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User experiences of situational awareness systems in infrastructure construction

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ABSTRACT
Infrastructure construction (IC) projects are dynamic, complex, and difficult to control and manage. Situational awareness (SA) systems have attracted growing interest in construction literature as an aid for human decision-making in order to forecast changes in project and operations situations. While technological advancements have been achieved in SA systems, very little empirical evidence exists on the actual experiences of IC professionals in relation to SA system usage. We interviewed 23 IC professionals to obtain data, which data we then analyzed by utilizing open coding. Based on our analysis, IC professionals adopt and integrate SA systems individually. On the other hand, often their SA exhibits a bias in favor of the subjective viewpoint of whoever is the dominant or responsible individual in their unit or team, and concealing facts by one or more people appears common. We thus conclude that SA systems can raise IC professionals' awareness of a situation in ways that are objectively and easily visible and accessible to every individual. SA systems can also be used to conceal SA. This study contributes to earlier technology-focused research by revealing how the behavior of dominant individuals affects the user experience of SA systems.

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Situational awareness; infrastructure; construction management; individual judgment

Introduction

The challenges inherent in large infrastructure construction (IC) projects include budget and schedule overruns, as highlighted by Flyvbjerg *et al.* (2003). Georg and Tryggestad (2009) have found such challenges to be caused by difficulties in forecasting situations, a lack of information about a given situation on-site or in a design office, information asymmetries between the parties involved, inadequate techniques, or various combinations of the above. Moh'd *et al.* (2021) note that parties' incorrect information about a situation can be either unintentional (such as due to a lack of expertise or techniques for precise data gathering and dissemination) or intentional (such as due to implementing protective measures in a competitive environment). For both kinds of reasons, the concept of situational awareness (SA) has attracted interest in the construction industry among both researchers and practitioners (Lappalainen *et al.* 2021, Halttula and Seppänen 2022, Zhang *et al.* 2023).

SA is a critical concept in industries such as transportation, aviation, military operations, health care, and emergency response (Endsley 2015). Having more objective awareness of events in one's working environment can enable individuals and organizations in these industries to make better decisions, identify risks and threats and act more appropriately. SA is important for knowledge building and, thus, for faster and more effective decision-making in a changing environment than is the case for decision-making without SA (Munir *et al.* 2022). In dynamic and complex situations, SA systems enhance communication (Salmon *et al.* 2009).

Endsley (1995) has defined SA as a person's dynamic understanding of "what is going on." According to Endsley and Jones (2004), SA includes three levels of awareness: perceptions about the current situation (level 1), comprehension of the current situation (level 2), and projections of what will happen in the future (level 3). It is generally accepted in SA

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research and practice that at least levels 1 and 2 are prerequisites for effective decision-making (Salmon 2008, p. 11). Individuals and organizations with effective SA are more capable of making decisions and taking action than those without SA (Endsley 2015). Several concepts similar to Endsley's individual-oriented SA have also been developed as SA for teams and groups (Nofi 2000, Bolstad and Endsley 2000, Stanton *et al*. 2017). Both kinds of SA concepts and systems have spread across industries, proliferating not only in their original military aviation context but also in civil aviation, energy networks, sports, health care, traffic control, cybersecurity, and many other fields (Salmon 2008, p. 18).

Typically, SA use has been linked to technology (i.e. as a situational awareness system), designed to support and enable a more objective human understanding of the situation than otherwise and to present future scenarios to support decision-making (Endsley and Jones 2004). Among these technologies are various sensing and augmented-reality technologies such as sensors to detect events automatically, such as those used in air traffic control and military operations (Salmon 2008, p. 18, Akinci 2015, Endsley 2015).

The existing body of SA research in the field of construction has primarily concentrated on exploring different applications and descriptions of SA systems, rather than examining the impact of these systems on individual practitioners (Lappalainen *et al*. 2021). Research on SA and SA systems in the construction sector has primarily focused on digital applications and technology related to safety and infrastructure machinery, as well as equipment and worker location information (Oloufa *et al*. 2003, Lonsdale 2004, Lappalainen *et al*. 2021). Researchers have proposed various solutions to increase SA: Oloufa *et al*. (2003) have proposed GPS technology (a situational awareness system for measurement of the location and movement of site equipment), while Cheng and Teizer (2014) have proposed laser-scanning technology through a site tower crane; Fang *et al*. (2016) and Reinbold *et al*. (2019) have proposed radio frequency positioning technology through location and movement. Halttula and Seppänen (2022) have proposed a digital SA system using cameras, 360 videos, and positioning technology to monitor construction site production and thus to provide near-real-time information on the location of workers and materials. In their study, monitoring was based on a 15-minute observation cycle, with weekly comparisons to the project schedule for reporting (Halttula and Seppänen 2022).

Although scholars and industry experts are enthusiastic about the many benefits of SA systems at construction sites and in supervisors' offices, Kane (2019) has reminded of the human aspects of SA in construction. Some of the aspects are characterized by subjectivity and not only objectivity (Kane 2019). In the present study, we operationalize human thinking about SA systems, focusing on both the objective and subjective viewpoints of IC professionals. In doing so, this study relates to theorizing through two lenses. First, we focus on changing professional practices, framing this through adaptive structuring theory (DeSanctis and Poole 1994, Orlikowski, 2000). The theoretical contribution of the study is made through this theoretical lens and by using IC professionals' perspectives and perceptions. An IC professional, as defined in this study, is an individual who holds a managerial or expert position in a construction project to build or upgrade infrastructure such as roads, bridges, railways and energy networks. This person possesses both engineering expertise and managerial knowledge specific to these large and often public projects (Grigg, 2000), and in this study, also has experience of SA systems. Second, we expand and build upon Endsley's (2015) original theoretical work in air traffic control and military operations, extending it to the IC realm. Our aim is to reveal how SA systems work (or not) to improve SA in practical settings amid the complexities and intricacies of IC.

In this paper, we focus on the interplay between various project roles and teams of IC professionals in building SA, as well as the subsequent impact of such interplays on the transmission and understanding of SA. Our empirical evidence is based on interviews conducted with IC professionals. We focus on developing an understanding of how IC professionals define and perceive SA in their work contexts. We believe that understanding and modeling the pragmatism of the IC professionals we interviewed will improve the ability of other IC professionals to make decisions and forecast change.

The empirical setting of our study consists of complex urban infrastructure projects. Our primary research question is: *How do IC professionals experience SA in their use of SA systems?*

Research background

In IC projects, SA has traditionally been achieved through regular meetings to discuss problems, by sharing information, and by using updated plans and drawings (Aerts *et al*. 2017). Particularly in large and complex IC projects with many parties involved, physical meetings and traditional communication methods can be inefficient and time-consuming. The outcomes of such meetings are frequently documented for various purposes, with the resulting documents or reports shared with a large number of stakeholders. One disadvantage of this method is delayed flow of information: reports require time to create and distribute. Information is not always available in real time. Project managers often react to situations based on issues raised in previous meetings (Pena-Mora and Dwivedi 2002). Information becomes scattered across many documents and systems. This makes it challenging to see what the actual situation is in real time a challenge (Biersteker and Marrewijk 2023). This lack of real-time data and actual SA and the need to improve SA in the IC arena has recently motivated many studies of SA in IC and other construction sectors (Williams *et al*. 2006, Ghimire *et al*. 2017, Martinez *et al*. 2023).

The concept of situational awareness

The concept of SA was defined during World War I, when combatants realized the advantage of having information about the enemy's operations before the enemy had similar information. This idea of knowing the current situation in real time, rather than with a time lag, is at the heart of all SA models and systems (Stanton *et al*. 2001). The amount of information and the complexity of systems has since increased dramatically through automation, computers, and information systems, among other factors. Given such growing complexity, humans are increasingly distanced from the situations they control or operate. In turn, such distancing has led to a recognition of SA's importance in various fields (Gilson *et al*. 1994); SA systems, SA applications, and the impacts of SA have received much academic research attention (Horita *et al*. 2023).

As one result of such recent research, a sound consensus now exists on the definition of SA: SA is "an individual's awareness of an ongoing external situation" (Salmon 2008, p. 6). Researchers have constructed numerous models for the perception-comprehension-projection loop. These models include a *sensemaking* model, where people make decisions about situations they encounter based on their understanding of the situation at hand (Jensen 2007, Brehmer 2007), a *perceptual cycle* model (Smith and Hancock 1995), and an *activity-based* model (Bedny and Meister 1999). Of these other concepts and models, the most salient one for this study is Taylor and Selcon's (1994, cf. Flach 1995) concept of the "situational picture." Smith and Hancock (1995) note that the situational picture is not SA, however, but rather a concept, a representation, or a description of a static "scene," a "canvas," or a "snapshot" of a situation (Tikanmäki and Ruoslahti 2019, Lundberg 2015, Sarter and Woods 1991). Lundberg (2015) coined the term *object framing* to refer to the process of emphasizing sampling (objectivity) and comprehending the world by constructing a comprehensive "mental picture" (subjectivity). Evidently, these ideas distinctly embody varying degrees of objectivity and subjectivity. According to Endsley's most widely accepted model (1995), SA consists of an overarching model with three pre-decision-making components or levels of awareness: *perception*, *understanding*, and *future projection* (Salmon 2008, p. 8). Our study also builds on Endsley's model.

In the construction industry, much like the operationalization of a situational picture, professionals often take SA to be about "capturing" the situation and knowing how to present it (Lappalainen *et al*. 2021). But capturing this picture is not the same as possessing SA; rather, it is only an initial step in the process of obtaining SA (Smith and Hancock 1995). A situational picture is generally confined to collecting data and representing data as information. But although the SA concept is related to the idea of perception in Endsley's model, the SA concept is more comprehensive than merely perception. SA is also linked to comprehension and to decision-making that projects decisions and actions into the future (Salmon 2008, p. 8).

A review of SA in infrastructure construction

IC projects are an integral component of the constructed environment, typically situated in various locations such as outdoor spaces, streets, underground systems, and above waterways. They are frequently connected to complex networks of logistics and transportation and communications, and they often expand and diverge across a vast region. These phenomena are commonly linked to a range of dynamic and unpredictable occurrences, including traffic, river flows, the mobility of individuals and commodities, and seasonal variations (Sheng 2018). In these dynamic and complex settings, managers need good SA before they can make sound and objective assessments and decide upon courses of action (Akinci 2015), but the acquisition of management abilities alone is insufficient to achieve mastery in these endeavors. Consequently, the situational pictures of IC projects exhibit a high degree of both complexity and dynamism. Traditional data gathering methods on construction sites result in a severely reduced situational picture due to the absence of data, delays, and inaccuracies. Data are still, even today, commonly collected manually and assessed subjectively (Taneja *et al.* 2011; Cheng and Teizer 2013). Numerous scholars have emphasized the significance of objective SA, combined with digitized data collection, as an imperative in facilitating subjective human decision-making amid the presence of "fragments" of contradictory project information (Han and Golparvar-Fard 2017, Kärkkäinen *et al.* 2019, Sacks *et al.* 2020, Martinez *et al.* 2023).

Stakeholders in significant IC projects generate a large amount of information at various phases. Information often conflicts with earlier data or data produced by others. Significant technical idiosyncrasies are often encountered in IC to a degree that sets such locations apart from other projects and has served as a catalyst for the emergence of IC professionals' interest in new and improved SA systems (Pakhale and Pal 2020, Lappalainen *et al.* 2021). The pursuit of authentic and veracious knowledge in such situations of potential significant conflict is highly valuable (Flyvbjerg and Gardner 2023).

Various practices may be characterized as SA in IC. Lappalainen *et al.* (2021) presented a collection of studies conducted within the construction industry, with a particular emphasis on the advancement of SA systems, many of them in IC. These studies encompass a wide range of applications, including hazard recognition, distributed surveillance and coordination of construction vehicles, the use of eye-tracking to measure workers' SA, tower-crane operations, localization of workers and materials, work-progress monitoring, and conflict visualization (Lappalainen *et al.* 2021).

Even though stakeholders in the construction industry have started to employ SA principles and create SA systems from a technical standpoint, little research has been conducted on professionals' perspectives about SA in complicated IC projects. Research on SA systems in the construction field has increased rapidly (Zhang *et al.* 2023), although professionals' experiences have been eclipsed by this viewpoint. We thus feel justified in designating experience as the central focus of the present study.

Methods

Our aim in this study was to identify how professionals in IC experience SA in their use of SA systems. We selected our interviewees by purposive sampling (Robinson 2014). We first identified, through public information, which large-scale infrastructure projects reported using SA systems; we then contacted the management of these projects to confirm that SA systems were indeed being used and that our prospective interviewees were willing to participate in the study. One criterion was that the organizations we selected were willing to participate in scientific research. Each interviewee we chose was given a separate agreement on data consent and anonymization of the data. We conducted face-to-face interviews with the interviewees.

As shown in Table 1, the interviewees worked in five companies; four built public railways, and one was developing SA software and providing field survey services. The interviews of SA service providers involved collecting SA data at IC sites (with drones, 360 videos, etc.). Our sample size was deliberately limited and did not adhere to a random selection procedure; indeed, the intention of our study was not to accurately represent the broader population (Ridder 2017). The research method we employed in our study deviated from quantitative reasoning, and our interviewees and organizations were selected based on their relevance to an exploratory research approach, characterized by comprehensive descriptions and analysis (Robinson 2014).

All four railway projects were urban rail projects financed by the municipal authorities. These projects represented investments in complex train infrastructure and substantial expenditures over a long period of time. In projects of this nature, budget overruns and delays commonly have considerable socially unfavorable effects (Flyvbjerg *et al.* 2003, Singh 2010). Table 1 provides contextual details of the projects and SA systems used by the interviewees.

Our 23 interviewees thus represented five groups (A–E). They were primarily men who worked in IC management roles. The participants were experienced construction professionals; two-thirds of them had worked in the construction industry for over 15 years. The interviews lasted an average of 69 minutes, varying from 44 to 107 minutes. In total, 1,591 minutes of interviews were recorded, and 128 pages of interview notes were produced. The interviews spanned 103 days and were conducted between the end of June and mid-October. Table 2 presents a summary of the interviewees' profiles.

The exploratory perspective in this research was to acquire a comprehensive comprehension of how SA was viewed in the professional practice and work of the interviewees. The selection of qualitative research for this study was thought to be more suitable than quantitative research in solving the research problem of discovering new empirical data on SA, as noted by Eisenhardt and Graebner (2007).

Table 1. Background information about the projects and SA systems used.

Group	Description	Project phase	Project duration	Budget
A	Subway line project	Commissioning	8 years	M€ 1,200
Description of the SA system: A physical situation room with touchscreens displaying project key performance indices (KPIs) updated every one to two weeks, sourced mainly from on-site project management contractors and a separate five-person status team. Data collection relied on spreadsheets and web-based tools without software integration, data automation, or sensor use. The SA team's responsibilities included developing the system, ensuring data quality and availability, and analyzing data for biweekly sessions where project managers assessed the situation and made decisions. The system prioritized project time scheduling, cost forecasting, and health and safety. During the project's commissioning phases, the final documentation and testing status were monitored.				
B	Light rail line project	Construction	6 years	M€ 350
Description of the SA system: The project managers initially explored commercial SA platforms but opted to develop an in-house system whose primary function was to aggregate reports and collect data from disparate digital systems. Monthly, the SA system overseer manually compiled data into PowerPoint, accessible via the project's data management system. Subarea managers were accountable for data accuracy. Monthly SA sessions, with a data collection cycle of one to four weeks, allowed project managers to assess actual progress and forecasts. The information covered cost and schedule forecasts, health and safety, and concise KPI descriptions.				
C	Tramway line project	Construction	3 years	M€ 200
Description of the SA system: The system gathers project-level data from various sources into a unified dashboard. Anomalies and defects are logged through a mobile app, while other information comes from software interfaces. Most data is sourced directly from partner software with minimal manual input. Initially developed on a spreadsheet, the system underwent incremental software integration. The primary SA dashboard was built using a public business intelligence cloud service. Instead of sensors, the system incorporates regularly updated drone photos on the dashboard. Notably, this SA system digitally collects data from designers, distinguishing this system from others in the study.				
D	Railway line project	Design	4 years	M€ 70
Description of the SA system: The system, created with standard office software, monitors project KPIs that reflect core processes such as schedules, costs, and health and safety. Data storage occurs at specified intervals (one to four weeks) linked to a commercial business intelligence cloud service. Because the system was in the developmental stage during the study, only a portion of the KPI data was functional. No sensor data was incorporated. Weekly SA system data reviews occur in construction team meetings, which emphasize schedules and costs.				
E	SA system service provider	Several phases	Several years	M€ 0.6*
Description of the SA system: The system uses a drone and helmet camera on-site to gather data for analysis in the company's 'control room.' The control room data, accessible via a cloud service on users' devices, includes chronological information and allows users to add their observations. Employing sensors and positioning devices, the system monitors workers and material flows. It is suitable for various construction projects and offers various interfaces. SA data collection occurs weekly, but the software imposes no restrictions on the cycle.				

*2021 revenue.

Table 2. Interviewee profiles.

No.	User group	Role	Gender	Age group (years)	SA experience (years)	Notes (page)	Duration (hours)
1	E	Expert	Male	30-34	0-4	3	0:44
2	A	Expert	Female	25-29	0-4	6	1:17
3	A	Expert	Male	25-29	0-4	12	1:09
4	E	Expert	Female	25-29	0-4	6	0:54
5	A	Management	Male	50-54	5-9	10	1:47
6	A	Management	Male	50-54	0-4	6	1:47
7	B	Management	Male	35-39	0-4	2	0:50
8*	D	Expert	Male	40-44	0-4	2	1:16
9	A	Management	Male	50-54	0-4	6	1:16
10	B	Management	Male	35-39	5-9	5	0:52
11*	D	Management	Male	35-39	0-4	2	1:16
12	B	Expert	Female	40-44	0-4	3	1:03
13	B	Management	Female	45-49	0-4	3	0:51
14	B	Management	Male	30-34	>10	5	1:01
15	A	Management	Male	40-44	0-4	4	1:02
16	A	Expert	Male	30-34	0-4	6	1:14
17	C	Management	Female	35-39	0-4	15	1:06
18	A	Expert	Male	30-34	5-9	7	1:22
19	A	Management	Male	40-44	5-9	5	0:50
20	A	Management	Male	40-44	>10	6	1:18
21	C	Management	Male	50-54	0-4	4	0:58
22	C	Expert	Male	30-34	0-4	3	1:16
23	B	Management	Male	40-44	5-9	7	1:22

*Interview held simultaneously with another interviewee.

Interviews

We carried out open-ended and unstructured interviews to answer the study's primary research question on how IC professionals experience SA in their use of SA systems. We asked probing questions to ensure that the interviews remained within the themes and research question to be addressed (Moerman 2010). These probing questions included, for example, (1) how professionals perceive what is meant by SA in their context, (2) what kinds of SA systems the

Table 3. Personal interpretations of SA.

Big picture of the project situation
[The SA allows us] to get as **broad an overview** as possible of the current situation on the site, from as many different sources as possible. (Expert 1, Group E)
You're aware of the **big picture**, and you're on the map of what's in the past and what's potentially coming and what the current status is in relation to what's planned. (Expert 4, Group E)
[The SA is like] the management of a complex puzzle, so we can form the **overall picture**. (Manager 11, Group D)
We have these **big goals** … for example … when this SA was set up, we had five years to get the job done … That's the path we've pretty much found in the SA … an annual path where 'These things must happen this year so we can reach the big goal.' (Manager 5, Group A)
[SA is] such an **overall understanding** of the project situation … the processes are in the background. (Manager 23, Group B)
Visual representation of the status of core processes
The use of SA … ensures that the **project management processes** are adequately implemented. (Expert 3, Group A)
The purpose of SA is to make those important **core processes visible**—to find the key impacts of those core processes and thereby build up an overall picture of them—which in turn allows the project and the project to be managed. (Expert 8, Group D)
[SA is] a **structured**, agreed-on way of collecting **project information** from the bottom up and also presenting the data and making decisions based on it. (Expert 16, Group A)
SA will provide input to our risk **management process** … in a way, we're up to date in this process. (Manager 13, Group B)
By using data analytics (which is *get*, *clean*, *visualize*), you create SA of the **project management processes** and make decisions based on that data. [SA is] specifically a management system. (Manager 20, Group A)
[SA means] … to be … aware of what's happening … in terms of the **schedule or … costs … risk management** … what's required for day-to-day management, through the SA. (Manager 21, Group C)
Access to metrics and indicators relevant to decision-making
You start with a plan with a schedule, a cost, and then you have SA to collect and **compare** how that plan has played out versus **what's really happening**. (Manager 6, Group A)
[SA is] a regular **summary** of how the project is doing **in different areas** … .The main role of the SA for me is to **generate discussion** … [SA is] not solely the answer to anything … it's just the initiator of the discussion … I don't think … the data perspective will achieve benefits where SA will add value. (Manager 7, Group B)
From the owner's point of view, of course … you need to have an understanding and perception of how the project is going in terms of schedule, quality, and economics … SA then **consists of different indicators**. (Manager 9, Group A)
If these entities have the **right kind of information compiled**, then the system is already a pretty good SA. (Manager 10, Group B)
[SA refers to] the state of the project at the time of the review … the **situation of all aspects** … SA in itself is not a report; it refers to the information **required for management**. (Expert 12, Group B)
We use several indicators for the same thing … an interconnected multi-meter system. (Manager 15, Group A)
We can get information to **support decision-making**, in many levels … through the feedback loop. (Manager 14, Group B)
The project management group meets monthly … and **makes decisions** that get reported to [supervisors] … .If we see any red lights, we discuss [the problem]. (Manager 17, Group C)
Objective data of the project situation without subjective opinions
[The SA system can] show where things are going, **without relying** on anyone's opinion or **gut feeling**. (Expert 2, Group A)
Real SA happens when **everyone** knows where they're going and **agrees on it**. Otherwise, things become distorted if someone disagrees or thinks we're in a different stage. (Expert 18, Group A)
Other definitions
I do see [SA] as **quality assurance** … tracking documentation and design completion. (Manager 19, Group A)
At its core, the SA is just a **way of reporting** … and it also reflects our predictions. (Expert 22, Group C)

Note: The quotes have been lightly edited for clarity.

professionals used, (3) how the use of SA was reflected in the professionals' projects, and (4) what influenced the professionals' or other actors' SA. We designed these probing questions around the research problem and question, but in such a way that they were purely exploratory and were only used at the point in an interview when the interviewee had run out of things to say or had moved away from the topic. An example of using a probing question at the beginning of the interview session is illustrated below. The quotes in this paper have been translated from Finnish and lightly edited for clarity in English.

> *Interviewer*: Here's an initial lightweight question to start with: How do you personally define or experience this situational awareness?
>
> *Expert no. 1*: Situational awareness?
>
> *Interviewer*: Yes.
>
> *Expert no. 1*: Well, if we're talking about our case, to get as broad an overview as possible of the current situation on the site, from as many different sources as possible. For example, we now have the information on the conditions and the location, where everyone is and where things are happening. We can quickly check what the situation is. That's the first thing that comes to mind.

We did not ask the probing questions beforehand, instead informally, gradually progressing according to the themes through open discussion (Moerman 2010). The interviews were conducted in an unstructured way, allowing for open-ended conversations without any fixed constraints. Interviewers aimed to cultivate an authentic and dynamic atmosphere throughout an open interview, allowing interviewees to freely articulate their thoughts, emotions, recollections, opinions, and arguments (Brinkmann, 2014). Despite the researchers' pre-established topics and study queries, as well as their compilation of a list of probing questions, the interview process was conducted in an unstructured manner, allowing participants to freely express themselves without any limitations. Some

Table 4. Overview of interview findings of emergent dimensions of SA in IC.

Sample quotes	Similar quotes*	1st-order codes	2nd-order themes	Aggregated theoretical dimensions (status quo)
The problem has been that some contractors, some sites, are able to produce more accurate, more timely, more **reliable** data than others. (9:10) SA is never better than the data sources used for it … the **quality** of data sources … can distort a lot. (3:55)	9:19, 9:23, 9:24, 14:32, 13:49, 3:59, 5:77, 5:79, 23:120, 12:129, 16:144, 16:145, 10:191, 7:195, 22:211	Data source quality → objectivity	Incomplete or erroneous information	What: Completeness of information
If there's **too much information**, it certainly degrades the quality of the SA. (5:87) **Too much data** then blurs the big-picture focus of the whole thing. (19:152) This is a pretty good system, in that it's limited to the **most important things**. (21:218)	13:51, 3:58, 3:64, 5:91, 19:153, 6:159, 6:165, 17:175, 17:178, 10:192, 7:204	Key performance indexes (KPIs) → objectivity	Individual or team goals	Why: Goals and objectives
1-2 times a week is appropriate. [That timing] is precisely the stage that correlates a lot to what stage is going on at the site, whether it's useful or not. (1:101) We get the contractors' costs … **every night** … from the designers … **once a month**, but then the client's costs come in about **three months** late. (7:202)	20:6, 9:11, 9:18, 9:22, 2:73, 5:90, 18:116, 12:128, 17:173, 10:183, 21:214, 21:215, 21:216	Data collection and analysis cycle → objectivity	Progress and situational updates	
They haven't checked the information … we need to push, create a process to make sure that **they check the data** and analyze that information. [Sometimes it feels] like **they don't care** about the information that's coming in. (5:83) **Those who do** poorer quality [work] … are not committed … to this … culture of wanting SA, and **they don't feel** they get anything out of it. (7:196).	9:15, 9:27, 15:29, 18:113, 18:115, 23:122, 19:148, 19:150, 6:164	Stakeholder engagement → subjectivity	Individual or team experience, training, roles, and assertiveness	Who: Stakeholders
[The system] is so standardized that [the data is] pretty quick to look at. Then, you learn what you're looking for. When [the system] is similar throughout the project for different areas or technology, you can [perform] pretty **quick … checks**. (14:45) All sites have the same format or content, which **reduces the influence of individual people** … when the data is displayed on the dashboard. (5:80)	14:37, 11:93, 8:94, 18:111, 18:119, 12:133, 12:134, 16:146	Information exchange → objectivity & subjectivity	Communication, communication links, and strategies	How: Effectiveness and assertiveness of communication
We try to ensure that the status **data is always checked**; we get a **second opinion** on whether that's true. (3:54) For me it's really important that … the background data is provided, but also that those who provide the data [have some kind of] personal relationship with those who produce the data, to understand … that there's something else **behind the numbers**. (16:139, 16:140) [The data is] discussed every week with the **person who's entered the information**. (17:172)	14:36, 14:38, 14:45, 13:50, 2:74, 5:80, 5:8:88, 8:97, 18:107, 18:108, 18:118, 23:126, 16:137, 10:189, 10:190, 7:201	Information contextualization → subjectivity	Increasing complexity of system	

Note: This table highlights the 1st-order codes and 2nd-order themes that emerged from the data analysis and subsequent aggregated dimensions; the quotes have been lightly edited for clarity.
*Code key example: 9:19 → interviewee no. 9, quote no. 19.

interviewees demonstrated the SA system they used during the interviews, which allowed the researchers to obtain information about the system and its use. We took notes during the interviews; some interviewees provided written material about their systems after the interviews. We recorded the interviews, transcribed them, and transferred the transcripts to ATLAS.ti software. We coded the answers using a coding plan based on the research questions. During the transcribing phase, the names of the interviewees were visible (because the interviews started with an introduction); in the later analysis phase, we anonymized the interviews.

Analysis of the interviews

We first analyzed the interview data using the inductive open coding method (with open coding, the entire transcribed dataset is examined). Inductive coding followed several steps: (1) careful reading of the text and reflection on the meanings contained in the text, (2) identification of text fragments containing meaning units, (3) creation of a category (or linking of the text to an existing category), and (4) description and linking of the meaning (Fereday and Muir-Cochrane 2006). The latter phase of categorization and relationship building differs from the phase of open coding, as explained by Williams and Moser (2019): During open coding, the researcher examines information and fragments, whereas categorization and relationship building involve ongoing analysis, cross-referencing, and refinement. We identified and categorized the concepts and their properties and dimensions as code groups (Friese *et al.* 2018) based on typification, which is the process of grouping a large set of codes in a manner applicable to all codes despite their minor differences (Vaismoradi *et al.* 2016). Through typification, we assigned common meanings to codes. In this study, we typified the interview respondents' answers and grouped them into dimensions of SA that influence SA system users in IC.

We used ATLAS.ti software for open coding. As the open coding progressed, we first transferred the coded quotes to an electronic whiteboard (using Miro software), where the interviewees' expressions of the same type were condensed and grouped. Simultaneously, references to quotes were created for all code groups in ATLAS.ti, which enabled analysis of the entire coded data.

The first-order codes in the interview data were categorized according to the traditional data-driven management language; the data and first-order codes were then contextualized into second-order themes to identify more general context, factors, and relationships for the conceptual approach (Yin 2009, Cloutier and Ravasi 2021). Table 4 illustrates the results of the data analysis and includes a summarized interpretation of the dimensions of SA in IC.

Validity and reliability

The validity and reliability of the study were assessed in five ways: (1) providing a detailed description and documentation of the background to the findings, (2) generating a visual illustration of the theoretical aggregation process that emerged from the findings and quotes, (3) examining rival explanations, (4) monitoring code saturation, and (5) addressing the findings through existing literature (Yin 2009, Ridder 2017). To reduce interviewer bias, with two exceptions, two interviewers (the main author and the second author) from our research team always participated in the interviews. The results of the data analysis were assessed jointly with all members of the research team, and after coding phase 1, we conducted the work by a team of four authors. We held regular weekly meetings during the course of the study in order to provide guidance for the study's advancement and to align their perspectives on the various stages of the study. We used the interview data to monitor code saturation, which enabled us to evaluate the data with a satisfactory level of confidence that the acquisition of additional data would not yield substantial novel insights (Hennink *et al.* 2017). In practice, the saturation point was defined as the juncture at which the replies had ceased to generate novel information, and the recurring codes and themes had become apparent.

Findings

At the beginning of the interviews, as a probing question, we asked our interviewees to articulate their personal interpretation of SA within the framework of management and their professional endeavors. The interviewees' responses are presented in Table 3.

Four different recurring perspectives on SA may be identified from the interviewees' definitions. Most interviewees understood SA as an overall description, a view summarized in the quote "… you're aware of the big picture … " (Note that many of the quotes in this paper are extracts of longer quotes.). The second-largest group of definitions described SA as a representation of project management processes: "… the purpose of SA is to make those important core processes visible … ” Some interviewees emphasized the data-analytical aspect of SA, and some emphasized SA as an indicator: " … we can get information to support decision-making, in many levels … "; SA is " … an interconnected multi-meter system." A final perspective, identified by several interviewees, was that of SA as a system that reduces opinions, guesses, and explanations: " … to show where things are going, without relying on anyone's opinion or gut feeling." It is worth mentioning that the majority of the definitions highlight objectivity in SA rather than subjectivity.

Emergent dimensions of SA within infrastructure construction

In total, 218 quotes related to perceived SA in IC were identified from the transcribed interviews. These quotes were summarized in the open coding phase into six first-order codes and second-order themes, as presented in Table 4. At the right side of the table, the emergent dimensions of SA in IC are presented in circles.

Observations on objectivity

The recurring perspectives on SA that emerged from the interviews included the following (see also Table 3): Some perceived SA as a general description that emphasizes awareness of the big picture; some perceived SA as a description of project management processes that make core processes visible; some emphasized SA as a data analysis system used to support decision-making that reduces reliance on human opinions, guesses, or hunches. A limited number of participants expressed in their responses the potential technical solutions for rectifying erroneous SA data. The project-related goals appeared to align with a shared schema among the participants, which refers to a structured framework that has clear objectives and performance limits.

The interviewees described different aspects of the presentation of SA data (e.g. the presentation of performance indicators or project goals in combined form), standardized dashboards (e.g. quote 14:45), the possibility of individual dashboards (e.g. quote 20:6), and the relevance of graphic presentation for SA users (e.g. quote 21:218). The approach to the systems' visual presentation was developed so that the system could also be used for reporting; one notable aspect of the interviews was the frequently repeated relevance of reporting (e.g. quotes 3:56, 5:79, and 18:116). Information from the displays could be presented or sent to stakeholders or others high in the organization's hierarchy as required, replacing some traditional monthly project reporting (e.g. quotes 2:74 and 17:181). The degree of automation in data collection varied across the user projects observed in this study, however. These definitions exhibited a strong emphasis on objectivity.

Observations on subjectivity

Another aspect of the interviews stressed the human role as a validator and guarantor of accurate information. This interpretation was further reinforced by the definitions of SA and coding (see also Table 4). In the present context, certain participants also encountered disillusionment in relation to their initial expectations when these human "guarantors" of the information had failed to uphold their responsibilities, resulting in subsequent inaccuracies in the collected data. The importance of a human presence was related to the responsible parties' duties to report situations in their areas of responsibility directly to the group (e.g. quotes 5:83 and 14:35). A number of participants opted for human-generated data verification as their preferred solution.

Several participants also voiced dissatisfaction with the portrayal of both negative and positive news. Interviewees highlighted well-established practices related to hiding the actual situation or informing others about good news late (e.g. quotes 3:56 and 5:77). They expressed limited concerns or proposed solutions regarding the inaccuracies in the measuring method or data, as well as the alleged failure of the SA system. The source of intricate, occasionally contradicting, and partially erroneous data could sometimes be traced back to someone within a separate company, such as a contractor gathering information on behalf of a client, as was the most common practice in these observed SA systems (e.g. quotes 6:162 and 9:10).

The findings underscore the necessity of consistently evaluating the data within SA systems. Typically, a single person was accountable for verifying the information. The interviews detailed these shortcomings and the inability to fulfil anticipated outcomes. The shortcomings observed in the responses were shown to be associated with motivation (e.g. quotes 6:164 and 18:115). Certain respondents still expressed the idea that the problem was not primarily due to motivation or neglect, but rather stemmed from inertia and potentially a deficiency in acquiring new skills among professionals who heavily depend on the tradition of shielding and hiding information (e.g. quotes 9:19 and 5:77).

Another observation related to learning was a lack of motivation, referred to in some of the interviews, which seemed to be related partly to shielding (e.g. quotes 6:155, 7:197, and 9:13). We also noted indications that, despite their novelty, little time was spent on training in using SA systems (e.g. quotes 14:48 and 18:110). Some interviewees also brought up the mismatch between client and contractor resources and competence differences, since the interviewees mainly worked on large public projects (e.g. quotes 9:14 and 14:47). At the same time, personnel with widely varying skills and experience used systems on the construction site. Of course, most respondents mentioned that they benefited from SA, regardless of whether they were project managers or experts.

One design basis of the systems seemed to involve verifying information about the project status that went to project management and reporting. The interviewees revealed that SA in IC requires dealing with incomplete information, leaving decision-makers to make judgments and choices based on the available information and knowing the uncertainties and risks associated with that information. The interviewees frequently highlighted the opportunity to have in-depth discussions with others about the topic (e.g. quotes 10:189, 14:38, and 17:172). We found that the most noteworthy elements of SA utilization in IC were the emphasis on collecting SA through conversation, having SA validated by a responsible person, and maintaining a careful balance between subjectivity and objectivity. The findings indicate that users of SA systems in the IC domain realized the importance of having a thorough understanding of a project's fundamental aims, as well as the critical role of people in interpreting information (e.g. quotes 5:84 and 10:191). These definitions exhibited a strong emphasis on subjectivity.

Discussion

Finding a balance between objectivity and subjectivity

IC practitioners appeared to face challenges in finding a balance between objectivity and subjectivity, or a balance between imperfect data and human verification validation. This situation raised several questions. For example, has the increasing use of SA and data transparency affected the shielding and hiding phenomenon that Moh'd *et al*. (2021) have also observed in their study? What motivates IC experts to depend on human validation rather than data? The projects examined in the present study are exclusively public IC projects, typically with the objective of fostering a more transparent exchange of information among stakeholders compared to private sector projects. This data guarantor phenomenon probably suggests the need for human judgment, a kind of expert perspective that is possibly expected to clarify and summarize complex SA data.

In some of the previous SA systems researchers have studied, individuals frequently exhibit bias and distortion in their interpretation of SA (Barnett 2005). For instance, in the aviation and maritime industries, such systems have been created to assist pilots in scenarios where they cannot depend on their perception or intuition, such as when flying or navigating a ship in dense fog. This phenomenon of human judgment appears to already occur during SA systems' planning phases. Of course, it is a natural starting point that SA systems are designed and implemented as systems that support human decision-making. Alternatively, looking through adaptive structuration theory, it is possible that SA system designers have integrated the conventional social structures (for example, human judgment and validation) of IC management into their use of SA technology (Orlikowski, 2000). As DeSanctis and Poole (1994) have proposed, replicating these structures and integrating human processes in putting a technology into use can generate novel structures for interaction as to SA in IC.

IC projects continue to encounter inaccuracies in data, and blindly relying on SA data often leads to difficulties (Soman and Whyte 2020). Building a SA system to support decision-making that relies on human interpretation can therefore lead to problems, resulting in a human perspective taking precedence over the objectivity of the data. Several researchers have identified various biases in human judgment in the group context (Jones and Roelofsma 2000, Dawson *et al.* 2002, Pronin 2007). Considering the biases generated by human judgment and the user-raised relevance of person-centeredness in SA systems observed in this study, a compelling avenue for future research could involve evaluating how these biases affect individual expert judgments of decisions. Exploring the extent to which biased subjectivity can divert decisions from those grounded in objective data could also be valuable. Organizing such an experimental arrangement in the SA system environment observed in this study is already possible.

Based on this research, information may also be updated on how SA in IC has developed in relation to the researchers' previous observations. Endsley and Jones (2004) established a clear connection between the use of SA and the dependence on technology and data. In the present study, however, Akinci's (2015) argument about a lack of digital data or problems related to the available data format did not seem to be a significant issue for users of SA systems. Instead, our findings suggest that data are available and can be collected and compiled digitally. Our key finding was not the absence of SA data, despite the fact that it was primarily gathered manually in these observed cases, but rather the significance of subjectivity in interpreting and validating the results of the data analysis.

SA for reporting: the IC approach

One interesting finding was the idea of reporting as a fundamental part of SA in these IC projects. This finding is notable because SA systems in other sectors have not generally been developed as reporting tools. Even if the collected data is used for statistics and reporting in other fields (Sarikaya *et al.* 2018), it would be difficult to imagine that the primary function of an airline pilot's or paramedic team's SA system would be reporting. The primary need for SA applications in other domains is generally to improve the user's SA and the performance of various tasks (Nadj *et al.* 2020). Nevertheless, the use of reporting in IC has been well established, and many public IC projects are also subject to legislative reporting obligations, possibly driving the development of SA systems in the direction we have witnessed in this study. One valuable avenue for future research could be to investigate the role of reporting for SA system users in the future in IC. For example, will real-time data utilization in systems move SA in IC toward a more dynamic model, will regulation steer the industry toward a more static SA model, or will a hybrid model emerge?

Perspectives on rival explanations and limitations

Qualitative research based on interviews is always subject to bias, and alternative explanations cannot be left unaddressed (Yin 2009). For example, the perception of SA varied between individuals in the present study, as shown in Table 3. Some respondents believed that the role of the responsible person and the discussion of SA in the group were crucial factors. The findings also indicate a different picture, however. For example, several respondents stressed the importance of data analysis in creating SA.

Perceptions may also be influenced by leadership style. A responsible person with a dominant leadership style may engender confidence among other group members in the manager's confirmations and discussions (Du *et al.* 2020). In a different management environment, people could accept the generation of SA through multiple channels; they could also accept the nature of a complex and dynamic project in which absolute truth is rarely achieved through the methods available.

A second rival explanation is that variation in project contexts is usually relevant when evaluating study findings (Collinson and Rugman 2010). The context of complex rail projects in urban environments was particularly salient in the participants' responses in the present study. The use of SA in the Finnish construction sector was initiated by one challenging rail project, and the links between project organizations in a small country are close. The organizations of the rail projects are also often similar, and the companies involved are frequently the same specialized actors. Because these factors may influence how the findings should be interpreted, the chosen boundary of this research could significantly affect the responses and reduce the study's applicability to other types of projects.

Despite the promising findings, this study has several limitations that should be considered. The first limitation is that the interviewee group did not include site staff, instead being limited to project managers and experts. Considering that SA is a new method in IC management, gaining more insight into the experiences of site staff is imperative when using SA. Based on previous research, we may assume that the site and management have different needs, particularly in the use of new technology. For example, Sezer and Bröchner (2019) have argued that site personnel resist using new technologies due to their complexity or simply because they do not perceive the need for such information and communication-based systems that will link them with management.

From the perspective of SA system development, we can thus ask the following question: *For whom and for what purpose are SA systems being developed in the IC?* Other research questions that require more clarification include *What are the needs of site personnel regarding SA?* and *Why do current SA systems fail to involve site personnel?*

The study's second major limitation was the interviewees' geographic location in just one country. The research was executed in such a way, however, that repeating similar research elsewhere is possible. We have also comprehensively documented our research results in connection with coding; in addition to reliability, the codes will enable the results to be combined with further research. The third limitation is the small number of interviewees. Finland alone has hundreds of IC users of SA systems, which means that including a larger sample and conducting more quantitative research in the future are both feasible and desirable. However, varying numbers of individuals from different projects participated. While this is not considered to significantly weaken the findings, it needs to be remembered that this study did not aim to differentiate between various categories or individuals within the IC profession. Instead, it focused on examining the experiences of professionals (Baker *et al*. 2012). If the intention was to compare perspectives or experiences, the quantitative distribution of interviews would have been more crucial.

The fourth limitation is that the research would have benefited greatly from a subsequent round of interviews. Doing so would have allowed the researchers to validate their assumptions and conclusions derived from the coding process by including the interviewees' feedback and new perspectives. This step was unattainable as a result of the research timetable and the availability of the interviewees, however.

Conclusions

The primary aim of this study was to investigate the experiences of professionals in the field of infrastructure construction (IC) regarding the use of situational awareness (SA) systems in infrastructure projects. We attempted to achieve this goal by discovering how IC professionals perceived the application of SA in their work environments. We commenced the study by assessing prior research findings from both within and outside the construction industry, as well as conducting interviews with 23 IC professionals from various companies in Finland.

Our research indicates that IC professionals tend to implement and incorporate SA systems based on the individual perspective of the dominant or responsible person on their team. In our study, the IC users of the SA systems considered it important to have responsible individuals and the opportunity for open communication among group members. They also set expectations for the SA systems regarding learning and relearning previous, even harmful, industry practices. Another noteworthy observation pertained to the prevalent phenomenon of concealing the actual situation. The use of SA systems that are visible and accessible to all project participants could potentially mitigate this shielding phenomenon, a common occurrence in construction.

This study is grounded in the belief that examining and comprehending IC projects can enlighten managers and others and enhance the execution of all construction projects. The empirical findings of this study offer a novel perspective on the trajectory of SA utilization in IC and the perceived relevance of SA systems by users in their work. These findings also illustrate the challenges, worries, and expectations of SA users in IC.

This work contributes a comprehensive and detailed description of the use of SA in the context of IC. Although the study had a small number of participants, it was the first to specifically examine SA in IC. The study's results will enhance the comprehension and examination of SA-related phenomena for scholars and practitioners. This study thus contributes to the existing body of knowledge on the IC and establishes a foundation for future research in the field of SA within the construction sector. The results of the study have led to a number of novel research inquiries pertaining to the utilization, development trajectory, and prospective ramifications of the decisions undertaken during the developmental stage of SA systems.

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No potential conflict of interest was reported by the authors.

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Data availability statement

Data available on request from the authors.

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