Estimate Uncertainty: Miscommunication About Definitions of Engineering Terminology

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Communication demonstrably affects engineering design processes, especially large-scale complex engineered systems. Drawing from engineering design, communication, and management, miscommunication is defined as when communication results in a "deficiency" or "problem" that hinders parties from fulfilling their values. This article details a consequential example of miscommunication at a Fortune 500 engineering firm with the potential to affect system performance. In Phase 1, interviews with engineering practitioners (n=82) identified disagreement about what constitutes a parameter "estimate" in the design process. Phase 2 surveyed engineering practitioners (n=128) about whether estimates communicated for system-level tracking approximate "current" design statuses or "future" design projections. The survey found that both definitions existed throughout the organization and did not correlate with subsystem, position, or design phase. Communicating both current and future estimates followed by aggregating those estimates constituted widespread or systemic miscommunication. Thus, even technical concepts may be susceptible to miscommunication and could affect system performance.

1 Introduction

As society's technological capabilities grow, so too does the prevalence of complex systems. Large-scale complex engineered systems (LaCES, or just complex systems) are engineering projects with significant cost and risk, extensive design cycles, protracted operational timelines, a significant degree of complexity, and dispersed supporting organizations [1] which include everything from civil (e.g. water, power, transportation) to commercial (e.g. e-commerce, financial, healthcare) to defense infrastructures (e.g. cyber, aircraft, spacecraft) [1–3]. Designing, coordinating, implementing, and operating such complex and increasingly-ubiquitous systems often requires organizations to employ and integrate numerous design methods including multidisciplinary design optimization [4, 5], concurrent engineering [6, 7], and systems engineering [8–10].

Consequently, communication plays a critical role in engineering design processes [11–14]. But just as "good" communication produces beneficial results, "bad" communication, "misunderstandings" between people, too little communication, and too much communication can have serious consequences. In 1999, the Mars Climate Observer infamously failed to orbit Mars because one ground software file "failed to use metric units" instead of imperial units in part due to "inadequate communications between project elements" during the design process [15, 16]. In 2003, the Columbia Accident Investigation Board assigned partial responsibility for the Space Shuttle Columbia disaster to multiple engineering communication issues including "organizational barriers that prevented effective communication of critical safety information and stifled professional differences of opinion" [17, 18]. In fact, in a review of 50 space system failures, J. Newman emphasizes that "communication failure" is one of the most prominent causes of complex system failure because "the vast majority of mishaps involved...misunderstanding or incomplete understanding of

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ambiguity" including design fundamentals such as "inadequate design margins, unknown synergistic effects, [and] invalid assumptions" [19].

These reports paint a daunting picture. The reader can likely recall one or more instances in their own work where "communication failure" created obstacles if not threatened the success of their work altogether. Scholars and practitioners alike refer to such instances of communication-that-causes-problematic-outcomes as "miscommunication" [20–22]. *Miscommunication* happens when communication results in a "deficiency" or "problem" that hinders at least one of the engaged parties' abilities to fulfill their individual or collective values [20, 23]. Communication scholars note the potential of miscommunication to impact organizational outcomes [21] as the aforementioned federal disaster reports and studies corroborate.

Despite evidence to the contrary, it is easy to dismiss instances of miscommunication as exceptions rather than commonplace in engineering communication. But is miscommunication the exception? Or is miscommunication prevalent? By definition, miscommunication is communication. Management studies have shown that organizational communication affects team performance [24, 25]. Engineering design research into communication describes how "communication breakdowns" occur in engineering design [11,26,27] and how network topologies affect performance [28–30]. Collectively these studies suggest that widespread or *systemic* miscommunication throughout an engineering organization likely affects system performance. Then how widespread or systemic is miscommunication in engineering design organizations?

To answer this question, the authors examined a recently-identified case of a commonly-used engineering term with demonstrated ambiguity. Several recent studies have called into question the ubiquity of the definition of "parameter estimates" in engineering practice. Ye et al. show that expert uncertainty estimates added negligible value compared to an architecture design tool [31]. Austin-Breneman et al. identified and simulated biased estimate passing through interviews with practitioners [32] suggesting estimate ambiguity. Further investigation by Meluso & Austin-Breneman into estimation strategies concurred that practitioners bias estimates as a "negotiation and resource conservation strategy" which may increase system uncertainty [33]. The ambiguity noted by these studies, coupled with pilot interviews for this paper, highlight the lack of understanding surrounding how practitioners define the term "estimate" in complex system design. To that end, this article addresses the following research questions:

(1) How do engineering practitioners define "an estimate" in complex system design?
(2) How do estimate definitions vary throughout an engineering organization?
(3) How does communicating varied estimate definitions yield miscommunication?

This study consisted of two phases. Phase 1 interviewed engineering practitioners ($n = 82$) about their design estimation practices to identify the existence of multiple definitions of what constitutes "an estimate". Phase 2 surveyed engineering practitioners about which definition they used when communicating with others in the organization. The data will show that what constitutes "an estimate" varied independent of subsystem, position, and design phase. Hence, differing definitions of a fundamental engineering concept created a high probability of systemic miscommunication indicating the potential of miscommunication to affect complex system performance.

2 Background

In order to understand miscommunication, one must first define communication. Both terms largely depend on the discipline of inquiry, so the following sections integrate multiple definitions into terminology applicable to engineering and management.

This section summarizes the approaches through which scholars study communication by drawing from communication studies, sociolinguistics, management, and engineering design. It then reviews the literature on and defines miscommunication before continuing with a brief recitation of parameter estimation and uncertainty definitions. Finally, it states the research gap and describes the organizational context in which the study took place.

2.1 Communication

Over time, two approaches have developed for studying communication. Quantitative models of communication (also called the Objectivist Approach [34,35]) trace the footsteps of Shannon and Weaver's seminal text, *The Mathematical Theory of Communication* [36], which treats communication as a process with a transmitting party, a transmitted signal, and a receiving party. This conception of communication as information passed from party to party has become known as the "process" model of communication. Out of the process model grew the idea of communication as networks [37, 38]. "*Communication networks* are the patterns of contact that are created by the flow of messages among communicators through time and space," and so *communication* is defined as the transmission and exchange of messages which may include data, information, knowledge, symbols, or "any other symbolic forms that can move from one point in a network to another" [39]. Even given their simple forms, network models of communication display powerful results by demonstrating social theories of self-interest, collective action, exchange theory, dependency theory, and homophily among others [39, 40].

Qualitative researchers (or the Interpretivist Approach [41]) critique quantitative models for oversimplifying the multiple processes involved in each communicative interaction including differences of meaning, context, and interactive asynchronicity [11, 38]. Here, *communication* is more broadly defined as "social interaction through messages" [42] to incorporate the *identities* of the participants, the *context* of the interaction, the *genre* (or medium) of exchange, and the *actions* intended by exchange [38, 43].

Note that quantitative models simplify transmission to illuminate the existence and patterns of communication, while qualitative models unsurprisingly emphasize qualities of communication to understand how it occurs. Need this be the case? Bavelas suggests that this difference presents an opportunity to "discover new, previously unexplored combinations of both approaches" [44] which this article capitalizes on through its mixed methods approach.

2.2 Communication in Engineering Design

Engineering design research focuses on three topics related to communication: (a) qualitative models of how communication contributes to design practice, (b) quantitative models of the effects of individuals' cognition on system performance, and (c) quantitative models of the effects of networked communication on system performance.

Eckert's framework aptly summarizes the focus of qualitative studies by differentiating "three layers of structure in design communication [including] the design process, interaction between participants, and representations of design information" [13]. Design process studies find that communication through virtual and physical objects facilitates "cooperation" and "mediation" of designs [45]. Interaction research notes the "integration, collaboration, and project completion" [46] faculties of communication including activities such as design handover, joint designing, idea generation, interface negotiation, conflict resolution, and decision making, among others [11]. And design representation studies find that communication aids "cognitive operations of generation, exploration, comparison, and selection" [47] or information, interaction, and situation [11].

Next, engineering cognition is studied through multi-agent systems (MASs) and agent-based models (ABMs). While the distinction between MASs and ABMs is slight, MASs tend to create small groups of highly interdependent decision-makers (usually less than 10) and optimize system performance given the agents' cognition rules [48–51]. ABMs, on the other hand, typically involve larger numbers of highly-autonomous agents (usually more than 10, often more than 100) with external influences [52–57]. As LaCES are "made up of many smaller engineered systems [that are] designed, developed, and operated by another large 'system' of dispersed, loosely connected people" [1], ABMs are more common in complex system modeling.

Finally, engineers have studied complex system design communication via field studies [58, 59], historical project data regression analysis [25, 60], and controlled laboratory experiments [61]. Several studies explore the relationships between network properties like modularity [28], centrality [28, 29, 62], brokership [63], and system design outcomes. Other investigations include curvilinear relationships between genres of communication and performance objectives [64, 65], how information flows and structures affect team performance [30, 66], and methods of evaluating communication quality [12, 24, 67].

2.3 Miscommunication

What makes communication into *mis*communication? It takes many forms, and not always intuitively: "Clear, concise, honest communication is frequently the *cause* of difficulties as it is the solution to them. 'Miscommunication' is therefore not… [simply] a deviation from some underspecified ideal" [68, emphasis in original]. *Miscommunication* is better defined as when communication results in a "deficiency" or "problem" that hinders one or more of the engaged parties' abilities to fulfill their individual or collective values [20,23]. What constitutes a "deficiency" or "problem" is a matter of individual participant expectations [69]. Context [22], action [23, 70], identity [71], and genre [21] shape miscommunication as they shape communication.

The quantitatively-oriented literature does not appear to define miscommunication, although similar ideas exist in perception of network structure [72] and forming networks from participant "interpretations of one or more significant communication messages, events, or artifacts" [39].

Engineering design examines similar concepts without explicitly defining miscommunication. Eckert, Maier, and McMahon suggest causes and ways of resolving "communication breakdown" or "communication problems" and provide methods for overcoming "information distortion", "not understanding the big picture", "missing information provision", and "interpretation of representation" [11]. Luck uses natural language processing to identify ambiguity and uncertainty in social interaction as different forms of "misunderstanding" [14]. She also noted the existence of "repair" processes to bridge misunderstandings [14], previously identified in sociolingustics [20]. Though valuable, both leave systemic implications to the reader.

2.4 Parameter Estimation & Uncertainty

Engineering estimates are critical for managing uncertainty when designing complex systems [73] and facilitating "mutually consistent solutions" across interfaces [11]. Despite its foundational nature, precise definitions of "an estimate" are difficult to find in engineering texts [74–77]. Those that address it refer the reader to texts on statistics [74] or require the reader to infer its meaning from context by giving imprecise definitions such as "a single number that is our 'best' guess" [77]. As mentioned in Section 1, several recent studies also support that how engineers estimate design parameters in practice differs from the textbook definitions [31–33, 73].

Uncertainty, on the other hand, receives significant attention. Engineers calculate uncertainty via the standard statistical concepts of confidence or uncertainty intervals [77, 78], the Method of Imprecision [79], design margins [32, 80], and cognitive heuristics of uncertainty [32, 33, 73, 81]. Classifications exist to assist engineers in selecting uncertainty estimation methods [82]. Ironically, some estimate uncertainty may arise from ambiguity in the qualitative definition of "an estimate" rather than the quantitative bounds.

2.5 Research Gaps

Organizational communication affects team and system performance. While anecdotal evidence documents instances of miscommunication in engineering design, a gap exists in the knowledge of how pervasive miscommunication is in engineering practice. The literature suggests that widespread miscommunication in engineering organizations would likely affect the performance of the systems that engineering organizations create.

Significant ambiguity also exists as to what "an estimate" is in engineering practice. While statistics provides definitions, engineering literature rarely does so and studies of industry definitions yield varying definitions. Therefore, a gap exists in understanding how practitioners define what constitutes "an estimate".

2.6 Study Context

To incrementally address the research gaps, the authors conducted a study at a Fortune 500 engineering firm that develops complex systems. The sponsoring division of the firm asked the researchers to investigate the estimation methods of engineers in their organization to help improve the quality of the system-level estimates that program management used to affect project outcomes. Systems engineers aggregated estimates from the artifacts that compose the system to form a system-level estimate.[1] This process of integrating artifact estimates played a crucial role in turning communication into miscommunication as the following sections reveal.

3 Phase 1: Practitioner Interviews

The first phase of the study sought to answer how engineers define "an estimate" in complex system design. Semi-structured interviews were conducted with engineering practitioners in the setting described in Section 2.6.

3.1 Interview Methodology

Over the past decade, interviewing has significantly increased in popularity in engineering design research [32, 83–91]. Interviewing is a powerful tool that "gives us access to the observations of others" [92] to reveal what, how, and why things happen [93]. Semi-structured interviews begin with a set of predetermined questions, but allow the researcher to deviate from the questions to inquire further about participant statements or implications [92, 94–96].

Two interviewers conducted 97 semi-structured interviews about estimation methods and definitions through an initial pilot study ($n = 13$) and the primary study ($n = 82$). The pilot interviews informed the design of questions for the primary study, resulting in 19 open-ended questions with both planned and organic follow-up questions. The researchers designed the questions to elicit responses about the participants' knowledge and experiences of estimation methods and definitions. For example:

- "Walk me through the process you used to come up with your first estimate for one of your artifacts."
- "What prompted you to update this estimate? Where did the information get updated?"
- "Through our interviews, we're finding that people define 'an estimate' in different ways. How would you define an estimate?"

Following well-established methods, each interview began with the participant's background to build rapport. The interviewer then asked each participant to describe how they estimate parameters using an example from their work. To avoid biasing the participants into using a specific definition of an estimate, the interviewer left explicit questions about how the participant defines an estimate until the final moments of the interview.

Most interviews lasted from 45 to 75 minutes and covered the majority of the defined questions, time being a significant limiting factor given the initial 60-minute time slots for the interviews. Many participants graciously and willingly spoke for an additional 15-30 minutes as they recounted their perspectives. The interviews included individuals across 10 subsystems, 3 positions, and 2 design phases.

Audio from the interviews was recorded and transcribed. The software NVivo was used to analyze and categorize interview responses as recounted in the following sections.

3.2 Interview Results

Most participants used "estimates" as requisites of their work and spoke of providing one another with estimates of their designs. However, there was no consensus about what the term "estimate" meant, even within subsystems, positions, and design phases.

To illustrate this, consider the ways engineers spoke about estimating parameters of their artifacts. Engineers spoke of numerous sources of their estimates including fundamental physical properties, information from managers and systems architects, and past experience. One engineer said: "I take my [basic physical properties], I try to approximate for better or worse, and then I just calculate the [properties] of my [artifact] by hand," what some call back-of-the-envelope calculations. Another engineer described a similar process but with the caveat that "we look [at] the previous [design] and we estimate. Then we say 'this previous design was X-by-Y-by-Z dimensions, and now I'm gonna be A-by-B-by-C'. I can just do a ratio, a quick estimate, and it's fairly accurate." While also an estimate-by-hand of sorts, instead of basic physical properties, the basis of this method was a previous artifact. Many engineers referred to this process as "benchmarking," using historical information or reference systems to predict an outcome. But the engineer also mentioned that the estimate is "fairly accurate." Against what are they comparing their estimates to gauge the accuracy?

[1] Some terms have been changed to generic terms such as "artifacts" and "parameters" for confidentiality of both the company and participants. The term "artifacts" serves as an umbrella term for any type of designed system element including physical parts, software, processes, information, etc. "Parameters" could be any property of an artifact such as physical, electrical, financial, data, time, etc.

Quotes like these indicated that some deeper point of reference was likely being used to define an estimate.

Engineers also spoke of managerial sources and methods of their estimates. “Typically, the project management will take a previous system, take some percentage off [a parameter,] and say ‘That’s your estimate, go meet that. This is what we want’.” Another mentioned that “from my system architects, I get a diagram, a very very coarse diagram that tells me this is what we’re going to have...I do some really coarse estimating just based on material properties.” Note that these quotes make reference to a future time by stating “go meet that” and “this is what we’re going to have,” implying action toward an objective which program management says is “what [they] want.” Others frequently used similar language referencing points in the future, such as “It’s not actual, so you’re taking either your best guess, or using what information you have to come up with a number, right? A ‘ballpark’ number.” The engineer contrasts “actual” prototype or completed artifact descriptors with preliminary or calculated “ballpark” artifact descriptors. A different engineer provided a more explicit example by describing that “An estimate to me is when we use best last data to guess, it’s kind of an educated guess on what the [value] is gonna be.” Hence, some engineers appeared to be defining their estimates as predictions of *future* values of a parameter.

However, the accounts of others contradicted the “future” definition. “So they’re asking me for an estimate, but they’re not *really* asking me for an estimate. They’re asking me ‘What do you currently have released?’ They call it an estimate, but I don’t view it as that. We end up coming back and taking what we got. We may look at it and go, ‘Okay, but I don’t have [most of my artifact] done yet’, so you might [guess] that number. But the rest of it’s gonna be what you’ve already released.” [participant emphasis]

In this excerpt, the participant articulates the tension inherent to a manager or systems engineer’s request for an “estimate” based on the definition of the term. The clause “but they’re not *really* asking me for an estimate” reveals the participant’s belief that more than one definition exists. “We end up coming back and taking what we got” suggests that an estimate *doesn’t* refer to a future point in time. This engineer believes that, when a manager or a systems engineer asks for an estimate, they are actually asking “What do you currently have released?” and providing that information instead. Indeed, several participants concisely described their estimates as a “snap-shot in time”. Yet another noted that “it’s based on what we know at this point in time, based on the information that we’ve been given...My estimate for the [parameter] today is...based off my understanding of information that’s available today. I don’t know what it will be later. If nothing changes then my number stays the same, if something changes then my number will have to change.” This was a common refrain among many engineers. How can I know what the value *will* be when I don’t know what changes to expect? As a result, these engineers simply provide *current* values of a parameter.

Is an estimate a representation of the current design status? Or is an estimate a prediction of the future, final design status? The answer is likely both, at different times, in different contexts, and for different reasons. Regardless of which definition is formally “correct” according to the management (the future definition), engineers widely exchanged information based on one definition, the other, and sometimes both.

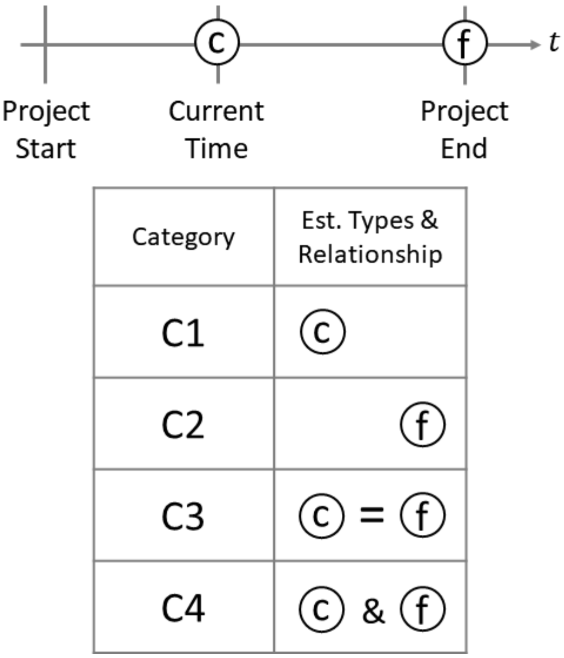

Fig. 1: A timeline and table showing the four categories of estimate definitions, how each is situated in the project timeline, and relationships between estimates within each category. **C1** involves only a current estimate; **C2** only a future estimate; in **C3**, the current estimate is the same as the future estimate; and **C4**, separate current and future estimates both exist.

The researchers investigated this hypothesis throughout the primary interviews by asking: “When you provided an estimate for your artifact, did that estimate represent a calculation of the current value or a prediction of the production value of the parameter?” The question captures the interactive nature of communication through the word “provided” while categorizing responses and was placed at the end of the each interview so as not to bias the responses.

3.3 Interview Analysis

The participants’ responses reflected even further complexity, falling into four categories (also in Figure 1):

C1. An estimate describes the **current** state of design.

> “It’s a calculation of the design as it is—we have a [model] in the CAD software...The software calculates what the [parameter value] is.”

C2. An estimate describes production intent, or predicts a **future** state of design.

> “Estimates are during sourcing...Here’s a good example: This was the first use of this

		Interview Responses			Survey Responses		
		Num. Resp.	Estimate Type		Num. Resp.	Estimate Type	
			Current	Future		Current	Future
Subsystem	1	8	5	4	19	7	5
	2	2	0	2	8	1	3
	3	5	4	2	10	7	1
	4	2	0	1	4	2	1
	5	10	5	8	8	5	2
	6	17	9	10	6	2	3
	7	2	1	2	23	10	8
	8	26	17	12	18	6	7
	9	9	6	4	16	9	2
	10	1	0	0	29	15	8
Position	Resp. Eng.	46	27	26	88	44	32
	Eng. Mgm.	31	18	16	10	6	4
	Sys. Eng.	3	1	2	23	14	4
Phase	R & D	32	20	16	49	24	13
	Prod. Dev.	71	41	38	116	55	38
Total		82	47 (57.3%)	45 (54.9%)	128	64 (50.0%)	40 (31.3%)

Table 1: Interview and survey response totals. Some interview participants responded that they use both types of estimates or worked multiple stages of design and so were included in both categories. The survey allowed individuals to select the type of value which they communicated "for system-level tracking", but selection of both current and future estimates was not an option. Some interview and survey participants chose not to respond to questions about their subsystem, stage of the design process, or their definition of an estimate. Consequently, the numbers shown may not add up to the number of individuals in a given subsystem, stage, or in total.

> size box and we had no experience with this type of architecture. So there was quite a bit of liberty and [we had] a pretty good idea of what it would [measure]. But going forward, [the estimate] is still that [same value]. This being the new system, the estimate is probably a little wider as far as how close we think we're gonna get."

C3. An estimate describing the current design *is the same as* production intent.

> "An estimate is whatever is close as I can get to what I think it's going to end up being when it's a real [artifact]. So right now, my estimate is what's actually in [the computer model], because I'm assuming that's *the most accurate I can be to what it will end up being* [emphasis added]. But if you came and told me that you had to [make a change]...you'd have to do some math, or something. There's no [model] yet, so I'd have to work with somebody to get a number to estimate it."

C4. Separate estimates exist for both the current design *and* production intent.

> "[My estimate] is my living judgment, and then the actual estimate that we give [the systems engineers] is based on [a computer model]. We don't ballpark it...Once we start hitting prototypes, we'll start bringing in [measured values], and that [measurement] gets reflected in the tracking system...We will start looking at the system and say, 'Okay, so our ballpark number is good.' And if my [model] number is higher, I know it's going to be that number. So, we'll [take] that [value]."

In the quotes, examples **C1** and **C2** refer to a single point, either the current design or the final design respectively. Participants using **C1** typically expressed uncertainty about the future and so only provided the current state of design, where as those using **C2** expressed uncertainty about the changes they would experience throughout the development process but confidence in the properties of a design they usually ended up with. Examples **C3** and **C4** indicate that some individuals track both current and future values as estimates. Some engineers use one shared value to satisfy both current value requests and future value requests (example **C3**). Others recognize that their current value is unlikely to stay the same and so they develop a separate, predicted value (example **C4**). But in all cases, the two points of reference were the current and final designs.

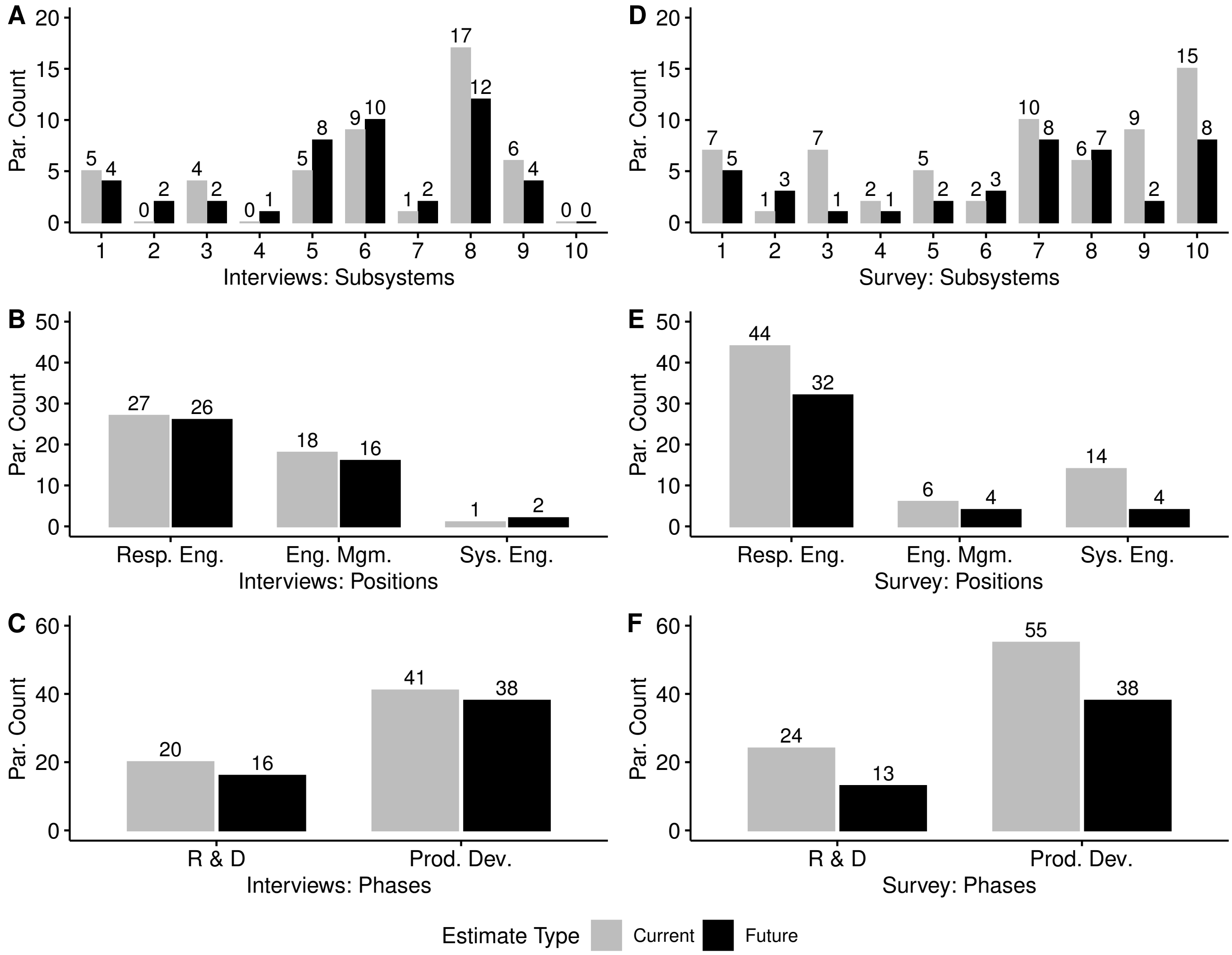

Fig. 2: Bar graphs of the results documented in Table 1 for the interviews (A-C) and the survey (D-F). Bars represent the number of participants from each group who responded that they use each estimate type. As in Table 1, the bars for each group may not sum to the number of participants in the group. Note that some participants in nearly every group expressed that they use each estimate definition demonstrating substantial variation in estimate definitions.

To confirm the existence of estimate definition variation, the number of interview responses associated with each of these two categories—*current* and *future* estimates—were coded and tabulated as shown in Table 1 and Figure 2. If an individual used both current and future estimates, whether as **C3** or **C4**, the participant was counted in both estimate categories. While participants were largely self-consistent in their definition use, both the interviewing and coding processes methodically identified those inconsistencies and resolved them through follow-up questions and/or grounded theory analysis [97] so as to code the responses appropriately. Responses were tabulated by different subsystems represented in the company's organizational structure, by three different types of positions (responsible engineers, engineering managers, and systems engineers), and by the different phases of the design process in which the individuals participated (research & development and product development). Participants only chose one subsystem but could choose both phases or neither phase of the design process.

Of the 82 interview participants, 47 (57.3%) used current estimates and 45 (54.9%) used future estimates in their work. Figures 2A-2C show that variation existed across nearly all subsystems, positions, and design phases, although many subsystems and one position were not sufficiently represented in the interviews. Nevertheless, the existing variation indicates varied definitions of "an estimate" throughout much of the organization. Phase 2 further examines this variation and examines its relationship to miscommunication.

Other factors may also affect estimate definition. Many participants knew of the existence of more than one definition of an estimate as evidenced by their use of separate numbers for current and future. When participants gave information to other engineers, they chose a value to pass corresponding to a definition. This introduces further complexity: Do engineers choose which estimate to pass? How? And when?

In **C2**, the participant mentioned "having no experience with this type of architecture". It's possible that variables beyond the subsystem, position, and design phase demographics may contribute to estimate definition, such as an employee's experience. Experience may be multiply defined depending on the context as experience with a particular artifact, system architecture, or career experience. Similarly, the objective or purpose of the estimate may influence definition choice. While some engineers needed to provide estimates for "sourcing", others' estimates were "living judgments" of design status. The recipient of an estimate may also affect estimate definition, whether a systems engineer, a manager, or a fellow responsible engineer. Estimate definition selection probably depends on the actions being performed through "estimating", the contexts in which engineers are estimating, the identities of the individuals and teams involved, and the medium through which the information is being communicated—whether via a formal requirement, just a friendly face-to-face update, or anything in between.

4 Phase 2: Practitioner Surveys

The second phase addresses how estimate definitions varied throughout the organization with statistical analysis of survey responses. Next, it demonstrates how such variation in fact constitutes miscommunication with problematic results for the system. A survey of practicing engineers in the same organization corroborated the variation in definition use as described in the following sections.

4.1 Survey Methodology

While "in-depth interviews yield descriptions of experiences, processes, and events" [98], surveys are effective tools which "report the distribution of people's actions or opinions in tables and statistics" [99]. After identifying the estimate definitions and existence of variation from the interviews, a survey of practitioners ($n = 128$) confirmed the definition variation across the greater organization.

Along with questions on other practices about estimation methods, the engineers were asked to respond to the following question: "The estimate I provide for system-level tracking (a) reflects the current state of design, or (b) reflects expected production intent." Of course, the interviews demonstrated that some engineers generate both types of estimates. The phrase "provide for system-level tracking" asks the individuals to respond with the type of information that they communicate to others working on the system so as to differentiate from any internal estimates the individual may keep separate from the distributed value. Thus, the question identified any variation in the values *formally communicated* by the participants to others in the organization for system-level tracking.

4.2 Survey Results

Table 1 also records the number of individuals who reported using either "current" or "future" estimates during the surveys. As with the interviews, responses are tabulated by subsystem, position, and design phase. Unlike during the interviews, survey participants were only allowed to specify one type of estimate that they provide for system-level tracking—either current or future estimates.

Participant responses varied significantly, with 64 of 128 (50.0%) participants reporting that they communicate estimates defined with respect to their current design and 40 (31.3%) with respect to their future design. Variation existed within every subsystem, position, and phase. Fisher's exact tests [100] of count data with a confidence level of 0.95 examined whether the definitions correlated with particular subsystems, positions, or phases and found that results for subsystems ($p = 0.3704$), positions ($p = 0.3009$), and phases ($p = 0.3045$) were not statistically significant with respect to estimate type and are therefore independent of estimate type. As participants could select one or both design phases, the Fisher's exact test was calculated using categories of R&D, Product Development, or both.

4.3 Survey Analysis

The survey results corroborate the interview findings that engineers throughout the organization *communicate* both "current" and "future" estimates for system-level tracking. Estimate definition communication varies independent of an engineer's subsystem, position, and design phase meaning that virtually every subset of the organization communicates both types of estimates.

Recall that systems engineers aggregated these artifact estimates (Section 2.6) into a future estimate (Section 3.2) for program management. Rather than combining all future representations of the system's artifacts, the survey results indicate that systems engineers combined some mix of current and future estimates into a system-level "estimate", which is likely composed of both definitions and unlikely to be a "future" estimate of the system.

This mixed system estimate yields numerous problems. First, program management did not ask for a system estimate mixing together the current evolving design and the final projected design. Program management was making decisions based on information representing something other than what they requested and cannot meet their stated goals accordingly. Next, mixing estimate types creates uncertainty in the system estimate because the estimate neither represents the current system nor the final system. While one may debate whether current or future estimates produce better system outcomes, an unknown mixture of the two does not accurately represent either type of estimate and therefore contains additional uncertainty on top of whatever existing uncertainty a current or future system estimate would hold. Furthermore, a study by Meluso et al. demonstrates that mixed estimate definitions may significantly degrade system performance [101]. Their study also shows that current estimates likely outperform future estimates suggesting that even requests for future estimates may constitute a "problem" if the organization seeks to optimize performance.

Communicating information representing two definitions of an estimate for the purpose of integrating those estimates constitutes a problematic outcome and is therefore miscommunication. If engineers did not need to communicate their estimates but instead used the estimates purely for their own purposes, it would not be considered miscommunication. Likewise, if those estimates did not play a valuable role in the organization through aggregation, the communication would not be perceived as problematic. However, because the information serves a valuable purpose through its communication, this *estimate uncertainty* neatly matches the definition of miscommunication as multiple definitions of estimates result in a problem that hinder parties from fulfilling their values. Moreover, the miscommunication is also *systemic* because, far from existing in isolation, estimate definition uncertainty was widespread throughout the organization across all subsystems, positions, and design phases.

5 Discussion

In Section 3, the interviews found that participants defined estimates with respect to their current design, their future design, with current and future designs as one and the same, and with separate current and future estimates. These estimate definitions exposed that two temporal reference points govern estimate definitions: a "current" point in time and a "future" point in time. The survey presented in Section 4 found that estimates communicated for system-level tracking, either "current" or "future" estimates, varied independent of the participants' subsystem, position, and design phase. These results are noteworthy for several reasons:

Estimate definitions. The interviews of Phase 1 found that practicing engineers in this organization defined estimates not based on a textbook statistical definition of what constitutes an estimate but with respect to a point in time in the design process, likely as a function of numerous contextual variables. That is not a judgement on the value or rigor of the practices engineers use—indeed, some participants attributed great value to parameter estimation while others expressed apathy. It does, however, expose that sufficient uncertainty exists regarding the definition of an estimate to merit clarifying what one means by "an estimate" when either giving or receiving such parameter value approximations. Estimation remains a crucial tool for understanding the development of complex systems and definition ambiguity may very well degrade the abilities of managers and engineers to accomplish their objectives if not addressed.

But as noted in the introduction, estimates are merely one case of ambiguity related to a commonly-used engineering term. Other examples of foundational engineering terms—and organizational language more broadly—may exist wherein "academic" definitions evolve to a state of ambiguity based on particular contexts; the identities of the parties involved in communicating about those concepts; the actions that individuals seek to perform through their communication; and the medium of communication. For example, "strategic ambiguity" about other "boundary objects" may similarly degrade the abilities of organizations to achieve their collective values, even as they benefit the individual [102, 103].

Miscommunication. The surveys of Phase 2 found widespread variation throughout the organization about what defines the estimates communicated for system-level tracking. The act of communicating and aggregating multiple definitions of estimates toward valuable system-level objectives thereby constitutes miscommunication. Miscommunication about theoretically simple engineering concepts—like what constitutes "an estimate"—may be more common than previously supposed.

The literature states that miscommunication is common and may affect organizational performance. This study extends the previous research by showing that, as in this firm, miscommunication may be widespread throughout organizations with potential implications for the products and systems created by an organization. While not evidence that serious and systemic miscommunication exists in *every* complex system design organization, other instances likely exist and by definition produce outcomes detrimental to project success.

Organizational contribution. Estimate definitions varied independent of subsystem, position, and design phase. According to organizational literature, such independence from organizational characteristics is unusual because knowledge (such as definitions of shared terminology) is embedded in organizational units [104, 105]. Why, then, do estimate definitions vary *within* units and *not* vary dependent on subsystems, positions, or design phases?

Section 3.3 notes that other variables may affect estimate definition choices. Frequency of artifact design changes, particular projects, organizational directions, estimation methods, engineer experience, etc. may all contribute to estimate definition selection. While it is easy to suggest that communication factors like context and action likely affect the selection, more specific causality requires further study.

6 Conclusion

In practice, miscommunication takes many forms, ranging from imperceptible differences in understanding (e.g. when you understand *most* of what another person is saying, but not quite *all* of it), to substantive disagreements based on differences in workplace cultural norms (e.g. managing supplier or customer expectations), to the meaning of shared terminology as in this case ("You meant X? Oh, I thought you meant Y!") [20]. The analysis herein suggests that miscommunication exists even about foundational engineering terminology like the meaning of "an estimate".

Phase 1 of this study interviewed engineering practitioners ($n = 82$) about how they estimate parameters of designed artifacts. Practitioner definitions of what constitutes an estimate referred to a point in time in the design process. Participants use "current" estimates that approximate the design as it is at that point in time and/or "future" estimates that predict the state of the design at some future point. In Phase 2, surveys of practitioners ($n = 128$) verified the interview findings. Communicated estimate definitions varied throughout the organization and within every subsystem, position, and design phase. Widespread definition variation indicates disagreement and therefore systemic miscommunication given the necessity of exchanging estimates in their work.

1. How do engineering practitioners define “an estimate” in complex system design?

   Engineers define estimates as approximations of a design with respect to a point in time. While some used “current” estimates representing their design at that point in time, others used “future” estimates representing an outcome later in the design process.

2. How do estimate definitions vary throughout an engineering organization?

   Estimate definitions varied both within and independent of an engineer’s subsystem, position, and design phase, suggesting some other variable causes estimate definition selection.

3. How does communicating varied estimate definitions yield miscommunication?

   Communicating parameter estimates that refer to different points in the design process increases estimate uncertainty because aggregating those estimates integrates designs which correspond to two different points in time.

In sum, engineering practitioners used multiple definitions of the term “an estimate” which yielded systemic miscommunication about designs. And while estimate miscommunication specifically may not be a problem in every engineering organization, most organizations *do* experience problems resulting from communication [21], precisely the definition of miscommunication. As demonstrated here, practicing engineers may even miscommunicate about engineering fundamentals which merits further study as it holds great potential to affect organization and system performance.

7 Future Work

More research is needed to understand how engineers estimate parameters in practice. While this study identified *that* estimate definitions vary in practice, further qualitative research could examine definitions in other industries, include larger sample sizes, training, geographical co-location, etc. to expose *how* decision-making leads engineers to those definitions and explain definition variation. Identifying other instances of systemic miscommunication in organizations may lead to further insights as to how and why miscommunication becomes systemic. Work should also go toward identifying ways of resolving such social systemic problems as their potential to impact organizational performance is clear. To that end, as in the Meluso et al. paper [101], agent-based modeling appears a promising avenue for developing methods of mitigating existing problems and solving others before they arise.

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