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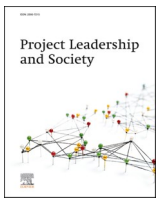

Empirical Research Paper

Cost estimation in major public projects' front-end phase: An empirical study on how to improve current practices

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ABSTRACT

Cost estimates in the front-end phase of public projects are critical in ensuring the selection of good projects that provide value for society. In this study, we use theoretical perspectives of front-end and cost estimation under uncertainty to address the gap in project management research on practices to produce realistic cost estimates. We interviewed 31 cost engineers and held a workshop with 53 participants who had a background in costing. The findings demonstrate substantial information and input data challenges in the front-end, and that cost estimation cannot be understood as an isolated process. This study contributes to the literature by demonstrating that the organization and management of the estimation process are critical for achieving realistic front-end cost estimates beyond merely applying specific models or methods. Our results also highlight that focusing on uncertainty is essential for realistic budgeting and responsible decision-making in major public projects. Finally, the study provides practical recommendations to enhance the quality of front-end cost estimates, such as improving the preservation and storage of historical data and maintaining a focus on uncertainty throughout the process.

1. Introduction

Numerous studies in the project management literature show that cost estimates in the front-end phase of public projects are critical in ensuring the selection of projects that maximize benefits and provide value for money (Ben Abdallah et al., 2022; Cantarelli et al., 2010, 2012; Samset and Volden, 2014, 2016; Williams and Samset, 2010). The front-end cost estimate should thus be realistic, to avoid selecting the wrong projects for further development (Cantarelli et al., 2010; Samset and Volden, 2016; Welde and Odeck, 2017; Williams et al., 2019a; Williams and Samset, 2010) or persisting with inefficient project proposals (Cantarelli et al., 2010, 2022).

The research literature is full of examples that document that cost estimates over different project stages and subsequent budgets have been too low (Flyvbjerg et al., 2002; Love et al., 2022; Morris and Hough, 1987). Far less research exists on how estimates can be evaluated. Jørgensen et al. discuss what constitutes realistic cost estimates and suggests that "[t]he best possible cost estimates are here those that perfectly represent the intended position in the cost outcome distributions, e.g., estimates where the estimated P50 (median) costs equal the actual P50 cost outcomes or the estimated mean costs equal the actual mean cost" (Jørgensen et al., 2023, p. 3483).

However, in the early front-end, aiming for a "good enough" outcome—an outcome that is within the estimated distribution—is likely more realistic than the "best possible." The project owner must then decide what range or uncertainty they are willing to accept at different project stages.

Previous empirical studies have documented the issue arising from unrealistic costs in the front-end. For example, Welde and Odeck (2017) found a mean cost increase of 53% from the first conceptual project description of road projects to the formal investment decision. Andersen et al. (2016) present similar findings, following their analysis of the magnitude and causes of exceptional cost increases in the front-end of a sample of 12 Norwegian projects. Three projects in their sample experienced a rise in cost of more than 500%, while most of the projects increased from 100 to 400% between the front-end phase to the start of the project execution phase (Andersen et al., 2016). Cantarelli et al. (2012) found a mean cost overrun in the pre-construction phase of 17% and 21%, for road and rail projects, respectively.

Eliasson (2023) documented that costs in Swedish road projects increased by, on average, 30% from the planning stage to the formal investment decision, and a further 21% until construction finally

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started. During construction, costs barely changed (+1%). The author argued that while it is natural that projects' content and design change during the planning process, the fact that costs are much more likely to increase than decrease suggests that there is a systematic problem that leads to a distortion of project selection and design. This ultimately leads to less benefit for society within a given budget than if planning had been based on accurate costs (Eliasson, 2023).

Uncertainty affecting the accuracy of the cost estimate can be reduced over time as more information becomes available for the cost engineers (Arend, 2024). However, the front-end phase is characterized by a high degree of uncertainty from factors such as undefined scope and lack of information, which can pose a challenge to cost estimation practices (Andersen et al., 2016). The general body of knowledge on cost performance in public projects is not specifically concerned with the front-end (Adam et al., 2017; Dlakwa and Culpin, 1990; Flyvbjerg et al., 2018; Rosenfeld, 2014; Terrill et al., 2016).

As such, existing studies on practices to ensure realistic cost estimates in the front-end are few, and these typically focus on the evaluation of a specific model or technique, such as building information modeling (BIM) (Taihairan and Ismail, 2015), reference class forecasting (RCF) (Bayram and Al-Jibouri, 2016), and the multistep ahead (MSA) approach (Dursun and Stoy, 2016).

The documented challenge of unrealistic cost estimates in the front-end, coupled with the scarce number of studies on realistic estimates, highlights the need for research to understand how current practices can be improved. Addressing this gap in the project management literature requires investigating how current practices of cost engineers can be enhanced in the uncertain environment of the front-end.

Our study contributes to the existing literature on cost estimation in the front-end (Amadi and Ahiaga-Dagbui, 2021; Welde and Odeck, 2017; Williams et al., 2019a) and provides empirical support for improving current practices to ensure realistic cost estimates for effective project selection. The findings answer the following two research questions (RQs):

RQ1: How can correct and sufficient information for realistic cost estimation in the front-end be ensured?
RQ2: Which practices and methods have the potential to provide realistic estimates in a context characterized by high uncertainty and little information?

These research questions were addressed using a qualitative approach through interviews with cost engineers experienced in cost estimation for major public projects in Norway.

This paper is organized as follows. Section 2 presents the literature review and theoretical background for the subsequent sections. Section 3 describes the methodology used in our study; we then present our findings in Section 4. In Section 5, we discuss these findings in light of theory, and in Section 6, we present our conclusions. Lastly, in Section 7, we present the limitations of our study, as well as recommendations and an agenda for future research.

2. Literature review

2.1. The front-end

The importance of addressing the timing of the cost estimate and the difference between the front-end phase versus the later implementation phases is described by Love and Ahiaga-Dagbui (2018) and Terrill et al. (2016). Compared with later phases of the project, the front-end is characterized by even higher uncertainty and a lack of information regarding important parameters, such as scope and historical input data (Badawy, 2022; Karaca et al., 2020).

The early phase of projects is when the business case is developed and the initial decision to fund the project is made (Edkins et al., 2013a; Pinto et al., 2022; Volden, 2019; Volden and Welde, 2022; Williams et al., 2019a). This phase—often referred to as the "front-end phase," "concept phase," or "initiation phase"—is critical, as it sets the direction for the entire project. At the same time, the front-end is an understudied topic in the literature (Samset and Volden, 2016). There is no univocal definition of the front-end phase, as it depends on how the project itself is defined (Edkins et al., 2013a; Williams et al., 2019b). The front-end phase can be perceived as where the project idea takes form through stakeholder recognition, identification of conceptual alternatives, and the decision to stop or move forward based on available information (Williams et al., 2019b). Toukola et al. (2023) broadly define the front-end in their study of value creation in urban development projects; they define the front-end as the time from the initial idea until the relevant parties engage in negotiations toward a possible contract (Toukola et al., 2023). Regardless of the definition, emphasis is placed on the importance of the front-end phase for long-term project success (Edkins et al., 2013a; Morris, 2009; Toukola et al., 2023; Williams et al., 2019b). Our study defines the front-end according to the Norwegian scheme for major public projects, later illustrated in Fig. 1 in Section 3.1. Nevertheless, the focus and data gathering is on the initial part of the process with the first conceptual cost estimate.

Morris (2009) points out that insufficient time is often allocated to a project's front-end phase. Additionally, he argues that a project manager should view a project as a whole, considering it beyond its implementation in order to realize its intended values and benefits. This recommendation is consistent with the general evolution of the project management profession, which in recent decades has seen a shift from instrumental management and a focus on product delivery to a more dynamic approach that can better manage complexity and has a greater focus on value creation and benefits (Ika and Pinto, 2022; Walker and Lloyd-Walker, 2016). Given the nature of the front-end phase, dynamic approaches are critical, and creativity and exploration are necessary to fulfill the purpose and further facilitate the continuation of the project in later phases (Ika and Bredillet, 2016; Morris, 2013).

2.2. Uncertainty in estimating costs of public projects

The early phase of a project is characterized by little access to information and thus high uncertainty (Williams et al., 2019b; Williams and Samset, 2010). A broad definition of uncertainty is the difference between the information required to perform a task and the related information possessed by the organization (Galbraith, 1974). According to Kay and King (2020), there are two types of uncertainty: resolvable and radical. Radical uncertainty, also known as "ontological uncertainty," is related to the unknown unknowns, or unforeseen events and conditions that cannot be predicted or planned for (De Meyer et al., 2002; Kay and King, 2020). Resolvable uncertainty, also termed "epistemic uncertainty," can be reduced over time as events unfold through research and data collection (Arend, 2024; Goodwin and Wright, 2014; Kerzner, 2018). Although "uncertainty" is a term often used in the project management literature, there is no shared understanding among scholars as to what the term means (Perminova et al., 2008), despite the fact that extensive work has been done to conceptualize and measure uncertainty

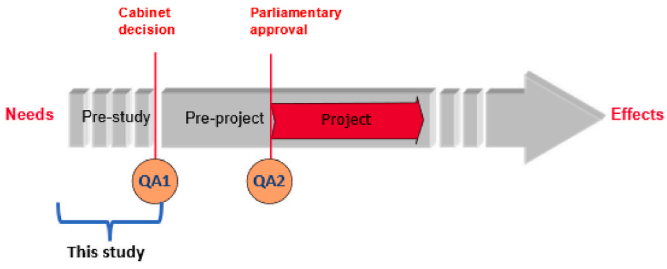

Fig. 1. The front-end phase of major Norwegian public projects and the part under study.

(Chapman and Ward, 2004; Child, 1972; Knight, 1921).

For project management, uncertainty can be distinguished from risk in that risk originates from the uncertainty that is more or less present in all projects (Project Management Institute, 2004). When uncertainty involves known unknowns (resolvable uncertainty) with identifiable probabilities, it enables quantifiable management strategies (Project Management Institute, 2017). Radical uncertainty, however—where outcomes and their likelihoods are indeterminate—necessitates adaptive and flexible management approaches, including opportunity management (Ward and Chapman, 2003). Uncertainty in major public projects is a much-studied topic in the project management literature (Atkinson et al., 2006; Love et al., 2024a,b; Perminova et al., 2008; Stock et al., 2021; Ward and Chapman, 2003). It encompasses various dimensions (including financial, technical, regulatory, environmental, stakeholder, and schedule uncertainties), and the management of uncertainty is crucial for effective project management (Atkinson et al., 2006). In a project context, we see a division, where uncertainty is mainly associated with either the actual project implementation (operational uncertainty) or the project's surroundings (contextual uncertainty) (Christensen and Kreiner, 1991). Other sources of uncertainty are associated with analyses and analysis models (conceptual uncertainty), and with the goals, criteria, and rules for decision-making (scenario uncertainty) (Austeng et al., 2005). All these sources of uncertainty come into play when making conceptual choices to do the right project, which is the main objective of the front-end (Williams and Samset, 2010).

The concept of "black swans" in the context of uncertainty was first defined as rare, unpredictable events that have massive impacts (Taleb, 2007). Flyvbjerg and Budzier (2011) provide empirical examples of such events in the cost estimation of projects, where 1 in 6 of the studied projects was a black swan, with an average cost overrun of 200%. One proposed measure to mitigate the risk of such black swan projects is the application of historical data through RCF (Baerenbold, 2023; Batselier and Vanhoucke, 2016, 2017; Tversky and Kahneman, 1974). Utilizing RCF in cost estimation can also be used to improve cost estimates and reduce the impact of strategic misrepresentation, where risk and uncertainty are downplayed by stakeholders to make a project appear more attractive or feasible than it is (Baerenbold, 2023; Flyvbjerg, 2006; Flyvbjerg et al., 2002). Although black swans are discussed in the literature mainly in the context of later project phases, we argue that uncertainty in the form of such unpredictable events (radical uncertainty) is even more relevant in the front-end phase, where less information is available.

Despite specifying what uncertainty is, risk and uncertainty have been defined as follows by the Project Management Institute: "risk is an uncertain event or condition that has a positive or negative impact on at least one project objective, such as time, cost, scope, or quality" (Project Management Institute, 2004, p., 238). Drawing on this definition, Perminova et al. (2008) highlight the importance of distinguishing these two terms, and describe the understanding of risk and uncertainty as consequence and cause, respectively. Furthermore, the authors stress the dual nature of uncertainty, defining it as "a context for risks as events having a negative impact on the project's outcomes, or opportunities, as events that have beneficial impact on project performance" (Perminova et al., 2008, p. 76).

Given that types of resolvable uncertainty can be reduced over time as the project matures, the early front-end is characterized by high uncertainty (Andersen et al., 2016; Edkins et al., 2013a). When we study cost estimation in this phase, both categories of radical and resolvable uncertainty are relevant for cost engineers. However, they materialize differently when it comes to practices, as radical uncertainty cannot be mitigated through means such as collecting historical data or the use of estimation methods.

In this work, we apply an understanding of uncertainty as being high in the front-end and that it can occur in the practices of cost engineers as both radical and resolvable (Kay and King, 2020). We thus define a realistic cost estimate in the front-end for the purpose of this study as one that is, given the information available, sufficiently accurate—or "good enough"—in the form of an outcome within the estimated distribution (Jørgensen et al., 2023). This definition supports Samset and Volden (2016) in that the primary goal of a front-end cost estimate is to provide decision-makers with enough information to avoid proceeding with unsuitable projects. It is not intended to set a final budget, as this is the purpose of cost estimation in later phases.

2.3. Practices to ensure realistic cost estimates in the front-end

The purpose of this section is to highlight the contribution of this study by reviewing previous empirical studies on practices to ensure realistic cost estimates in the front-end, thereby identifying the research gap that this work aims to fill. The studies were drawn from a systematic literature review across three scientific databases, providing a comprehensive foundation for our research (Brereton et al., 2007; Xiao and Watson, 2019). Our review was inspired by Xiao and Watson's (2019) proposed steps for enhanced rigor in literature reviews, as well as Brereton et al.'s (2007) recommendations, which emphasize the identification of gaps in current research. Further details about the review protocol and the search and filtering process can be found in in Appendix 1. The 21 findings from the literature review, divided by sector and category of contribution, are presented in Table 1.

Table 1 shows that all the reviewed papers use empirical data from construction or infrastructure projects, except for one study on the use of machine learning from the automotive industry (Bodendorf and Franke, 2021) and another that used empirical data from across different sectors in Norway (Andersen et al., 2016). Some studies focus on the quantitative evaluation of various estimation models through formal testing (Bayram and Al-Jibouri, 2016; Petroutsatou et al., 2012). Others highlight specific models or approaches for front-end estimation, such as the MSA approach (Dursun and Stoy, 2016) and the successive principle (Klakegg and Lichtenberg, 2016). Still others focus more on the cost-effectiveness of the process and which practices are profitable about securing the most accurate early estimate. Gardner et al. (2016) studied how to minimize efforts when inputting data, while also producing sufficiently accurate conceptual estimates. For the road projects presented in their study, the authors found that using more input variables than necessary in the conceptual estimate does not improve the estimate's accuracy (Gardner et al., 2016). This finding aligns with the recommended use of both top-down models and a conceptual cost-estimating practice based on expert opinions to produce fast and reliable results in a project's early stages (Fragkakis et al., 2011; Karaca et al., 2020; Torp and Klakegg, 2016). In addition, Torp and Klakegg (2016) point out how important it is to have a well-planned and structured estimation process with the right experts.

A Common feature of the empirical literature covering estimation practices in the front-end is methodological contributions, often accompanied by the use of input data to test and evaluate different methods and actions for improved accuracy. Examples are the mapping of the most central risk factors in the early stage of residential projects (Badawy, 2022), the evaluation of input variables in the estimation model to avoid collinearity (Meharie et al., 2019), and the integration of BIM models in the initial stages to improve the accuracy of the cost estimate (Taihairan and Ismail, 2015). Another study on construction projects demonstrates positive results on estimation accuracy when using unit costs based on current costs (Pujitha and Venkatesh, 2020).

The majority of the studies focus on enhancing the efficiency of the cost estimation process by identifying key factors to consider or recommending general strategies like model selection or organizational approaches. While the review does not highlight a single superior model—owing to the limited and diverse sample of studies across sectors, countries, and time periods—it does underscore several recommendations for adopting a "top-down" approach to early-phase cost estimation (Fragkakis et al., 2011; Gardner et al., 2016; Karaca et al., 2020; Torp

Table 1
Search results on empirical studies of front-end cost estimation practices.

Publication period and number of publications	Sector	Category of contribution/theme	Main findings summarized	Reference	Country/ geographical area of empirical data
2018–2022 (8)	Construction	Method, uncertainty analysis	Risk factors in the early stage of the project	Badawy et al. (2022)	Egypt
		Input data	Effective factors in the cost estimate in the early stage	Badawy (2020)	
			Input variable added to the estimating model, to avoid collinearity	Meharie et al. (2019)	Kenya
		Input data/model	Forecasting the total cost of construction project, based on the to-date information available	Pujitha and Venkatesh (2020)	India
	Automotive industry (vehicles)	Method, Machine learning	Accurate prediction of the costs of product components in the early design phase	Bodendorf and Franke (2021)	Germany
	Infrastructure	Process, investigating the front-end debate	Not much evidence to support strategic misrepresentation/optimism bias	Amadi and Ahiaga-Dagbui (2021)	Australia
		Method, models	Top-down models provide a means to improve the prediction accuracy of cost estimates	Karaca et al. (2020)	USA
		Evaluation of different methods	Identification of the most critical factors influencing the accuracy of estimation techniques	Akinradewo et al. (2020)	Ghana
2014–2017 (9)	Construction	Method, uncertainty analysis	Identification of factors to improve the results of uncertainty analysis of cost estimates	Torp and Klakegg (2016)	Sweden
		Method	Use of the Successive Principle in tough practice to make accurate, unbiased statistical prognoses of the actual project cost	Klakegg and Lichtenberg (2016)	Scandinavia
			Capability of BIM and its integration will help to minimize error and enhance project cost estimates in the future	Taihairan and Ismail (2015)	Malaysia
			RCF and regression analysis seem to produce more accurate and realistic forecasts than other methods	Bayram and Al-Jibouri (2016)	Turkey
			Conclusive evidence suggests that the MSA approach significantly outperforms the prediction accuracy of conventional practice	Dursun and Stoy (2016)	Germany
	Construction/ shipbuilding	Input data and feature-based method	The feature-based estimation method proved successful, based on the preliminary specifications to estimate ship costs.	Lin and Shaw (2017)	Taiwan
	Infrastructure	Method	Use of multivariate adaptive regression splines (MARS) successful for modeling the conceptual cost of bridge projects	Zhang and Minchin (2017)	USA
		Input data	Conceptual estimates using the minimum amount of input data to produce an estimate with a reasonable level of confidence is cost effective.	Gardner et al. (2016)	
	Public projects across different sectors	Evaluation of front-end cost estimates and causes for underestimation	Underestimation in the front-end phase found significant in the sample and posed a serious problem in that suboptimal projects were approved	Andersen et al. (2016)	Norway
2011–2013 (4)	Construction	Method	The tool allows users to evaluate the functionality, economics, and performance of buildings concurrently with building design.	Cheung et al. (2012)	UK
	Infrastructure	Method	Preliminary engineering (PE) for a roadway project encompasses two identified efforts.	M. Liu et al. (2013)	USA
		Method—development of models	Cost-estimating models for road tunnel construction developed using two types of neural networks.	Petroutsatou et al. (2012)	Greece
		Method and input data using expert opinion	Conceptual cost-estimating methodology involving three stages to provide fast and reliable results that can be very useful in the early stages of a project.	Fragkakis et al. (2011)	

and Klakegg, 2016). Table 1 shows that the data used in the studies span a broad geographical area and that there are more studies from 2015 onwards, versus only four from 2011 to 2013. The 21 studies reviewed represent a small fraction compared to the extensive research on other related topics in project management, such as cost performance in later project stages, indicating a knowledge gap in early-phase cost estimation.

In this paper, we report on findings from our study of best practices in the cost estimation of major public projects, in the context of uncertainty in the front-end. We expected to find that practices adopted by cost engineers play an important role in ensuring realistic estimates. However, it should be noted that an evaluation of the outcome in the form of deviations between estimates and actual costs is outside the scope of this study.

3. Methodology

Given the nature of our research questions and the recognized need for more insights into cost estimation in the front-end of projects, we chose a qualitative approach with an exploratory purpose. This approach is aligned with an interpretive research paradigm, which acknowledges multiple realities (ontological stance) and posits that reality

can only be partially understood through individuals' lived experiences (epistemological stance) (Denzin and Lincoln, 2011; Saunders et al., 2019). Our starting point was an inductive approach (Saunders et al., 2019). However, the aim of our research was not primarily to develop a new theory, but to elaborate on existing theory, based on the use of abductive elements to generate hypotheses and best-fit explanations through an iterative process between theory and empirical data (Kovács and Spens, 2005). We used a qualitatively driven multimethod sequential design (Hesse-Biber et al., 2015; Saunders et al., 2019), where the first step was comprised of semi-structured interviews and the second step consisted of a workshop, during which preliminary findings from the interviews were presented for further elaboration through group and plenary sessions.

3.1. Research context

After several cost overruns and project failures, Norway introduced a project governance regime that set out requirements as to how projects should be appraised and developed in order to be considered for government funding. The State Project Model, as it now is called, is mandatory for all government projects with an estimated cost above c. EUR 90 million. Among its requirements is external quality assurance of cost estimates before projects can pass decision gates (Samset and Volden, 2014). The regime comprises two decision gates: QA1 and QA2. QA1 concerns the conceptual choice, which aims to give the central political level real control over investment decisions. QA2 concerns the management base and cost estimates, aiming to ensure budget realism and the most efficient use of resources. This study focuses on the earliest estimate, the front-end cost estimate, which is the process leading up to QA1 (Fig. 1). In Norway, the public agency has a governing role in the estimation process for major public projects.

3.2. Interviews

The empirical data were collected from semi-structured interviews with subject matter experts in the form of cost engineers. To obtain information about the first-hand experiences of cost estimation, participants were selected strategically from relevant positions within three public agencies—infrastructure, construction, and defense—together with external consultants who performed quality assurance (QA1) of major public projects in Norway. The participants were typically individuals responsible for cost estimation in their respective organizations, and many had several years of experience in the field. Several methodological contributions support the strategic selection of "information-rich" cases or participants, particularly when resources are limited (Creswell and Piano Clark, 2011; Marshall, 1996; Patton, 2002; Saunders et al., 2019). We conducted 13 group interviews with a total of 31 participants.

Including several participants per interview enabled us to benefit from some of the advantages of focus group interviews, such as the experience of a sense of "safety in numbers" when mentioning common problems, leading to more sharing than might otherwise occur in an individual interview (Blumberg et al., 2014). An interview guide was created in advance of the interviews and was discussed and agreed upon by all researchers.

The interviews lasted one–two hours each and were conducted digitally via Teams or in person from May–October 2022. Using Teams enabled us to have a geographically diverse sample, making it possible to recruit a larger number of participants. Guided by our research questions, the interview guide was structured around various themes and included open-ended questions such as, "Do you use any type of guidelines when you estimate costs in the front-end?" and "Does a project's different geographical locations affect the cost estimation?"

During the interviews, one researcher was in charge of the guide, while a second researcher was responsible for writing down the interview as close to verbatim as possible. The other researchers in the group took additional notes and were able to ask the participants to elaborate on their answers when needed. The additional notes were used as input for the final report from the interviews to strengthen the findings. Details relating to the interviewees and interviews are listed in Table 2.

Before the interviews, all participants received an invitation and written information about the study, enabling them to prepare by gathering documentation and reflecting on their practices. This approach increased the study's validity and reliability (Saunders et al., 2019). We also used the "snowballing" method (Tjora, 2012), whereby we encouraged the participants to recommend other potential participants, based on their experience and knowledge of the field.

3.2.1. Data analysis

When analyzing our interview data, we followed the six steps suggested by Creswell (2014): (1) organize and prepare data for analysis; (2) read and look at all data, reflecting on the overall meaning; (3) start the coding process and establish categories and terms; (4) generate detailed descriptions, using codes and terms to establish themes for analysis (reducing categories), representing significant findings; (5) advance how the description and themes will be represented in the qualitative narrative; and (6) interpret the findings and results, comparing them to existing theory. Within steps 3–5, we also performed a thematic analysis inspired by the work of Braun and Clarke (2006) and Saunders et al. (2019). The data were systematized and coded using NVivo (QSR International, 1999–2022, NVivo Release 1.7). Our use of thematic analysis related specifically to our goal of investigating the underlying ideas and assumptions that shape the cost estimation process in the front-end. Furthermore, we followed Braun and Clarke (2006) in acknowledging the active role of the researcher in identifying patterns and themes. This approach enabled us to take advantage of our professional backgrounds and years of professional experience (Braun and Clarke, 2006).

The initial round of analysis resulted in 20 codes, which were subsequently grouped and aligned with the overarching themes from the

Table 2
Interview participants.

Participants' agencies and consultancy firms	Date (2022)	Number of participants	Interview duration (hours)	Number of researchers
Concreto (consultancy)	May 25	5	1.5	5
Metier (consultancy)	June 3	2	1.5	4
Marstrand (consultancy)	June 15	2	1.5	3
Holte/Menon/A2 (consultancy)	June 15	3	1.5	2
Norwegian Defence Materiel Agency	August 19	1	1	4
Norwegian Railway Directorate	August 24	3	1.5	5
Norwegian Directorate of Public Construction and Property	August 25	3	1.5	5
Norwegian Defence Estates Agency	September 1	2	1.5	4
Dovre (consultancy)	September 2	1	1.5	3
Norwegian Defence Materiel Agency	September 6	1	1.5	3
Atkins (consultancy)	September 7	2	1.5	3
EY (consultancy)	September 7	2	1.5	3
Norwegian Public Roads Administration	October 4	4	2	5

interview guide (see also Figure A2 in Appendix 2). For each theme, an analytical text was written based on the codes and their content, providing a deeper description of the findings (Creswell, 2014). This then resulted in categories that depict the cost estimation process and could be compiled into a simple system model of the different steps within cost estimation. Further details of the analysis, along with a detailed coding tree, are provided in Appendix 2.

3.3. Workshop and validation of results

After the interviews were completed, we invited representatives of all 12 participating agencies and consultancy firms to participate in a workshop. In total, 53 people—all with broad expertise and experience in project cost estimation—participated. The purpose of the workshop was to validate and elaborate on the findings from the interviews, as well as to discuss issues related to front-end cost estimation, following the sequential approach of the QUAL + qual methodology described by Hesse-Bieber et al. (2015) and Saunders et al. (2019).

The workshop began with a presentation of findings from the interviews, which was followed by a group session in which participants were asked to reflect and provide feedback on those findings. The researchers invited the participants to emphasize challenges in the estimation work and whether there were differences across agencies and consultancy firms. The provision of examples of working practices and good experiences in light of the interview findings was also encouraged from the participants. The group work ended in a plenary session. An extended team of nine researchers took notes during the workshop and gathered written material from the group work. The findings from the workshop were used for additional validation and elaboration of the findings from the interviews.

3.4. Validity and reliability

In our research, we followed the recommendations of Gibbert et al. (2008) and Yin (2018). We emphasized validity and reliability in the different steps of the design phase and data collection, and through to the completion of the analysis phase (Gibbert et al., 2008; Yin, 2018). A study protocol was written before conducting the interviews to increase the study's trustworthiness and reliability (Kallio et al., 2016; Yin, 2018). Throughout the study, we aimed for methodological transparency, accommodating both the reliability and external validity criteria. Additionally, reliability is strived for by being several researchers and using key sources we have strived to accommodate the reliability criteria. To ensure internal validity yet further when collecting empirical data through interviews, we chose only experienced participants representing different entities in the cost estimation process. Another accommodation was to discuss the results among peers. We applied a rigorous coding approach whereby co-authors who had not conducted the coding provided feedback and validated the results. Finally, we implemented data triangulation by analyzing materials from the agencies that described the cost estimation processes, interviews, and the workshop.

4. Findings

In this section, we present the findings from the interviews and the workshop. The coding process resulted in 20 initial codes, which were further regrouped based on similarities in the material and the overall themes of the interview guide. Further iterations allowed us to summarize the findings in the simple system model for cost estimation with three categories: prerequisites, process and deliveries (illustrated in Fig. 2). The presentation of the results is organized according to this model. Under the process category, the informants particularly emphasized the use of historical data and the uncertainty analysis; we therefore present these two topics in detail.

Our two research questions (RQ1 and RQ2) cover two parts of Fig. 2.

The purpose of the front-end phase is to clarify and establish a foundation that allows the central political level to maintain effective control over the investment decision. This, in turn, enables the selection of a conceptual choice to be carried forward into the subsequent project phases. However, many participants indicated that no real conceptual choices are made in the front-end phase, as the choice of the actual solution appears to be made in advance. Hence, this part of the front-end phase becomes more of a budgetary cost estimate rather than an effort to lay the grounds for choosing between different conceptual solutions. This paper aims not primarily to discuss the political decision-making processes related to the estimate, but rather to understand cost estimation as an isolated, professional process.

4.1. General findings

Several participants involved in cost estimation work over the years referred to how complexity had increased. The complexity affected the estimation process in many ways, such as greater demands for social cost–benefit analyses, expectations linked to the inclusion of sustainability, non-priced effects, and externalities. They linked another facet of complexity to the many stakeholders involved in the project.

Increased complexity was said to require new approaches to cost estimation and trigger a need for interdisciplinary input. Previously, only a few experts were involved in the estimation process, putting together and using unit prices, but current practices bring together specialists with expertise in various fields who try to produce the best possible estimate.

In addition to increasing complexity and size, the participants noted

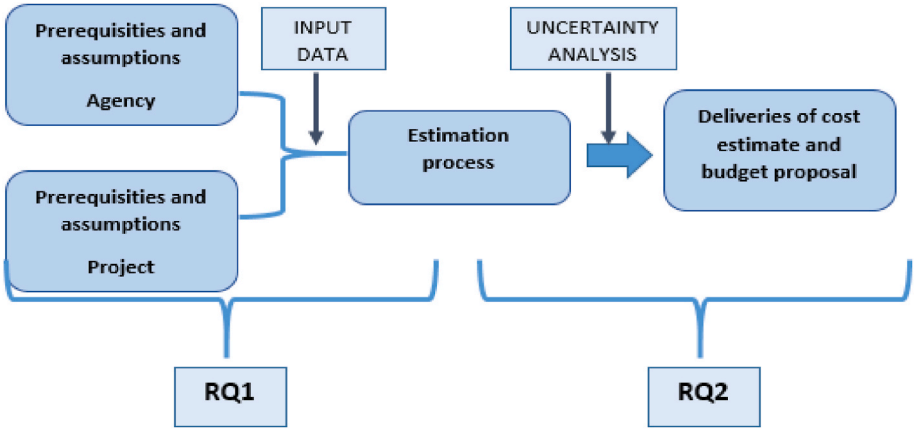

Fig. 2. Simple systems model for cost estimation.

that there was a greater variation in project type. To address this, a suggested solution was to distinguish projects based on their uncertainty. The participants claimed it was important to identify the project's special features, to improve the estimation process.

Furthermore, the importance of documentation was emphasized throughout the entire cost estimation process during the interviews. There are variations in how the public agencies do this, but the participants pointed to a potential for considerable improvement linked to the documentation throughout all project phases. Regarding project documentation, it was stated that the intention of the project was often lacking: "[O]ne has to be a detective to figure this out afterward, what we meant and what we thought of beforehand"[1] (Respondent 4).

Our participants reported challenges in using the front-end estimate in later project phases. They also noted an increased emphasis on keeping costs down, influenced in part by political signals. Major public projects typically have a long lifespan, and when our participants were asked about the focus on life cycle costing (LCC), they mentioned different practices between sectors. Some participants reported that the main emphasis in the front-end was on investment and that the focus on the LCC perspective was consistently poor.

4.2. Prerequisites and assumptions

Prerequisites and assumptions form the basis of both the cost estimation and the final cost estimate, and they come from both the public agency and the project. Interviewees from the agencies reported that prerequisites are in place that are linked to structure, culture, and resources (time and personnel) expressed through the project's mandate.

One reported challenge centers on defining the project scope. The participants stated that it was important to be confident regarding what to do by understanding the scope through the actual needs that the project should meet. Poor descriptions of scope and needs complicate the estimation and may lead to subsequent substantial and costly changes. It was further argued during the interviews that the challenge does not lie with the calculation method itself, but rather with the basis on which the estimate is made: "The goodness of the estimate has to do with stakeholder knowledge and the ability to handle future uncertainty" (Respondent 5).

Concerning the estimation method, participants said that much of it was based on mark-up percentages, which vary. They shared that it varies as to the degree to which individual items are detailed, as does the weighting between items. Moreover, they noted that good historical input data are lacking.

4.3. Process

With regard to the cost estimation process, the participants saw it as time-consuming, challenging the need for consistency and continuity following the requirements of the State Project Model. The interviews indicated that such consistency and continuity were lacking in the front-end phase of project development regarding personnel, expertise, documentation, and communication.

The participants emphasized that the appropriate composition and expertise of the team conducting the estimation were crucial to achieving a successful outcome. This was identified as a challenge, as professionals from different fields tend to think differently: for example, some adopt a more conceptual approach, while others can be more concrete. The human factor plays a significant role, as stakeholders often view the project from different perspectives. This places high demands on the competence of the individual in charge of the cost-estimation process; they must possess extensive knowledge and experience and have the confidence to challenge the views within the group.

Participants reported that, at times, detailed calculations are carried out in the front-end, despite a lack of information. They emphasized the importance of maintaining a holistic perspective and taking more general approaches, due to the immaturity of the project at this stage: "Methodologically, one could certainly be much more light-hearted and creative […] regarding the final product. We tend to dive into the deep [end] right away. Being methodologically narrow, we don't dare to see the full width of the front-end, [and we] don't quite get the starting point" (Respondent 2).

It remains unclear as to why estimators tend to go too deep into details in the front-end. However, one explanation that emerged in the interviews was that there is a tendency to use what is at hand and to quantify the quantifiable as a way of navigating the uncertainty (availability bias). The participants pointed to the external requirements of the project—such as a need for precision, expressed by decision-makers—as a possible explanation. Most participants saw this as unfortunate, as it could hide inherent uncertainty and a lack of maturity, which would lead to a poor estimate. Many participants pointed to the need to use top-down approaches and "keeping at a high level" for as long as possible (i.e., before starting to detail the estimate).

4.3.1. Uncertainty analyses

Uncertainty analyses of cost estimates are carried out in all government sectors represented in our data set, as this is a mandatory part of the estimation process in Norway. Participants described the uncertainty analysis as one of the most challenging parts of the estimation process. They stated that the uncertainty analysis was primarily important for providing valuable guidance for subsequent processes, rather than for identifying the cost consequences of the project: "Being able to show what is needed to avoid an undesirable outcome, expressing this in numbers, getting it into the tornado diagram, and showing what the relationship can mean is good pedagogy" (Respondent 1).

Nevertheless, the interviews revealed that there is room for improvement in both the uncertainty analysis and the implementation of its results. Representatives of two of the three public agencies mentioned that they either brought in external expertise or outsourced parts of the analysis to external parties. The use of external expertise was seen as a potential challenge to continuity and to the further use of the estimate in later project phases within the public agency.

Participants also cautioned against the belief that a poor estimate could be "repaired," either through the uncertainty analysis or by incorporating too-wide a range of uncertainties, as this would cause the base estimate to become too high. They often pointed out that, while it was acknowledged that a cost existed, it was so difficult to estimate accurately that people would instead include it in the uncertainty analyses.

4.3.2. Use of historical data

Using historical data in one form or another is a common approach within cost estimation, to establish a starting point for the estimation and a basis for comparing alternative concepts. The participants emphasized that historical data were helpful in the estimation process, but several noted the need for improvement in data collection, storage, and accessibility. The participants who functioned as external consultants in QA1 and had exposure to projects across various public agencies expressed dissatisfaction with the access to historical data: "Access to that type of data, that type of competence, is relatively small, which surprises us" (Respondent 1).

The participants claimed that historical data are kept in arbitrary "individual systems," and this related to the data not being openly shared but instead preserved as part of individuals' competence and experience. Some participants indicated this might be due to the competitive nature of the situation, while others were concerned that such data were being misused. Furthermore, it was argued that the existing data sets should be much more structured and could be tested to a far greater extent: "Our challenge is that we have data that may not be

[1] The transcription of interviews was in Norwegian, and quotes were translated into English by the researchers.

good enough. You don't know what you are using, or the data is irrelevant to the current project" (Respondent 3).

4.4. Deliveries

The deliveries from the estimation process have several uses: (a) as a basis for decisions, (b) for external quality assurance, and (c) for cost control in later project phases, as a basis for developing more exact estimates and calculations.

The participants noted that documentation of the estimate was a challenge. Poor documentation makes it difficult to identify the assumptions made as a basis for the project when the estimate is delivered. Additionally, communication linked to the delivery of the estimate poses its own challenge. The participants pointed out that it was sometimes difficult for decision-makers to understand that the estimate contained high uncertainty. In these instances, the estimate was perceived as an absolute and that "the dice is cast" once a particular amount has been presented: "I felt that I presented a number, and that's what mattered, not that this was an estimate" (Respondent 6).

It was considered important to communicate the estimate's uncertainty to those responsible for the decisions—and that they, in turn, must acknowledge the uncertainty. Additionally, participants also highlighted misunderstandings related to terminology: "The terminology is established, but the understanding of it varies […] Many are getting this wrong. The budget is not the same as the estimate" (Respondent 3).

Although uncertainty is substantial in the front-end of the project, most participants had experienced a positive shift toward more realistic early estimates. Additionally, there was greater awareness of the potential pitfalls in such work, compared to the past.

The participants asserted that there is often pressure to adhere to the QA1 estimate and scale down in later project phases. There is an increased focus on cost reduction, partly driven by political signals. The timeline is long, and the funds might not be needed immediately. As expressed by one of the participants: "[It] is not perceived well by the Ministry to demand funding you don't need right away" (Respondent 10).

The participants were also asked how they addressed the life cycle cost (LCC) perspective, including the operation and the management costs that arose after the investment period, in the front-end phase. Their responses revealed varying practices between the sectors: some include LCC, while others do not. The impression gathered from the external consultants was that the primary focus in the front-end is on investment, with consistently insufficient attention paid to the LCC perspective, including operation and management costs: "Investment 'rules'. […]We immediately see the effect of investment. Operations and management are not so 'hot'" (Respondent 10).

Table 2 provides an overview of the empirical results according to each part of the estimation process illustrated in Fig. 2. The columns "reported best practices" and "reported challenges" are complementary to achieve realistic cost estimates. Where there are challenges, there is also room for improved practices.

Our results offer insights into best practices for producing realistic estimates and highlight the obstacles and challenges associated with underestimating costs. This deeper understanding facilitates discussions on how to improve practices for achieving realistic cost estimates in the front-end.

5. Discussion

5.1. Front-end characteristics shaping the cost estimation

Our findings align with the literature on the front-end phase of project management, which highlights that dynamic approaches—along with exploration and creativity—are needed when uncertainty is high (Edkins et al., 2013b; Ika and Bredillet, 2016; Morris, 2013). As suggested by previous literature explaining the underestimation of costs, the cost engineers in our study report that the process in the front-end can also be prone to different forms of bias (Chen et al., 2023; Flyvbjerg et al., 2002; Mackie and Preston, 1998). These biases manifest as external pressure from decision-makers or politicians, either directly (to reduce costs) or indirectly, through optimism and ignoring the estimates' uncertainty and the costs that will arise after the investment period.

In RQ1, we ask, "How can correct and sufficient information for cost estimation in the front-end be ensured?" Some participants pointed out the risk of including expertise with strong connections to the project, as this could lead to excessive detail or bias. Interestingly, our respondents reported a positive shift toward more realistic front-end cost estimates, noting that many of the challenges stemmed from external factors or in from communication issues when the estimate was delivered. Our findings here align with the work of Love and colleagues, who found no support for optimism bias within the team environment (Love et al., 2022), as well as with the Morris and Hough's (1987) claim that factors outside the project itself contribute to unrealistic estimates.

5.2. Uncertainty impacts all stages in the estimation process

Our findings support the importance of uncertainty analysis in the front-end, with respondents considering it just as critical as the estimate itself. However, they also identified it as one of the most challenging parts of the cost estimation process. While emphasis is placed on the importance of uncertainty analysis and communicating uncertainty to decision-makers, the respondents pointed to a lack of a shared understanding of uncertainty. In the project management literature, Perminova et al. (2008) also highlight this lack. In our study, decision-makers did not always consider the substantial uncertainty range of the estimate in the front-end, and they expressed the need for a precise number—as a budget, rather than an estimate. The participants saw the need to delve into details too early as unfortunate, as it could obscure the inherent uncertainty and lack of maturity behind the estimate. This focus on details by cost engineers could further hinder the identification of uncertainty factors, such as unknown unknowns. The real world contains unknown unknowns and cannot be portrayed through a positivistic, reductionist, decomposition approach—there is thus a need to adopt other methods (Ward and Chapman, 2003).

When it comes to such radical uncertainty, or "unk unks" (De Meyer et al., 2002; Kay and King, 2020), there are reported practices on how to identify and deal with these unk unks in project management. Ramasesh and Browning (2014) point to the importance of project design and behavioral approaches in their framework to address unk unks. The emphasis placed on project design is supported by our findings, which highlight the value of a clear project scope alongside a shared understanding. The authors also highlight complexity in various forms as a key factor contributing to the increased likelihood of unk unks (Ramasesh and Browning, 2014), a finding echoed by respondents in our study. With regard to practices to reduce unk unks, it is recommended (among other measures) to adopt a project design approach that involves "[d]ecomposing the project […] [by] breaking it down into elements and their relationships—essential steps toward confronting the project's complexity" (Ramasesh and Browning, 2014, p. 201). In their case study of a nuclear power plant, Maronati and Petrovic (2021) assess the impact of unk unks on costs specifically. The authors propose a methodological approach that assesses risk, including the impact of unexpected events by use of historical cost data before and after the unexpected event took place (Maronati and Petrovic, 2021). Building on our study's emphasis on the importance of historical data, the strategies suggested by Maronati and Petrovic (2021) for assessing unknowns by learning from past events further underscore the added value of properly storing such data.

Our findings further show that there is substantial room for mitigating resolvable uncertainty (Arend, 2024; Goodwin and Wright, 2014; Kerzner, 2018). Several previous studies (Badawy, 2022; Fragkakis

et al., 2011; Gardner et al., 2016; Lin and Shaw, 2017; Pujitha and Venkatesh, 2020) have identified historical input data as a crucial factor in the estimation process. Our study participants agreed that such input data are beneficial, but they also highlighted that more needs to be done to make good use of them, such as sharing reference data sets and exchanging information. Existing research shows that despite the use of RCF, cost overruns remain common (Flyvbjerg, 2021; Love et al., 2022a, b), indicating that relying solely on historical input data cannot solve the problem.

In light of RQ1, our results point to several additional factors that can reduce uncertainty; a good definition of the scope (politicians/decision-makers), ensuring enough time for several iterations (the public agency in charge), guidelines to ensure a shared understanding of terminology along with access to historical data, and sharing experiences between projects and over time. What all these factors have in common is that they are mainly outside of the control of the estimation team—suggesting that how the estimation process is organized by the public agency plays an important role in reducing uncertainty.

5.3. Practices to ensure realistic estimates in the front-end

Regarding our RQ2 ("Which practices and methods have the potential to provide realistic estimates in a context characterized by high uncertainty and little information?"), one theme that emerged from the reviewed literature was the importance of having the right team (in terms of composition and competence) to carry out the estimation and understand the significance of the human factor in cost estimation (Torp and Klakegg, 2016). Similarly, our study participants emphasized the crucial role of the human factor in leading the uncertainty analysis, which requires individuals with sufficient knowledge and experience. Torp and Klakegg (2016) also highlight the need for a well-composed group of experts in the process.

Karaca et al. (2020) suggest that using top-down methods for complex projects under uncertainty can increase the accuracy of cost estimates. Our findings point out that complexity also requires that different competencies be involved—in the form of expertise in various fields—to improve the estimate. Many participants expressed the need to use top-down approaches in the front-end phase. This finding is supported by studies identified in our literature review, where a top-down approach is described as cost-effective and suitable for producing realistic estimates under high uncertainty (Gardner et al., 2016; Karaca et al., 2020; Torp and Klakegg, 2016), as well as the promotion of "rules of thumb" or "smart heuristics" (Love et al., 2024).

Our study's findings reveal that front-end cost estimation is not an isolated activity; the quality of the estimates is significantly influenced by factors external to the estimation team. While much of the existing literature on front-end estimation practices focuses on specific models or methods, our study highlights that these techniques alone are insufficient to solve the problem. The organization of the estimation process—particularly in terms of reducing uncertainty through, for example, definition of scope or storage and access to historical input data—plays a crucial role in achieving realistic estimates.

6. Conclusions and practical recommendations

Improving front-end cost estimates to mitigate cost overruns in public projects represents a relevant but under-researched area. In this section, we summarize the findings concerning the two RQs that guided our study. Our research approach does not prioritize definitive, generalizable conclusions. Instead, we aim to offer the best-fit explanations of the complex phenomena of front-end cost estimation, given the available evidence. The study's findings have theoretical implications for the scholarly discussion around how current practices can be improved to ensure realistic cost estimates in the front-end of major public projects.

Our findings related to RQ1 show substantial challenges in the front-end phase related to information and input data. Projects will benefit significantly if project owners adopt a stronger sense of duty and responsibility to organize the knowledge (in the form of data, information, and assumptions) about the costs of future planning and estimations. Thus, there is great potential for more realistic costing of public projects by acknowledging these technical aspects and improving the storage, use, and sharing of historical reference data sets.

This study contributes to the literature by demonstrating that the organization and management of the estimation process are critical for achieving realistic front-end cost estimates, beyond the mere application of specific models or methods.

Our findings related to RQ2 show that factors such as stakeholder involvement, competence, and communication of uncertainty to decision-makers are central to ensuring realistic estimates. Rather than favoring one costing method over another, the focus is on practices that remain relevant regardless of the method used. Our results highlight that cost estimations in the front-end must focus on the uncertainty (what we do not know) instead of what we are sure of (what we know). Focusing on uncertainty in major public projects is the only viable path to realistic budgeting and responsible decision-making in major public projects.

The findings from our research provided the basis for a set of nine practical recommendations for realistic cost estimates in the front-end. These recommendations target cost professionals, cost engineers, project managers, and project owners working on public projects. Although this study focuses on public projects, many recommendations should also be relevant to the private sector.

1. *Historical input data must be preserved and used.* It is in the public project owner's interest that this experience is shared across different sectors and agencies; this will also enable learning from past unforeseeable events.
2. *Better documentation of assumptions and background for the estimate.* The public agencies report that there are established guidelines to ensure good documentation. Nevertheless, we recommend that such documentation is followed up on to a greater extent.
3. *The mandate should facilitate realistic estimates by clearly outlining the purpose and scope of the project initiative as much as possible.* The importance of project design is highlighted as beneficial to assess uncertainty in the form of unk unks, both by our findings and in previous studies.
4. Concerning process, we recommend the need *to recognize the complex front-end context and understand uncertainty*. Those who make decisions and those who prepare the basis for those decisions must recognize what estimating costs in the front-end phase means.
5. *Use a top-down approach for front-end cost estimation.* By using a top-down approach, the risk of going into too much detail too early can be avoided, and the complexity and uncertainty can be acknowledged.
6. *Given the project's gradual maturation, ensure sufficient time for multiple iterations of the estimate.* Cost estimation is part of the entire project and cannot be seen as an isolated process.
7. *Focus on what we do not know.* All subject matter experts are concerned with the area they know the most about—they intuitively focus on what they know. The uncertainty, however, lies in what we do not know and cost engineers must refrain from going into too much detail too early**.** We need to focus on uncertainty, both radical and resolvable, if we want better analysis, realistic cost estimates, and a reasonable basis for decision-making and project management.
8. Regarding deliveries, we recommend *dialogue and communication before, during, and after estimation.* All relevant levels of the organization should be involved early on to clarify the project's purpose and ensure a shared understanding of the delivery as well as the terminology.
9. Finally, those responsible should *make the uncertainty in the estimates visible.* Our participants reported that individual figures tend to stick and be used regardless of their uncertainty. Thus, there is a need to communicate uncertainty for the estimate to remain realistic.

7. Limitations and research agenda for further studies

7.1. Limitations

Our study is subject to limitations, suggesting that caution is needed when considering the generalizability of the findings beyond the studied context. The main limitations arise from the focus on just one country, together with a small number of participants, who were selected purposively and were considered well representative of the expertise on cost estimation in the front-end of major projects within Norway. The findings are also based on the best practices reported by the participants in the interviews and the workshop, rather than a quantitative evaluation of practices and actual outcomes in the form of realistic cost estimates.

7.2. Research agenda for further studies

Our findings have increased our understanding of practices to produce realistic cost estimates in the front-end of major public projects. Based on interviews and analyses of qualitative data, we have provided a set of recommendations that could help to improve future practice. However, the quality of research recommendations such as those in this paper and the ongoing efforts of government agencies to reduce the extent of front-end underestimation can only be measured empirically. We thus suggest that future studies should use data from projects' front-end through to completion to assess whether the efforts to improve practice have been successful. Finally, our findings highlight the importance of the human factor through the competence and experience of the person in charge of the estimation process. Building on this, future studies could explore how various leadership styles, such as charismatic versus distributed leadership, impact the cost estimation process.

CRediT authorship contribution statement

Helene Berg: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Anne Strand Alfredsen Larsen:** Supervision, Project administration, Methodology, Data curation, Conceptualization. **Ole Jonny Klakegg:** Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Morten Welde:** Writing – original draft, Validation, Supervision, Resources, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Details of the structured literature search

The literature reported on in Subsection 2.3 is the result of a structured literature search on empirical studies of practices in cost estimation in the front-end. To ensure relevance according to current practices and organizational structures, the search was limited to literature published in the last 10 years, from 2011 to 2022. The review protocol was established as follows:

- relevant to our research questions
- peer-reviewed journals, emphasis on papers written in English
- excluded: books, lecture notes, technical reports, academic statements (gray literature)

In our development of the search strings, we followed the suggestion of members of the broader research group at (*information on university is removed to ensure blind review*) to include all relevant synonyms in project management terminology (e.g., "early phase" and "front end"). This resulted in the following search string being applied across the databases:

"cost estimation' OR "cost estimate" OR "costing" OR "cost appraisal" OR "cost forecasting"

AND "early phase" OR "front-end" OR "conceptual stage"

AND "empirical" OR "survey" OR "document study" OR "Delphi research" OR "experiment" OR "case study."

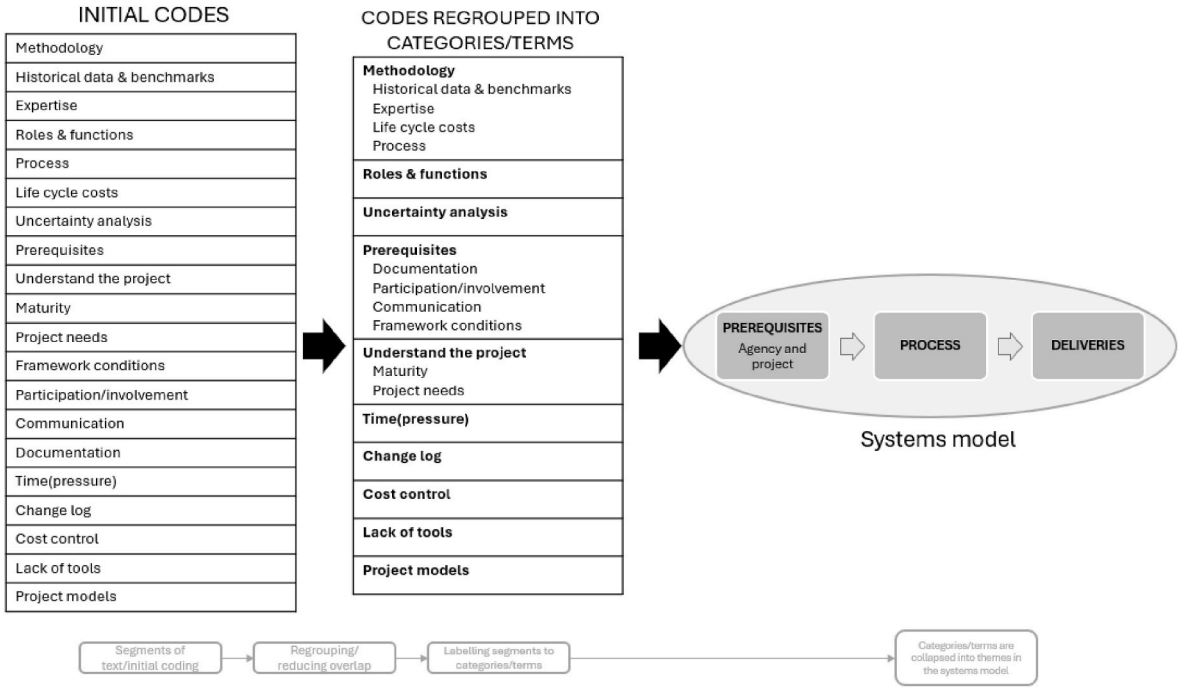
We applied the search strings in three scientific databases. The search in Google Scholar was conducted in June 2022, the search in Web of Science in October 2022, and the search in SCOPUS in January 2023.

Our first step was to apply the search strings to identify previous literature reviews, which returned six publications of relevance (Castro Miranda et al., 2022; Kitchenham et al., 2006; Liu and Zhu, 2007; Schiffauerova and Thomson, 2006; Sharma et al., 2021; Trivailo et al., 2012). In addition to these, relevant literature reviews that focus specifically on early cost estimation in software projects were identified, such as those by Jorgensen and Shepperd (2007) and Bilgaiyan et al. (2016). In the following description, we exclude software-specific studies, as the themes are not directly transferable to other projects, and they are typically centered on estimation of incremental effort, function points, or agile development in general. No previous literature reviews were identified that exactly covered the specific theme of practices within cost estimation in the early phases.

By applying search strings to the databases to explore empirical studies on cost estimation in the front end of major projects, the filtering process returned the findings presented in Section 2.3. All relevant studies returned from each database search were prepared for analysis by using an Excel spreadsheet, and the filtering was done in 10 sequential steps. The systematic search in the three databases yielded 13,865 results, of which the majority of papers (80%) were excluded based on a review of their title. The filtering in that step was conducted using an additional second search for relevant words in Excel, based on our initial search string. This step thus enabled us to remove studies with topics including one or more of the words in our search string, such as titles containing "cost effective management" or "optimizing early warning systems," but where the paper's topic was not specifically "cost" or "early."

Appendix 2. Details of the data analysis

Figure A2 shows the coding tree from the data analysis, with the bottom section illustrating the different analytic steps as described by Creswell (2014). In the final stage of our data analysis, we organized the themes using a simple systems model, as reflected in our presentation of findings in Section 4. This approach enabled us to address our two research questions by considering the various stages and stakeholders involved in front-end cost estimation.



Appendix Fig. A2. Coding tree from the data analysis of interview transcripts in NVivo

Data availability

The authors do not have permission to share data.

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