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INSTANTANEOUS PROJECT CONTROLS AS A SOURCE OF INNOVATION IN DESIGN AND CONSTRUCTION: EXPLORING CUMULATIVE AND TRANSFORMATIVE CHANGES IN COMPLEX SYSTEMS DEVELOPMENT

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SUMMARY: *Construction relies on rapid, reliable information sharing among distributed teams to enable project success. This article presents an empirical exploration of eleven organizations that serve as early adopters of advanced information technologies for instantaneous, i.e., real-time or near real-time, project controls and reporting capabilities. The study employed a grounded theory approach, in which analyses informed subsequent steps. Constructs were coded from the transcription of interviews with corporate managers affiliated with owner, contractor, software developer, and manufacturing organizations. Contextual and processual findings were leveraged to support a theoretical model that captured the changes and implementation steps for successful technology diffusion. The study also defined the drivers that demand and justify an instantaneous or frequent reporting capability in the design and construction sector. Results offer actionable insights. Organizations can more effectively adopt advanced project controls by proactively planning and embracing necessary organizational changes. Researchers should consider both contextual and processual factors to support effective exploration of technology integration in construction.*

KEYWORDS: *information technologies, technology adoption, real time, project controls, innovation.*

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1. MOTIVATION

Complex projects —such as those in the energy, life sciences, manufacturing, or infrastructure sectors— add to the inherent uncertainty of their complexity the combination of challenges that makes the construction industry unique. In the private industry, complex projects are commonly delivered in an Engineering-Procurement-Construction (EPC) delivery mode in which tens or hundreds of thousands of components are uniquely designed, procured, manufactured or fabricated, delivered to the project site, and eventually installed. Such complexity results in a high level of risk and uncertainty that have historically plagued complex projects with endemic cost and schedule deviations (Flyvbjerg et al. 2002; Isidore and Back 2002; Kim and Reinschmidt 2010; Kim and Reinschmidt 2011; Mulva and Dai 2012; Back and Grau 2013; Back et al. 2013; Grau et al. 2017; Wefki et al. 2024; Zhang and Zhang 2024). Such deviations are not marginal. According to Flyvbjerg et al. (2002), 90% of 258 infrastructure projects completed between 1927 and 1998 experienced cost overruns, with an average cost escalation of 28%. No positive trend emerged to alleviate these deviations throughout the seven-decade span. More recently, nearly 70% of a sample of 975 complex projects experienced cost and schedule deviations greater than 10% (Mulva and Dai 2012). In addition, the analysis of an additional 135 complex projects completed between 2005 and 2013, worth $29 billion, provided additional evidence on median cost (6%) and schedule (8%) overruns (Back and Grau 2013). These deviations are even more pronounced in complex megaprojects, i.e., those with budgets exceeding $1 billion. Notably, 65% of these projects experience average cost overruns of 59% (Ernst & Young 2014), and schedule delays exceed 31% (Aschman 2018). Increasing regulation and compliance, labor shortages, supply chain complexity, weather, permitting, design errors and omissions, low productivity, or industry defragmentation are just a few of the myriad challenges affecting the construction industry, thus adding to the uncertainty of complex projects.

Complex projects are information intensive. The ability to share and communicate reliable and timely information among dispersed and diverse teams becomes fundamental to project success. A large amount of information and documents, produced in various formats, must be efficiently shared and integrated (Martínez-Rojas et al. 2016, Wang et al. 2024) by the project team, which includes designers and design consultants, procurement experts, fabricators and suppliers, contractors and subcontractors, and client/owner/sponsor representatives. Owner and contractor organizations rely on the project controls function to monitor progress during execution and reliably predict completion outcomes, such as total installed costs (TIC) and completion times. Reliable reporting of project status on "performance to date" is essential for guiding informed decisions on individual projects, the portfolio of projects, and the organization. Performance against objectives is a contractual obligation requiring deviations from planned outcomes to be reported. Failure to meet project outcome objectives often results in negative consequences for the involved organizations and stakeholders. Despite these information needs, nearly the totality of owner and contractor organizations delivering complex projects still rely on batch reporting (Grau et al. 2019). In such batch reporting mode, information is sequentially reprocessed at multiple review and decision gates, such as the project manager, controls, financials, client, or third-party financing providers. In this prevalent batch reporting mode, information ages as it moves down the reporting chain, and opportunities for informed, timely decisions are missed. Thus, data is lagging in the reporting cycle. This lag in reporting hampers the ability to generate prompt responses. Indeed, the National Institute of Standards and Technology (NIST) estimated that the costs of the US capital facilities industry's inability to share and communicate project data properly totaled $15.8 billion (Gallaher 2004). In response to such a fundamental problem, there has been a long-held perception that the ability to gather, analyze, and communicate project information in real-time would constitute a meaningful breakthrough (Grau et al. 2009; Abbaszadegan and Grau 2015; Martínez-Rojas et al. 2016; Louis and Dunston 2017; Abbaszadegan et al. 2022; Rahimian et al. 2022). For example, the integration of project controls data alone has been shown to improve field productivity across trades from up to 33% (Zhai et al. 2009) and reduce costs between 13% and 21% (Gerbert et al. 2016).

Indeed, advanced information technologies can, for the first time, enable instantaneous controls and reporting capabilities. This study distinguishes between the instantaneous capabilities of real-time, where latency is negligible, and near real-time capabilities, where data is processed and reported at a frequency of one day or less, yet a significant departure from traditional weekly or monthly project control cycles. According to Wright et al. (2015), project controls are the single construction facet that can benefit the most from the implementation of information technologies. However, there is a need for detailed guidance in such technological implementations (Kang et al. 2012; Xue et al. 2024). Such a lack of guidance drives decision-makers to rely on perception or intuition rather than following recommended steps when making information technology adoption decisions (Lee

2004; Elmisalami et al. 2006; Kim et al. 2024). Representative sources of emerging construction technologies include mobile devices, augmented and virtual reality, automation and robotics, advanced analytics and artificial intelligence, visualization, tracking and tracing, and wearables (Matarneh et al. 2022; Mehranfar et al. 2024).

Technology-sophisticated organizations can streamline resources and operations, and reengineer and integrate functions (Abbaszadegan and Grau 2015). Seamless access to accurate, timely, and readily available information enables sound decision-making, minimizes errors, and promotes efficiency (Vipond et al. 2023; Fang et al. 2024). Data integration supports enhanced design, planning, and construction (Wu et al. 2002), and labor productivity (Kazerooni et al. 2020). The seamless integration and sharing of information becomes a source of innovation, transformation, and competitive advantage (Peansupap and Walker 2005). Information technologies can drive change across an organization's operations and business functions (Dewett and Jones 2001; Zhao 2021). Implicit to this statement is the notion that the adoption and diffusion of information technologies across multiple projects requires cumulative or transformative changes within the organization.

The rest of this article is structured as follows. The next two sections review the literature and discuss the research methods. Then, the grounded theory methodology is leveraged to generate a model that explains the processual and contextual changes elicited within organizations as they adopted instantaneous mechanisms of project controls. Next, the model is instantiated to provide a rationale and explain the distinct levels of success and failure in advancing project controls across three case studies. Finally, the conclusions outline the contributions and significance of the study presented in this manuscript.

2. BACKGROUND

Innovation through the adoption of information technologies is paramount to the management information systems (MIS) and business disciplines. Innovation is defined as the first or early use of an idea by "one of a set of organizations with similar goals" (Rogers 1995). The MIS literature supports the notion that technological diffusion through organizational culture and structures is crucial to success and impact on performance (Wu and Chen 2014; Eczan et al. 2020). Technological diffusion generates asset and capability resources within an organization (Santhanam and Hartono 2003; Wade and Hulland 2004; Nicoletti et al. 2020). Subsequently, information technology capabilities represent "repeatable patterns of actions in the use of assets to create, produce, or offer products/services to a marketplace" (Wade and Hulland 2004;). Thus, capabilities represent the skills and expertise developed because of the assimilation and use of information technologies. Technology innovations ultimately aim to develop assets and capabilities that can provide a market advantage and a positive impact on operations (Bharadwaj 2000; Santhanam and Hartono 2003; Cassia et al. 2020). Several innovation models have been developed in the business domain, and the technology-organization-environment (TOE) contextual model of technological adoption, as proposed by Tornatzky and Fisher (1990), is meaningful to this study. The environmental context encompasses factors that facilitate or inhibit, including the market, competition, and regulations. The organizational context captures culture, structure, size, resources, and communications. The technological context encompasses all relevant technologies within a firm, as well as those commercially available. The model posits that the interconnected contexts of environment, technology, and organization influence the adoption and acceptance of technologies. In this article, an organization is perceived as a complex system with multiple functions, whose behavior has interdependent effects (Yoon and Kuchinke 2005; Alter 2007; Dubrovsky 2004; Yang et al. 2023). In reality, the interaction between the organization and the environmental and technological contexts in which the organization operates shapes its components, ultimately aiming to enhance its capacity and sustainability. Such a contextual model has been instantiated and developed to understand the quantitative and qualitative aspects of innovation across distinct sectors and various technologies, notably through e-commerce and supply chain management (Wu and Chen 2014). Multiple case studies and grounded theory are recommended for developing explanations from qualitative data (Malak 2016), as was the case in this study. Given its sustained and prevalent use, the TOE framework was adopted as a set of sensitizing concepts (Blumer 1954) to guide the initial inquiry. The framework did not serve as a rigid, deductive template or a predetermined code set that could compromise the grounded theory process. Instead, it provided a broad analytical lens that kept the study rooted in the data, ensuring that specific themes and categories emerged inductively. Such an approach facilitated the identification of key areas of interest while maintaining the freedom to capture the 'loops of causation and connectivity' (as described in the iterative methodology) that surfaced during the research process.

The construction literature has also developed domain-specific models and empirical findings that separately encompass the instantaneous exchange of data and adoption of technologies. In the domain of BIM-enabled project controls and information integration, Wang and Chen (2023) systematically reviewed BIM capabilities across the project lifecycle and found that, despite rapid publication growth, the actual integration of BIM with project management remains weak. Elghaish et al. (2019) proposed BIM to enable automated earned value generation in support of Earned Value Management (EVM) within an Integrated Project Delivery (IPD) environment, enabling real-time cost tracking through an EVM-web grid accessible on computers and mobile devices. Similarly, Turkan et al. (2013) proposed an automated progress-tracking approach to estimate earned values for object components, illustrating the potential for automated data flows to feed directly into project controls. Regarding data governance, Sharma et al. (2025) proposed a regulatory framework for big data governance in construction organizations, noting that fragmented data standards, siloed storage, and underutilized analytics continue to pose significant barriers to seamless, data-driven operations. Complementary, Alreshidi et al. (2016) identified the lack of suitable governance mechanisms for BIM-based collaboration as a critical barrier, emphasizing the need for cloud-based governance solutions to address data security, confidentiality, consistency, and access concerns. In lean construction, Schimanski et al. (2021) integrated a variant of the Last Planner System with BIM at data-processing level through the "BeaM!" production management system, translating lean planning and control concepts into functional software requirements that were intended to facilitate data exchange and access. Yeung et al. (2025) advanced a related concept by integrating an ontology-based digital twin with agent-based simulation to support adaptive production during design and preconstruction, embedding lean principles such as pull planning and continuous flow control to reduce decision latency through automated data ingestion. Finally, Sepasgozar and Davis (2018) delineated a construction-specific technology adoption process framework through which construction organizations can decide to adopt new digital technologies, encompassing both customer and vendor activities. Despite the success of these efforts, their contribution has been mostly limited to the technical domain without exploring the broader organizational diffusion and processual changes that characterize whether technology innovation can be successfully adopted and institutionalized, beyond the context of a single project.

In the construction literature, agreement is virtually unanimous on general facets: that information technologies can automate data collection, information generation, and seamless sharing of data and information (Vaughn et al. 2013; Hasan and Sacks 2023); that timely and accurate information is critical to support well-versed decisions and reduce uncertainty and deviations (Abbaszadegan and Grau 2015; Zhang and Zhang 2024); and that construction organizations are composed of social and technical systems that influence the adoption and perception on novel technologies (O’Brien 2000; Taylor 2007; Erdogan et al. 2008; Erdogan et al. 2014; Elkhayat et al. 2024; Duo and Bo 2022). However, the notion of innovation –the cumulative and/or transformative changes in an organization's modus operandi for its benefit and survival– by means of diffusing advanced information technologies, and in consideration of its contextual and processual factors, is missing from the body of knowledge. In practice, tools and data communication interfaces are often assembled temporarily during a project to meet its information and control needs and those of its team. Such project-specific and temporary communication interfaces tend to depend heavily on human involvement and availability of resources, so reporting frequencies become subordinate to that involvement and often fail to inform decision-makers (e.g., managers, superintendents, or supervisors) promptly. Such limitations are understandable given the project-centric nature of construction and its temporary nature. In response to the aforementioned gaps in the literature, this study investigates innovation through the adoption of emerging information technologies from the perspective of early-adopter organizations.

3. METHODS

The grounded theory method was adopted to enable a focus on processual and contextual components, including key roles in behavior (Pettigrew 1990; Orlikowski 1993), which have been overlooked in technology studies in the construction literature. The grounded theory, proposed by Glaser and Strauss (Glaser and Strauss 1967; Glaser 1978; Glaser 1992; Strauss 1987; Corbin and Strauss 2008), represents an inductive discovery method that enables "the researcher to develop a theoretical account of the general features of the topic while simultaneously grounding the account in empirical observations" (Martin and Turner 1986). This inductive reasoning method has two basic premises (Urquhart 2013). First, no theoretical model or hypotheses should be anticipated. The model emerges during the analysis. Grounded theory is leveraged when specific models or explanations have not yet been devised, as in the case of the topic of study. Second, constant comparative analysis of evidence is necessary for the emergence of an empirically consistent theory. Such constant analysis grounds the emerging theory in the collected data and their interpretation (Denzin and Lincoln 2000). Thus, the grounded theory approach requires an intertwining between data collection and analysis. The emerging theory guides data collection steps (Glaser and Strauss 1967), with analyses informing subsequent data collection efforts. In this manner, the emerging theory and concepts are "systematically worked in relation to the data during the course of the research" so that the emerging model can fit and function. In this study, the inductive, contextual, and processual facets inherent to grounded theory aim to develop a solid understanding of the problem under study, which "gives primacy to realism of context and theoretical and conceptual development as research goals" (Pettigrew 1990). Thus, in the study presented in this manuscript, the grounded theory approach enabled the generation of a model that meets empirical and inductive evidence.

The data collection and analysis presented in this manuscript were conducted in accordance with the ethical standards of the Institutional Review Board (IRB), which approved the protocol for this study. Prior to participation, all interview and survey participants provided informed consent outlining the study's purpose, data usage, and voluntary participation. To ensure participant anonymity, interview data were de-identified. Personal identifiers were replaced with alphanumeric codes, and any specific organizational references were generalized to prevent deductive identification.

3.1 DATA COLLECTION AND ANALYSIS

Qualitative data were collected through various techniques, including unstructured and semi-structured interviews, online survey tools, project documentation, observations, and expert feedback. Such a combination of sources becomes especially valuable in the grounded theory approach, as it enables numerous viewpoints on an issue, enables cross-referencing, provides substantial information on emerging categories and properties, and results in the verification of stronger themes (Eisenhardt 1989; Glaser and Strauss 1967; Pettigrew 1990). The researchers collaborated closely with a steering committee of fourteen industry experts throughout this study. Experts brought an average of 28 years of experience in the management and control of complex projects. Researchers and experts met in person every other month and virtually weekly. Close collaboration enabled researchers to gain detailed insights into control functions, reporting expectations, recurring problems, and decision and accountability dynamics. The expert collaboration was leveraged to plan, design, and test data collection instruments and to obtain formative feedback.

The initial stages of the study examined the controls and reporting conditions in the construction industry using data collected via an online survey. A literature review and four face-to-face and multiple online meetings were conducted to identify issues of interest, formulate research questions, and determine the structure and content of the online inquiry. The controls and reporting functions were divided by project phase (engineering design, procurement, construction, and commissioning and startup), and each was incorporated into the corresponding survey tool. As an example, Table 1 lists the control functions for the commissioning and startup phase. Survey questions were grouped into five categories: personal, organizational, project information, project controls software and tools, and reporting frequencies to the project manager, client(s) (e.g., owner), and ultimate authority. In all, the project controls condition of 38 projects was documented with responses from an equal number of project managers and control experts, who averaged 24 years of experience. The reported projects accounted for total installed costs above $41 billion. Reported projects were representative of different affiliations (public, private, both), sector (commercial, industrial, infrastructures), delivery method (design-bid-build, design-build, construction management, turnkey), contract type (lump sum, reimbursable, guaranteed maximum price, cost plus fixed fee), or nature (greenfield, brownfield, renovation, expansion).

To promote iteration and identify loops of causation, corporate managers from a diverse sample of eleven early-adopter organizations were interviewed. The sample of organizations, comprising four owners, one construction management provider, two contractors, and four software providers, was purposely selected to strengthen the study's validity and facilitate analytical generalization. See Table 2. The identified organizations were targeted specifically for their commitment to prioritizing project functions through advanced information technologies. Following Eisenhardt’s (1989) framework for theory-building case research, the qualitative data collection and analysis progressed iteratively. Initially, iterations were open-ended and facilitated by the steering committee, informal conversations, and solicited feedback. At later research stages, they were led by emerging concepts, a targeted choice of informants, and a semi-structured interview protocol. This iterative approach allowed for "flexible data collection", providing the freedom to make adjustments as theoretical insights surfaced.

Table 1: Control Functions - Commissioning and Startup.

Cost	Schedule	Scope	Quality
Plan Baseline/Control Budget	Develop Baseline Schedule	Develop Control Scope (Baseline Scope plus Approved Change Orders)	Monitor Quality Tests and Inspections
Monitor Committed Cost (actual obligated/contracted cost to perform work)	Monitor Major Milestone Progress / Commissioning Performance Against Baseline Schedule	Monitor Change Order Status	
Monitor/Control Change Order Cost	Estimated Time to Completion	Monitor Change Order impact on project schedule and cost	
Monitor Budget (Baseline Plus Approved Change Order)			
Monitor Actual Cost/Expenditures to Date			
Estimate Total Installed Cost			
Monitor Commissioning Performance Measurement - performed vs. planned (hours & quantities)			
Monitor Risk (should include contingency reconciliation)			
Monitor Accounts Payable			
Monitor Accounts Receivables			

The semi-structured interviews enabled the researchers to gain insight into corporate managers' experiences and perspectives on the adoption of prioritized controls. Each interview lasted between one-and-a-half and two-and-a-half hours. The authors asked the informants about the prioritization of controls, changes and their implementation, as well as the barriers they had encountered. Thus, interviewees comprehensively shared their experiences, insights, and information about their organization; history of implementation of prioritized controls; business rationale; implementation strategies, benefits, and key roles; leadership support; integration with legacy systems; enabling technologies; upfront and maintenance costs, schedule, and human resources; user involvement; training; implementation and adoption barriers; design of incentives; contracts; and transformation in transactions, workflows, or communication of information.

Interview data were systematically analyzed using thematic analysis grounded in established qualitative research frameworks (Braun and Clarke 2006). The process began with transcription of all recorded interviews, followed by an initial familiarization with the data through a comprehensive reading of transcripts. Open coding was conducted inductively, identifying meaningful units that captured participants' experiences with the adoption of prioritized controls. Through iterative rounds of axial coding, individual codes were consolidated into broader categories and progressively refined into coherent themes. For example, process implementation, policy enforcement, or compliance requirements were later grouped under the construct of workflow management. Similarly, coding structure, data communication and exchange, or single data/repository were integrated under the construction of information integration. The research team maintained rigorous analytical standards by conducting inter-coder reliability checks, documenting an audit trail of all coding decisions, and performing member checking with a subset of participants to validate thematic interpretations. Inter-coder agreement was established by having at least two researchers independently code a subset of transcripts and then reconcile discrepancies through discussion to reach a consistent, shared coding scheme.

It was often evident that themes emerging from an early-adopter organization would not hold up against those from other organizations. The analysis of diverse contexts and experiences led to fundamental evolution and clarification in the emerging theoretical model, prompting a reevaluation of themes. For instance, a preliminary construct of “instantaneous reporting” did not include those design and construction functions with a non-instantaneous but targeted and frequent reporting capability. Such a member-checking process enhanced the credibility and trustworthiness of findings by ensuring that emergent themes accurately reflected interviewees' intended meanings and experiences. Interviewees were reached via email to provide clarifications, additional insights, and information. This iterative refinement continued until theoretical saturation was achieved —the point at which no novel concepts, categories, or patterns emerged from additional data collection and analysis, indicating that further data collection was unlikely to alter the core findings.

Table 2: Summary of case studies, including organizational roles, sectors, units of analysis, and reporting characteristics.

Case study number	Organizational role	Sector	Unit of analysis	Reporting function(s)	Reporting frequency	Number of interviews
1	Owner	Energy	Oil and gas projects	Project Cost and Schedule Progress	Daily	1
2	Owner	Automotive	Car assembly	Production, quality, and business metrics related to car assembly	Instantaneous	2
3	Owner	Aerospace	Facility projects	Project information	Instantaneous	1
4	Owner	Semiconductor	Semiconductor projects	Planning, Budgeting, and Scheduling for Capacity Planning Decisions	Weekly	1
5	General contractor	Construction	Commercial and industrial projects	Craft labor productivity	Daily	1
6	Design-build contractor	Construction	Infrastructure projects	Cost and schedule progress	Daily	1
7	Construction management	Construction	Commercial and industrial projects	Project Cost, Procurement, Change Management, Portfolio financials	Daily	2
8	Software provider	Construction	Construction projects	Payment transactions	Instantaneous	1
9	Software provider	Construction	Design and construction projects	Project information	Instantaneous	1
10	Software provider	Construction	Design and construction projects	Project information	Instantaneous	1
11	Software provider	Construction	Design and construction projects	Design engineering progress, craft labor productivity	Instantaneous / daily	2

Indeed, data triangulation strengthened the validity of the study's conclusions by integrating multiple perspectives: (1) interview narratives providing rich contextual understanding of adoption experiences; (2) verification from follow-up communications with participants; and, (3) evaluation by two different sets of external experts. Regarding the latter, emerging concepts and constructs were further evaluated by the steering committee and 10 additional construction experts, with no prior relationship with the study, during a dedicated workshop. For instance, during the workshop, the experts were exposed to findings and responded with their insights, experiences, and feedback. Further evidence of theoretical saturation was demonstrated when these two additional verification activities yielded no additional codes or changes to the final thematic structure. Finally, to provide additional validity, the ability of the model to explain the distinct success in adopting instantaneous controls was contrasted with that of an additional set of early-adopting organizations -see Section 8. This multi-source approach enabled convergence of evidence and comprehensive assessment of prioritized controls adoption patterns.

4. STATE-OF-THE-ART OF PROJECT CONTROLS

A summary of the survey results follows. The information provided by the experts indicated the use of a myriad of often proprietary, non-interoperable software packages to support cost estimating, scheduling, change management, progress tracking, procurement, and document management. See Table 3. The prevalence of information silos within control functions emerged as an obstacle to immediate information sharing, transparency, and accountability, facets investigated during the interviews. The first report of information (typically provided by the project manager) for most control functions ranged in frequency from two weeks to one month. Table 4 illustrates key reporting frequencies during the construction phase. Instances of sequential reprocessing and reporting were also documented, extending up to half a year (i.e., six-month-old data).

Table 3: Number of distinct software tools by function.

Function	Count of Distinct Tools
Building Information Modeling (BIM)	3
Scheduling	5
Cost Estimating	10
Progress Tracking	16
Change Management	12
Procurement	8
Document Management	15

Table 4: Median reporting frequencies during construction by organizational role.

Reporting	Owner (days)	Contractor (days)
Schedule progress	15	7
Change order status	7	7
Committed costs	15	15
Risk monitoring	30	30
Construction progress	30	7

5. DRIVERS FOR INSTANTANEOUS CONTROLS

The grounded theory approach provided a rationale for prioritized reporting, i.e., what makes a control function require more frequent or even instantaneous information sharing and reporting. According to expert feedback, it became apparent that a pervasive implementation of instantaneous reporting would be complex, expensive, and unjustified. Even though subject matter experts could not provide a rationale for what should be controlled instantaneously, the grounded theory method enabled the emergence of two principles that explained the rationale for real-time or near real-time reporting frequency.

1. The first principle states that the controlled function must be subject to variability.
2. The second principle states that such variability must have the potential to impact project or organizational performance, and that, if left unmitigated, its impact will worsen over time.

Thus, the iterative analysis of the case study data led to the emergence of a formal proposition that defines the relationship between reporting frequency, variability, and impact. The required frequency of information reporting is positively associated with the magnitude of process variability and the time-sensitive nature of its impact on organizational performance, as expressed by the theoretical proposition $R_f = f(V, I_t)$ where, for a specific function,

R_f= reporting frequency

V = magnitude of variability

I_t= time-amplified impact of unmitigated deviations

Multiple triangulations of data and evidence substantiated the generalizability of these principles to the construction industry. The nature of the information reported instantaneously varies widely across early-adopter organizations in construction, depending on environmental, technological, and organizational factors. An example of instantaneous reporting follows. The ability to update on a daily basis the owner's financials with project costs was highlighted as a competitive advantage by a construction management organization serving clients with multi-project and multi-billion-dollar capital investment portfolios. The daily financial updates enabled clients to respond to actual and forecast costs in a timely manner, for example, reallocating unused funds for the start of new facility projects.

In addition, the findings from the car assembly industry provide further triangulation evidence for those observed in the construction context. Specifically, this study reveals that the prioritization of information in lean manufacturing closely mirrors that identified in construction, as reflected in the principles outlined above. Interviews with procurement and operations managers at the car assembly firm enabled the establishment of an initial relationship between reporting frequency, variability, and performance. In the car assembly context, events on the assembly line trigger immediate responses, whereas business metrics—such as work hours per product type—are reported at predetermined intervals (e.g., biweekly or monthly) to support managerial decision-making. That is, events that can propagate through the assembly line, such as quality or productivity issues, are addressed as they happen, while other events and information, such as work hours per car model, are reported at a predefined frequency. The reader should notice that such prioritization closely aligns with, and thereby reinforces, the patterns identified in this study, providing additional cross-industry support for the underlying findings.

6. INNOVATION MODEL

The qualitative analysis revealed nine common constructs or change components to sustain the successful diffusion of instantaneous control mechanisms. These contextual and processual components were grouped into three categories: organization, project, and information technologies. In addition, the analysis revealed a common sequence of 11 implementation steps, grouped into strategies for business case, process and transaction streamlining, and end-user engagement. Figure 1 illustrates the innovation model. The arrows indicate how the institutional change context and adoption strategies interact. Common to the magnitude of the effort towards prioritized controls in support of multiple projects was an intertwining of organizational, project, and information technology contexts, which the following text characterizes.

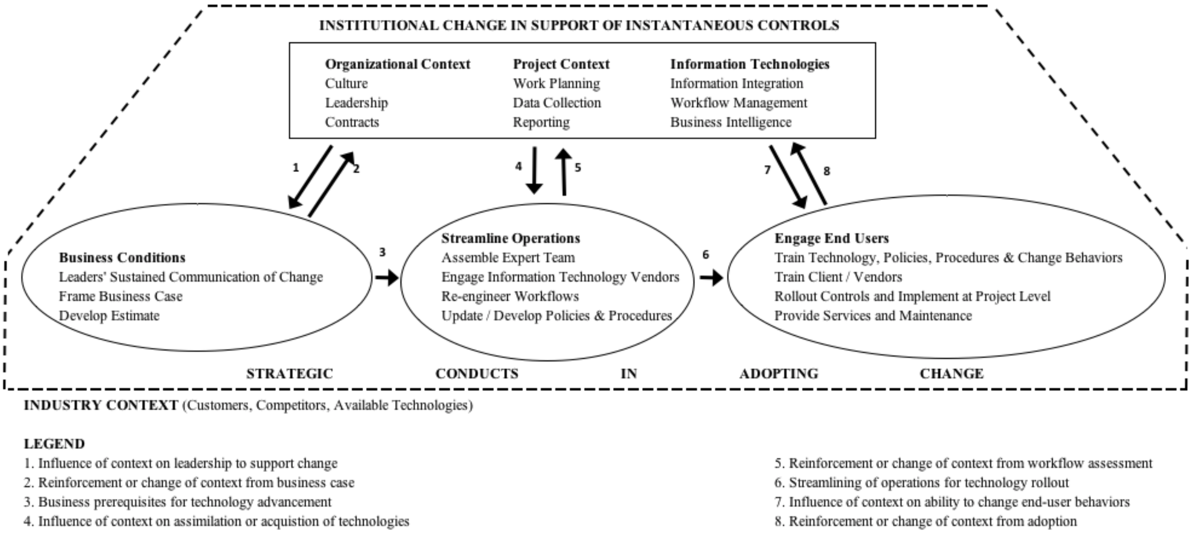

Figure 1: Innovation model.

1. *Culture*. The organization's culture sets the normative behavior in which individuals challenge current technologizes, tools, and processes and test / implement those that promise to improve prioritization, data collection, or seamless information sharing. Instructions, procedures, and policies support process improvement and innovation. Individuals understand the relevance of timely and accurate reporting, for instance, in support of decisions. Experts noted that "*culture must promote not only innovation but also individual accountability*" since accountability plays a key role in fostering responsible and accurate reporting.

2. *Leadership*. Upper management must communicate a sustained vision of prioritized project controls. Leaders must support, communicate, and encourage the adoption and use of prioritized controls. Complementarily, leaders must be tolerant of justifiable implementation problems and failures. Leaders recognize that allocating dedicated resources is necessary. Instances of incentives, rewards, or recognition mechanisms to motivate employees were documented. Leaders ensure that a detailed budget and business case are in place before committing resources. For example, an expert explained that a detailed business case plays a central role in envisioning how information flow can streamline and/or eliminate major processes, procedures, or transactions. An owner organization estimated more than $1 million in yearly courier savings alone. The same expert explained that such an ability to envision processual gains had been foundational to successful implementation and that the details were set out in accordance with the business rationale.

3. *Contracts*. Data and reporting requirements, as well as communication interfaces, are enforced through contracts and customized to each contracted entity. Alignment regarding code structures, work breakdown structures, and metrics is preserved in the contractual agreements. Experts stated that contractual requirements were perceived as critical to maintaining "*an unbroken communication chain*." Experts noted that such contractual requirements were easier to realize under specific project delivery methods (e.g., integrated project delivery).

4. *Work Planning*. A single code structure is designed to support all aspects of project controls and enables "*the flow of information between estimating, design, and construction*." Individuals recognize the importance of work planning in supporting informed and proactive decision-making. Organizations promote work planning practices across organizational boundaries and establish accountability and alignment with expectations for continuous data feed and prioritized reporting.

5. *Data Collection*. A well-defined set of instructions, procedures, checklists, and/or standards exists for collecting project data. Project and controls data is continuously collected. Whenever possible, data collection is semi-automated or automated at the source. Enforcement of single data entry practices is in place. Experts emphasized the need for the collected data to be "*clean, consistent, and complete*" (C3). A focus on the consistent and effective implementation of data collection methods exists.

6. *Reporting*. The reporting frequency of each control metric is prioritized to support reliable and timely decision-making. Reports should be automatically generated, i.e., on demand. Experts emphasized the need for the reported information to be "*reliable and presented with the right set of metrics, level of detail, and the correct format for informed decisions*." Remote, mobile, and cloud technologies for pervasive access to reporting were documented.

7. *Information Integration*. Data and information must be integrated and seamlessly shared. Barriers to communication interfaces must have been identified and mitigated. Manual or semi-manual data transfer of information between project and organizational functions should be avoided to prevent errors, omissions, or delays. Data and information need to be protected through appropriate access, confidentiality, redundancy, and security protocols. Mechanisms for the communication of data and information should be enabled for all players. For example, a client was observed to facilitate the submission of data by non-sophisticated subcontractors in a basic spreadsheet format, with the intention of "*satisfying the contractual data submission requirement while maintaining the contractor within the pool of vendors*."

8. *Workflow Management*. Processes, procedures, and transactions are reengineered and automated around information technologies. Specific and appropriate review/access privileges are established for different users in the organizational or project structure(s). Timely compliance with audit requirements and regulations is enforced through technology functionalities. For instance, a request for a scope change triggered automated messages (e.g., emails) to the appropriate approvers —small changes handled by the superintendent, medium changes by the project manager, and large changes by the program manager. If the change request had not been approved within the specified time, the issue was "*automatically escalated to upper management*."

9. *Business Intelligence*. Advanced analytics is set to instantly "*answer or anticipate critical questions*" on the project or portfolio investment. Ad hoc querying and reporting functions are in place to support informed decision-making. Intelligent functions automatically and instantaneously identify, alert, and trigger actions on potential and/or actual issues and events, incorporating them into the reported information. Indeed, instances of intelligent functions capable of alerting to potential change orders inferred from email communications were documented.

7. ADOPTION STRATEGIES

This section describes the sequence of 11 adoption and diffusion steps in the model, grouped into the constructs of business conditions, streamlined operations, and end-user engagement. Initially, the leadership envisions and communicates the need to prioritize the reporting of controls. An in-depth business case is documented, and a temporary team of experts is assembled. The communication of a solid business case is critical to justify the human resources and technology nuances during adoption, training efforts, or technologies upfront and maintenance costs. The team includes experts from departments or functions directly or indirectly associated with project management and controls, such as engineering design, planning and management, human resources, information technology, finance, procurement, or accounting. Although temporary, team experts were observed to be commonly dedicated full-time during successful adoptions. The broader the scope of the controls to be prioritized, the more time and resources are required. Comprehensive implementation efforts were documented to last between 1 and 2 years. The implementation of very narrow control functions, such as an automated payment mechanism and lien releases, was completed within a few weeks.

Once assembled, the team solicits information and budgets from technology product vendors that enable seamless integration, advanced analysis, and data and information sharing. The instantaneous and comprehensive assessment of project performance often requires implementing project and/or enterprise information integration solutions or providing communication interfaces between existing software packages and tools. Vendors are requested to present their products and respond to the inquiries of the team. Once the technology vendor is selected, vendor technical experts integrate with the team to plan for the streamlining of work processes, procedures, and transactions related to the functionality of the information technology. Work planning codes are defined with the premise of streamlining communication among estimating, design, procurement, and execution. In terms of data collection, the team generates a well-defined set of instructions, procedures, checklists, and/or standards that enable the collection of appropriate data throughout all project phases, i.e., design, procurement, construction, commissioning and startup. Finally, project control functions are tested, and users are trained. Technology and prioritized project control function are rolled out and implemented. A small number of dedicated workers (typically one or two) are employed to maintain and service technologies and users.

8. EXPLAINING CUMULATIVE AND TRANSFORMATIVE CHANGES

This section provides additional evidence of the model validity by explaining the varying success of three different efforts to adopt prioritized and instantaneous project controls. The insights discussed below, and most importantly, those that the observation of the model can generate within a particular context of adoption, should guide both researchers and practitioners in avoiding pitfalls and grasping the competitive advantage that an instantaneous feed and read of information can provide.

8.1 Cumulative changes towards monitoring craft labor productivity – Case I

Leadership at a sophisticated contractor communicated the need to estimate, plan, and execute projects with predictable craft labor productivity ratios. Continuous improvement and constructive criticism characterized the culture of the organization. The hierarchical structure of the organization was horizontal, so managers were encouraged to continuously evaluate emerging technologies and novel processes. A sophisticated work coding structure had been developed that could enable the rapid flow of information through contractor and subcontractor organizations. Contractual arrangements, such as shared incentives combined with an integrated delivery process, enabled alignment among owner, contractor, and subcontractors, and guaranteed the timely collection and sharing of field data.

Since several of the contextual and processual needs identified in the model (see Figure 1) had already been met, the effort focused on stabilizing production through continuous monitoring of individual crews, which could trigger immediate corrective actions when deviations from agreed-upon work production targets occurred. With support from mobile and data communication technologies, craft labor production rates were measured and shared twice a day through a customized software tool that enabled the fine-grained analysis of craft labor progress. Managers' immediate intervention led to the identification of the root causes of variation and the stabilization of the workflow. The leaders' long-term vision included aggregating field records into a historical database, allowing factual data to be used reliably to predict resources and work performance through estimating, design, planning, and execution.

8.2 Thoughtful transformation towards prioritized project controls – Case II

This case illustrates a comprehensive transformation within an owner organization aimed at enhancing the flow and accuracy of project controls information. Yearly capital expenditures totaled billions of dollars, with hundreds of new and renovation projects being completed simultaneously. In the past, legacy tools had assisted in project management and controls. Legacy tools were regarded as standing barriers to automated analysis and information communication. Information processing and reporting tasks were manually performed or required substantial human intervention. Contractors and subcontractors relied on their own data governance and tools.

In such a scenario, the leadership developed a business case for replacing legacy tools with information integration and management software, thereby streamlining communication and reporting of project information. Reductions in support costs, manual and paper-based tasks, priority mailing, and administrative / support staff were major line items in the estimated return on investment (ROI). A three-year break-even ROI time was estimated. A team of experts from core departments was appointed full-time for the 2-year adoption effort. Leadership empowered the team to think beyond existing policies and procedures, streamlining processes and transactions.

The expert team designed a bid package to solicit tools for information integration and project controls. The solicitation was characterized by the fact that the owner also provided its own construction services; hence, the solicited tool had to simultaneously satisfy the information needs of both owner and contractor roles. Three vendors were invited to extensive interviews before a vendor was selected. Work processes, transactions, and information flows were mapped and scrutinized as a preliminary step to reengineer (or eliminate) them with the functionality of the acquired software tool. Once the flows were mapped, the software provider configured the tool functionality to support the reengineered processes and procedures.

Two waves of functionality were required for implementation. The first wave included non-financial project management processes such as proposal preparation, contracting, electronic signatures, requests for information, submittals, safety tracking, inspection tracking, schedule submittals, issues, and action items. The second wave included financial aspects, detailed schedules of values, contracting, automated invoicing, forecasting, and detailed transaction flows. Then, user acceptance tests preceded the development of training materials centered around the new processes and procedures. Employees were trained in the reengineered processes, tool functionality, and use. Two full-time positions were allocated to provide maintenance and support services.

8.3 Unsuccessful technology-centric attempt – Case III

The authors documented two unsuccessful instances in which the purchase and implementation of a commercial technology tool were entrusted to enhance control reporting capabilities. Common to both pitfalls was a lengthy, cumbersome, and technology-centric implementation effort. Such efforts failed to address the fundamental constructs of the innovation model (see Figure 1) and thus to account for necessary shifts in organizational and project contexts, as well as in information technology planning and implementation strategies. Significant monetary resources were invested and eventually lost, positions were terminated, and an opportunity to gain a competitive advantage was missed. The paragraph below summarizes one of such failed attempts within an owner organization.

The owner resourced the vendor of a software cost management and controls software tool in order to provide an instantaneous cost reporting capability for turnaround projects with the following objective: "provide timely, forward-looking cost information to enable informed and proactive decision-making; and, highlight associated problems and opportunity areas in a timely fashion in order to efficiently support planning and execution efforts." Mapping and reengineering of existing work and communication processes were not considered, and a business case was never ascertained. The plan was limited to piloting the information tool on a couple of small projects.

The two pilot tests sequentially failed to implement the tool. The scope of the pilot tests was never defined, despite high expectations having been generated. Unrealistically short schedules for technology integration were expected. The technology vendor failed to provide resources to resolve issues during the tests. Another example of inadequate planning is that the existing servers were unable to support the client software's functionality. The cumbersome testing process lasted for 18 months. Possibly due to deception and accumulated losses in the tens of millions of dollars, the firm decided to halt its adoption efforts indefinitely.

9. LIMITATIONS

While this study provides a formalized rationale for instantaneous project controls, several limitations must be acknowledged. First, the empirical evidence is primarily derived from 11 case studies, mostly in the energy and infrastructure sectors in North America; thus, the findings may reflect the specific complexities and risk profiles of large-scale, high-capex environments in such region. Second, while the proposed innovation model and theoretical proposition (see Section 5) are to remain stable, the rapid evolution of information technologies may alter the practical ease of adoption. Future technological advancements could eventually simplify the implementation steps described herein, potentially lowering the threshold for organizations to transition from batch to instantaneous reporting. Thus, while this research achieves analytical generalization regarding the "when" and "why" of control frequency, further longitudinal studies are required to quantify the long-term impact of real-time information integration and reporting.

10. CONCLUSIONS

The construction industry has historically employed a wide range of non-standard practices, methodologies, and tools to manage the delivery of capital projects. The current state is best described as “batch mode,” in which information is unavailable for a considerable time after an event triggers. However, a widely held perception exists that real-time, or at least near real-time, reporting capabilities would constitute a significant breakthrough and yield substantial benefits. This study reveals that prioritizing project control functions must be driven by the goal of reducing or eliminating variability and its impact on performance. Events that affect variation and performance must be communicated and corrected rapidly, if not immediately. Consequently, as the variability and impact on project performance increase over time, the required reporting frequency also increases. Under these premises, the construction, commissioning, and startup phases benefit the most from instantaneous reporting, as costs, risks, and variability are at their peak.

The primary theoretical contribution of this research is the formalization of the relationship between reporting cadence and project risk through the innovation model proposed in this manuscript. A mathematical proposition defines the reporting frequency (R_f) as a functional dependency of process variability (V) and the time-amplified impact of deviations (I_t), as expressed by $R_f = f(V, I_t)$. This logical proposition explains why high-impact functions, such as change orders or risk management, require real-time updates, unlike other functions that do not have such a time-escalating impact, such as cost or schedule performance indexes. Furthermore, the study advances the understanding of construction organizations as complex systems, proving that innovation through advanced sensing and information technologies requires the simultaneous reengineering of fundamental system components, including attitudes, behaviors, and policies.

For practitioners, the evidence suggests that achieving a competitive advantage through instantaneous reporting requires more than a technology-centric focus. Successful implementation depends on several key managerial actions: aligning data requirements across contracts to ensure seamless inter-organizational sharing, adopting a single code structure to facilitate seamless information integration, and leveraging business intelligence to automate escalation procedures. Managers should use the variability and impact logic to prioritize control functions where risks are at their peak, ensuring that reporting frequencies inform decision-makers promptly rather than remaining subordinate to human involvement. Successful adoption requires the organization to undergo cumulative or transformative changes in fundamental components such as attitudes, behaviors, structure, practices, and policies. Thus, the impact of this study transcends its project controls scope by advancing understanding of how construction organizations should plan for and respond to change to successfully diffuse technological transformations.

Evidence suggests that a shift toward frequent and instantaneous reporting has already begun in the construction sector. While this paradigm shift may not be immediately noticeable because it is not systematically communicated, it remains a latent trend. The constant evolution of data collection, analysis, and communication technologies —combined with the pervasiveness of mobile devices— enables fine-grained, timely control over projects. Early technology adopters leverage these tools to gain a competitive advantage and, optimally, reengineer their business models. Corporate executive officers expressed a clear vision for instant access to updated project information on handheld devices.

Future research should investigate and quantify the specific impact of instantaneous controls on project performance, as well as the optimal update frequency for information metrics, particularly those requiring instantaneous updates. Additional insights for practitioners should include case studies and expert guidance to support the design and implementation of prioritized control functions in small projects.

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