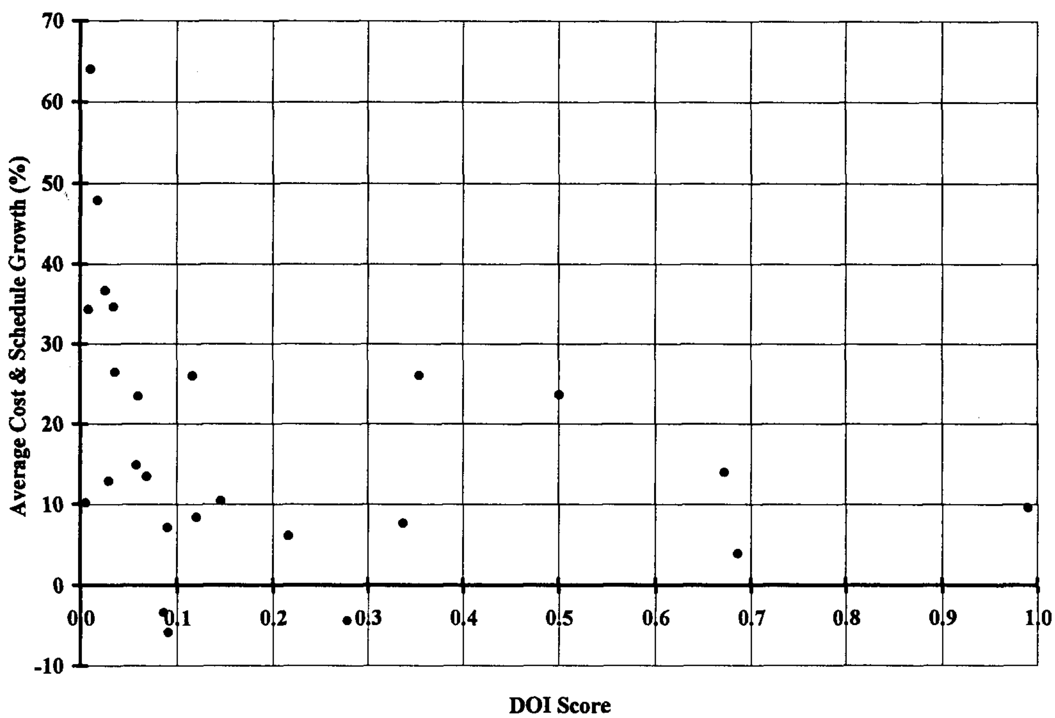

FIG. 7. Relationship between Average Project Cost and Schedule Growth and DOI Score

Combination projects are those that used two or more of the alternative approaches, including constructability.

For each project, Table 3 lists final cost, final duration, cost growth, schedule growth, and number of contract modifications per million dollars of final contract amount. Contract modifications are divided by million dollars of final contract amount because the average project costs of each category are quite different. This conversion puts all projects on the same scale for a more useful comparison. Finally, cost growth and schedule growth are combined into an equally weighted average score, as shown in column 8. Strictly speaking, the unweighted average of cost and schedule growth is not a separate performance indicator. However, this average can be a useful indicator that may be tracked by many owners and project managers. Average values are also listed for each category.

Table 4 provides a summary and analysis of the Table 3 data by category. An analysis of sample means was performed using the t test for samples with unequal variances. The null hypothesis is that sample means of the alternative approaches are equal to those of the traditional approach. Columns 3, 5, 7, and 9 of Table 4 list the statistical probability that the sample means would be equal. Based on the data, the projects using partnering and combinations of alternative approaches tend to have better performance than traditional projects. In particular, using a significance level of 0.10, the partnered projects have significantly less schedule growth, fewer modi-

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TABLE 7. Results of Regression Analysis

Dependent variable (1)	r^2 (2)	Variables (3)	Coefficient (4)	Standard error (5)	T (6)	P (one tail) (7)
Cost growth	0.023	Constant	$\alpha_1 = 9.358$	2.504	3.737	0.001
		x	$\beta_1 = 5.190$	21.366	0.243	0.405
		x^2	$\gamma_1 = -10.207$	23.924	−0.427	0.337
Schedule growth	0.250	Constant	$\alpha_2 = 45.004$	9.294	4.843	0
		x	$\beta_2 = -193.406$	79.296	−2.439	0.012
		x^2	$\gamma_2 = 179.389$	88.791	2.020	0.028
Number of modifications	0.276	Constant	$\alpha_3 = 5.904$	1.621	3.643	0.001
		$1/x$	$\beta_3 = 0.096$	0.033	2.895	0.004
Average cost and schedule growth	0.225	Constant	$\alpha_4 = 27.183$	5.008	5.428	0
		x	$\beta_4 = -94.110$	42.731	−2.202	0.018
		x^2	$\gamma_4 = 84.596$	47.848	1.768	0.046

Note: x = DOI score.

TABLE 8. Average Project Performance by DOI Score

Performance indicators (1)	DOI < 0.2 (2)	DOI > 0.2 (3)	$P(T \leq t)$ one tail (4)
Cost growth	9.95	7.84	0.208
Schedule growth	32.59	14.29	0.027
Number of modifications/million dollars	10.76	3.42	0.001
Average cost and schedule growth	21.27	8.95	0.021

TABLE 9. Variance by DOI Score

Performance indicators (1)	DOI < 0.2 (2)	DOI > 0.2 (3)
Cost growth	74.76	14.71
Schedule growth	1,172.65	287.07
Number of modifications/million dollars	61.82	3.29
Average cost and schedule growth	331.64	88.86

fications, and lower average cost and schedule growth than the traditional projects. Results are mixed for design-build projects, with less cost growth and fewer modifications, but with no statistically significant difference between them and traditional projects. The combination projects are better than traditional projects in every performance indicator and have significantly fewer modifications. Fig. 2 presents the same data graphically.

DOI Score by Category

Similar to the preceding results for project performance by category, DOI scores for alternative approaches tend to be better than for the traditional projects, as listed in Table 5 and shown in Fig. 3. Again, a t test was used to compare the sample means, with the null hypothesis that mean DOI scores for the alternative categories equal the mean DOI scores for the traditional category. Partnered projects have significantly higher scores than the traditional projects, and combination projects have the highest average score of all categories.

Relationship between Performance Indicators and DOI

Relationship Table

Our next step is to set aside the issue of categories and focus on the relationship between project interaction and performance. Table 6 summarizes the DOI score, cost growth, schedule growth, number of modifications, and average cost and schedule growth for each project.

Relationship Charts

Scatter diagrams were made from the data in Table 6. A chart presenting the relationship between cost growth and DOI score is shown in Fig. 4. The chart in Fig. 5 presents the relationship between schedule growth and DOI. The relationship between the number of contract modifications per million dollars and DOI score is shown in Fig. 6. Finally, the relationship between average cost and schedule growth and DOI score is shown in Fig. 7.

Trends

There is generally a strong relationship between project performance indicators and DOI as shown in Figs. 4–7. For each performance indicator, there is a wide range of performance scores for the projects with low DOI scores. But once DOI increases beyond a certain point, the performance tends to both improve and stabilize.

Fig. 4 shows the percent cost growth plotted against the DOI score. The variance of cost growth decreases significantly with higher DOI in Fig. 4, but the average cost growth remains

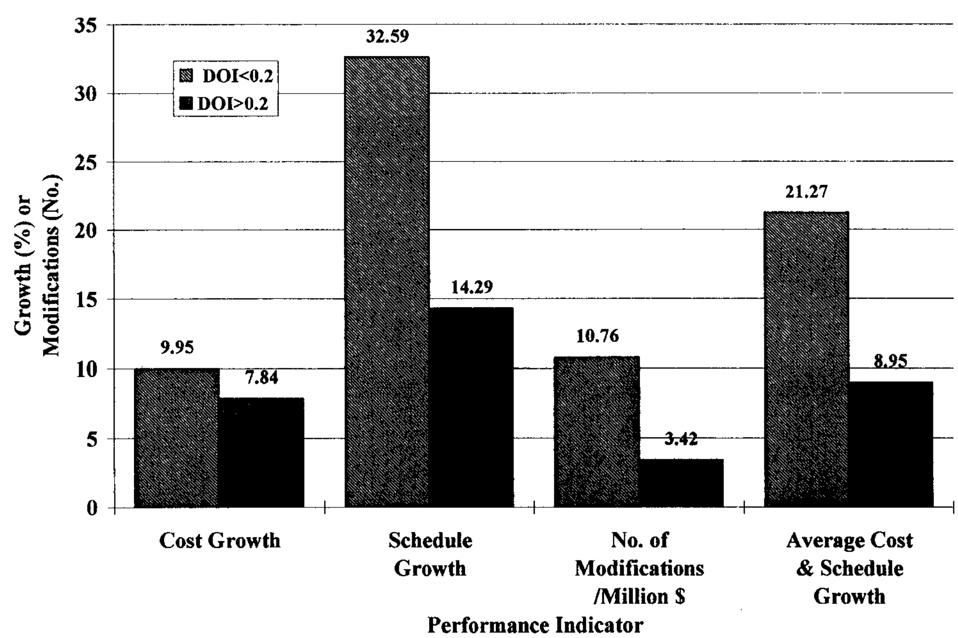

FIG. 8. Average Project Performance by DOI Score

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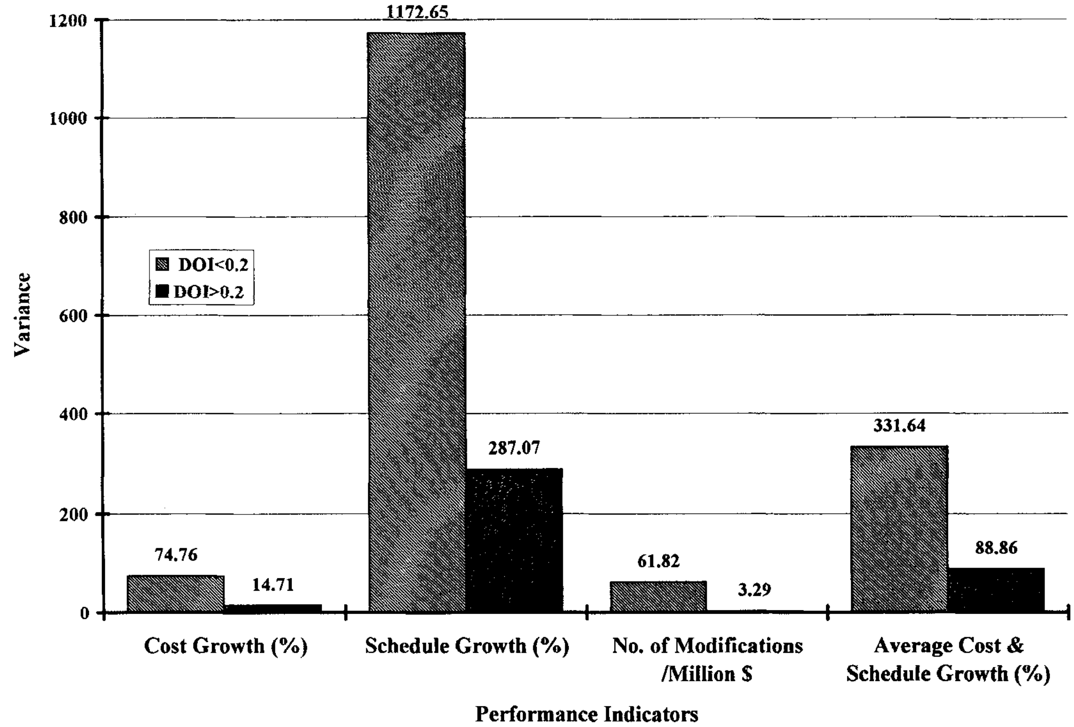

FIG. 9. Average Variance of Performance Indicators by DOI Score

TABLE 10. Comparison Scale [Adapted from Saaty (1980)]

Intensity of importance (1)	Definition (2)
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between adjacent scale values

approximately the same. One project had a high DOI score (0.5) but the worst cost growth in the study (28.5%). This project had the misfortune of being resited after the design phase through congressional intervention. This required extensive redesign during construction, resulting in large cost and schedule growth, and a larger number of modifications. Because of these unusual circumstances, this project was considered a statistical outlyer, and was not included in the results listed in Tables 7, 8, and 9, and shown in Figs. 8 and 9.

Fig. 5 shows the percent schedule growth plotted against the DOI score. Not only does variance decrease as the DOI scores increase, but also the average schedule growth clearly decreases.

Fig. 6 shows the number of contract modifications per million dollars plotted against the DOI score. As with schedule growth, the trend of improved performance and less variance with high DOI score is clear.

Fig. 7 shows the average cost and schedule growth plotted against the DOI score. Once again, as the DOI score increases, performance indicators improve and the variance is reduced.

Regression analysis was used to verify the relationship between project performance indicators and DOI, based on the scatter diagrams in Figs. 4–7. Three equations were used as regression models: $y = \alpha + \beta x + \varepsilon$, $y = \alpha + \beta/x + \varepsilon$, and $y = \alpha + \beta x + \gamma x^2 + \varepsilon$ (where x is each DOI score and y is each performance indicator). Based on the regression analysis, the equation $y = \alpha + \beta x + \gamma x^2 + \varepsilon$ is a better representation for the scatter diagrams in Figs. 4, 5, and 7, while the equation $y = \alpha + \beta/x + \varepsilon$ is a better fit for that in Fig. 6. Results of the regression analysis are listed in Table 7.

In this analysis the null hypothesis is that there is no relationship between performance indicators and DOI. As for coefficient β, the null hypothesis is $\beta = 0$, alternative hypotheses are $\beta_1 < 0$, $\beta_2 < 0$, $\beta_3 > 0$, and $\beta_4 < 0$, respectively (see Table 7). Based on the analysis, we cannot reject the null hypothesis in the case of cost performance, but we can for schedule performance, number of modifications, and average performance, at the 0.028 level of significance. As for coefficient γ, the null hypothesis is $\gamma = 0$, the alternative hypotheses are $\gamma_2 > 0$ and $\gamma_4 > 0$, respectively. In the same way, we can reject null hypotheses for schedule performance and average performance, at the 0.05 level of significance. Therefore, based on these

TABLE 11. Comparison Matrix for Project Phases

Phases (1)	Planning (2)	Conceptual design (3)	Detailed design (4)	Procurement (5)	Construction (6)	Start-up (7)	Weight (8)
Planning	1.00000	2.00000	2.44949	3.87298	4.24264	9.00000	0.347
Conceptual design	0.50000	1.00000	2.44949	3.87298	4.24264	9.00000	0.277
Detailed design	0.40825	0.40825	1.00000	2.44949	3.87298	9.00000	0.179
Procurement	0.25820	0.25820	0.40825	1.00000	3.00000	7.00000	0.108
Construction	0.23570	0.23570	0.25820	0.33333	1.00000	7.00000	0.069
Start-up	0.11111	0.11111	0.11111	0.14286	0.14286	1.00000	0.021

Note: λmax = 6.45332; and consistency index (CI) = 0.09066. Here the consistency index (indicator of closeness of consistency) = (λmax − n)/(n − 1), λmax = the maximum eigenvalue generated in the comparison matrix; n = the number of activities in the comparison matrix. In general, when CI is less than 0.1 we may be satisfied with the consistency of our judgments.

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hypothesis tests, we cannot say the cost growth varies according to the DOI score. But from the scatter diagrams and the hypothesis tests, it is clear that schedule growth, number of modifications, and average cost and schedule growth decrease at a decreasing rate as each DOI score increases.

Many factors besides the degree of interaction influence each of the performance indicators. Therefore it is not surprising that the values for r^2 in column 2 of Table 9 indicate a modest correlation, while the P values in column 7 show a strong level of significance. This means, for example, that 25% of the variability in schedule growth can be explained by DOI, and the low P value means there is clearly a linear relationship between the two.

Categorical Analysis

Throughout each of the scatter diagrams there appears to be a marked transition at about the 0.2 DOI score. Below this score, projects have a wide variety of performance scores. Above the 0.2 DOI, project performance is better and more consistent. Tables 3 and 9 summarize this point. Projects with a DOI score above 0.2 are clearly better in terms of schedule growth, number of modifications, and average cost and schedule growth. This means that even a relatively modest effort at project integration can make a significant improvement in project performance.

To illustrate the amount of interaction represented by a DOI score of 0.2, we use the explosive handling wharf project as an example. Interaction in the procurement and construction phases gave this partnered project a DOI score of 0.216. During the three-month procurement phase, 10 persons, including designers, contractors and government engineers/project managers, interacted an average of 8 h per month. During the 30 months of construction eight persons, representing the same groups, spent an average of 60 h per month in interaction. Comments on the questionnaire indicated that the partnering relationship on this project worked well.

When the DOI score becomes higher than a certain point, we can predict that projects will be more successful in terms of the selected performance indicators. In addition, project performance does not appear to improve significantly beyond a certain point. This could be because other factors begin to have more impact on project performance than interaction as the DOI score rises beyond that point.

Regardless of whether their performance improved, projects with a higher DOI averaged dramatically less variance than projects with DOI below 0.2. Project managers and owners should be able to predict that future projects with DOI scores above 0.2 would not only have a better average performance, but also that performance would be more consistent.

These results are based on a study of 25 projects. Future research will attempt to validate these results by studying a larger number of projects. In the meantime, public owners can make use of the DOI methodology to study the relationship between interaction and performance on their projects.

CONCLUSIONS

This paper presented a method for directly measuring project DOI and relating it to project performance indicators. Data were collected from 25 recently completed construction projects. Statistical techniques were used to analyze the data and validate the method and relationship.

Partnering and combination projects average better performance than traditional projects. Partnering projects have significantly less schedule growth, fewer modifications, and less average cost and schedule growth than traditional projects. Combination projects are significantly better in the number of modifications than traditional projects. Although design-build projects have less cost growth and fewer modifications, they are not statistically different from traditional projects.

Each of the alternative approaches averaged higher DOI scores than traditional projects, with combination projects clearly the highest. However, none of these were statistically different from DOI scores for traditional projects.

There is generally a strong relationship between project performance indicators and DOI. Based on scatter diagrams and regression analysis, it is clear that schedule growth, number of modifications, and average cost and schedule growth decrease when DOI scores increase. However, we cannot say conclusively that cost growth decreases as the DOI score increases.

Projects with low DOI have a mixture of poor, average and good performance indicators, but projects with a high DOI score tend to have better performance indicators. Specifically, if the DOI score is above 0.2, a project tends to have significantly less schedule growth, fewer modifications, and less average cost and schedule growth. Projects with higher DOI scores also have more consistent performance indicators. So we can predict that projects with high DOI scores would be more successful and more consistent in terms of schedule performance, number of modifications, and average cost and schedule performance. The performance indicators did not tend to improve beyond a certain DOI score.

As presented in this paper, the degree of interaction is a measurable and useful approximation of project integration and is related to key project performance indicators. Owners can use the DOI methodology to verify this relationship for their projects.

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APPENDIX I. AHP DATA

In general, the analytical hierarchical process (AHP) decision-making process is used as follows (Skibniewski 1988):

1. A complex problem is structured by decomposing it into a hierarchy with enough levels to include all attribute elements to reflect the goals and concerns.
2. Elements are compared in a systematic manner using the same scale to measure their relative importance, and the overall priorities among the elements within the hierarchy are established.
3. The relative standing of each alternative with respect to each criterion element in the hierarchy is determined using the same scale.
4. The overall score for each alternative can then be aggregated, and the consistency of comparison can be measured using a consistency index.

Table 10 lists the comparison scale used in pairwise comparisons. Table 11 is a comparison matrix showing the pairwise comparisons were made and how the final weights were calculated.

APPENDIX II. REFERENCES

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