Testing the Value of 4D Visualizations for Enhancing Mindfulness in Utility Reconstruction Works

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Abstract: This paper reports on an ethnographic-action research study of four-dimensional (4D) based coordination in three utility reconstruction projects. This research shows that implementation of 4D models in planning meetings supports mindful behavior, making stakeholders: (1) sensitive to operational processes, (2) pre-occupied with errors and inaccuracies, (3) resistant to simplifying construction plans, and (4) resilient and aware of process alternatives. By being first in synthesizing 4D implementation and mindfulness literature, this study makes a step toward a more systematic and comprehensive analysis of the impact of 4D on coordination. This study provides a practical contribution by showing that stakeholders in utility projects can use 4D to better anticipate and contain unwanted situations. This helps them tackling coordination issues effectively, and may eventually reduce the overruns and rework in utility construction. **DOI: 10.1061/(ASCE)CO.1943-7862.0001126.**

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Introduction

Urban subsurface utility projects have an adverse impact on life in surrounding public space (Nguyen et al. 2014). Reconstructions of, for example, sewer tubes, electricity cables, and gas pipes often obstruct traffic routes and public spaces, create noise, and lead to potentially unsafe situations. To minimize the public impact of these works, authorities impose tight spatial restrictions and urge service providers and their contractors to streamline their construction plans.

To cope with these constraints, project stakeholders need to integrate their parts of the overall construction plan into a feasible design and reliable master schedule. When developing this plan, stakeholders need to anticipate design errors and process conflicts. Two developments have complicated this coordination process in utility construction. First, decades of liberalization and privatization have gradually shifted responsibility for construction, operation, and maintenance of subsurface networks from a few public organizations to myriads of private utility companies (e.g., Steenhuisen et al. 2009). Second, the accelerated rollout of smart grids (EU 2010, p. 14) and introduction of other network technologies, such as fiber glass, subsurface waste collection, and energy storage systems, increased the density of cities' subsurface networks. Both developments added more organizations to the utility sector.

The proliferation of subsurface networks and stakeholders increased the need to align utility construction plans. To this end, service providers and municipalities organize multidisciplinary coordination meetings. During these meetings, stakeholders are involved at different moments in time and use distinctive ways to formalize their construction plans. Such integration of construction plans is extensive and time consuming in current manual coordination practice (Kim et al. 2013).

Although the utility coordination need gradually increased, time pressures often reduce the possibilities for stakeholders to analyze and align design details and process interfaces. This may result in oversimplified construction plans and tight schedules. Errors that could have been anticipated upfront then become visible onsite, requiring ad hoc improvised actions and renegotiations about resources and costs. Frequently, these issues turn even small-scaled utility projects into a complex coordination puzzle that causes overruns and public hindrance.

To support such complex coordination processes, literature suggests that practitioners can adopt four-dimensional (4D) instruments (e.g., Khanzode et al. 2008; Trebbe et al. 2015). These tools integrate parts of the overall 3-dimensional Computer Aided Design (3D-CAD) with the project's master schedule, resulting in a multidisciplinary animation of a planned construction process. Although literature reports about the specific purposes and task-related benefits of 4D (e.g., Russell et al. 2009; Kang et al. 2013), little is known about how 4D impacts the dynamic coordination process as a whole. One reason for this might be that it is difficult to study this relation because of the limited uptake of 4D in construction projects. Furthermore, the different nature of existing 4D projects, and the limited availability of reliable project performance information, makes it difficult to quantitatively assess the impact of 4D on performance. Besides, existing literature does not provide a structured way to evaluate how specific benefits of 4D contribute to dynamic and creative coordination processes. To address this gap, this study's objective was to test qualitatively and systematically how 4D influences coordination in utility reconstruction works. Therefore, this study implemented the mindfulness concept and used it as lens to evaluate the impact of 4D on coordination and performance.

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This study used ethnographic-action research to implement 4D in three utility reconstruction cases. Findings confirm the hypothesis that 4D supports mindful behavior in utility reconstruction works. Specifically, it was found that 4D allowed stakeholders to follow mindfulness principles. This means that they became (1) sensitive to operational processes and their interactions, (2) reluctant to simplify, (3) focused on inaccuracies and failures, and (4) committed to resilience. Literature argues that mindful behavior allows organizations to detect and manage accumulating errors and derailing processes (cf., Weick and Roberts 1993; Weick et al. 2008). This study's empirical evidence therefore shows that 4D effectively helps avoiding and containing process disruptions during planning and construction, eventually contributing to enhanced project performance.

The remainder of this paper is structured as follows: (1) an elaboration on existing research on 4D and on how the concept of mindful organizing helps in evaluating the impact of 4D on coordination, (2) an elaboration on how the authors implemented 4D to support and observe coordination in three utility reconstruction cases, (3) discussion of examples that illustrate observed mindful behavior, and (4) summary of findings, an elaboration on their implication, and recommendations for future research.

Theoretical Points of Departure

The construction sector is known by its large degree of subcontracting and fragmentation (Eccles 1981). Multiple organizations, therefore, align plans to achieve their shared goals. Also in the utility sector, the growing amount of stakeholders and increased heterogeneity of actor constellations result in institutionalized fragmentation (Steenhuisen et al. 2009). Such fragmented contexts create challenges to achieve effective anticipation and containment of potential process obstructions (De Bruijne and Van Eeten 2007; Vogus and Sutcliffe 2012).

One consequence of industry fragmentation is that subsurface construction work consists of multiple utility projects from various contractors and network owners. These stakeholders work within the same physical space to construct their assets. Although they prepare most of their construction plans individually, they also need to align their plans to ensure that their construction activities are well integrated with concurrent work of other stakeholders. To achieve this goal, project teams could implement technologies such as 4D. Such systems integrate geometrical 3D-CAD models with time-plans as fourth dimension (Koo and Fischer 2000), and visualize the transformation of space over time (Webb et al. 2004) to graphically represent the relationship between construction space and a project schedule. When used in meetings, these integrated visual models of stakeholders' schedules can help managers, for example, to develop detailed understanding of operational complexities and to identify potential problems (Heesom and Mahdjoubi 2004).

Literature shows that 4D tools support: (1) project management tasks such as communication, design review, and bid preparation (Hartmann et al. 2008); (2) evaluation of construction methods and scheduling strategies (Russell et al. 2009); (3) constructability reviews (Hartmann and Fischer 2007); (4) construction planning, workflow planning, and resource utilization (Wang et al. 2004; Jongeling and Olofsson 2007); (5) risk management (Kang et al. 2013); (6) safety management (Zhou et al. 2013); and (7) mechanical, electrical, and plumbing design coordination (Khanzode et al. 2008). Furthermore, infrastructure case studies have shown that 4D (8) supports environmental impact visualizations (Zanen et al. 2013); (9) collaborative planning and scheduling (Kang et al. 2007); and (10) cobuilder coordination (Trebbe et al. 2015).

Literature evaluates 4D tools in different ways. Technology development studies, for example, use criteria such as system performance, system memory, and capacity (Tsai et al. 2010) to evaluate 4D tools quantitatively. Other researchers tested the technical features of their prototypes by applying them to real life cases (Hu and Zhang 2011; Chen and Luo 2014) by asking practitioners for feedback (Wang et al. 2014) or by conducting surveys (Boton et al. 2013). Site observations and surveys also were used to obtain insights in how practitioners perceive the usefulness of 4D (Mahalingam et al. 2010). Further, engaged studies, researchers' experiences, interviews, and site observations helped identify how 4D supports specific project tasks (e.g., J. Haymaker and M. Fischer, "Challenges and benefits of 4D modeling on the Walt Disney Concert Hall Project," CIFE Working Paper No. 64, Stanford University, Stanford, California; Kam et al. 2003; Mourgues et al. 2007; Trebbe et al. 2015). Another way to evaluate 4D is by asking practitioners to estimate how its use on their project influenced metrics such as the number of change orders, requests of information, reported injuries, and hours of rework (Khanzode et al. 2008).

Although these evaluations eventually culminate in technical performance figures or descriptions of how 4D supports specific tasks, they only provide limited insights about the causal chain of 4D implementation, construction plan integration, coordination, and project performance. Further, existing quantitative criteria seem less suited to explore this chain comprehensively as they focus on the technology itself, and not necessarily on its interaction with dynamic work routines. Rather than systematically evaluating the impact of a tool on the dynamic coordination processes and project performance, implementation studies mostly have a local focus on identifying 4D-benefits for management tasks [e.g., safety management in Zhou et al. (2013), or specific application areas (Hartmann et al. 2008)].

Currently, the lack of a qualitative lens seems to limit the possibility to integrate specific findings about 4D benefits into a comprehensive higher-level analysis of how 4D impacts creative and dynamic coordination processes. Mindfulness, the lens introduced in this study, supports such an analysis. At its core, mindfulness focuses on how multiple actors collaborate effectively when dealing simultaneously with unwanted process disturbances. The mindfulness concept and its applicability to construction coordination studies is elaborated subsequently.

The concepts mindfulness (Langer 1997; Sternberg 2000) and collective mindfulness (Weick and Sutcliffe 2007; Vogus and Sutcliffe 2012) were first adopted by high-reliability organizing scholars. These scholars used the concepts to describe error prevention and error coping in high-hazard organizations. Later, the concepts were adopted in other scientific domains to study, for example, how manufacturers (Gebauer and Kiel-Dixon 2015), business schools (Ray et al. 2011), airport builders and operations (Brady and Davies 2010), and house framing crews (Mitropoulos and Cupido 2009) anticipate disruptions and errors, and contain emerging unwanted situations.

The unwanted situations that the mindfulness concept focuses on are referred to as dysfunctional momenta (Barton and Sutcliffe 2009). Such momenta arise when derailing processes are not reevaluated and remain uninterrupted. When organizations behave mindfully, they identify the subtle cues that trigger such a reevaluation. To this end, they use a more differentiated and creative way to code data, and create concentrated attention in the present time (Weick and Sutcliffe 2006).

Although to a lesser extent than in high-hazard organizations, mainstream organizations also are confronted with unwanted situations that significantly impact their performance (Roberts et al. 2001). In the case of utility construction, for example, stakeholders aim to realize their projects timely and within budget. Therefore, they need to effectively coordinate their activities to avoid process disturbances. Because the mindfulness lens focuses on error coping during these processes, it serves the pragmatic goal of studying construction plan integration (olde Scholtenhuis and Dorée 2014). This study assumes that 4D also contributes to effective error coping, and, therefore, hypothesizes that 4D supports mindful behavior in utility reconstruction works. The mindfulness lens can be used to test this hypothesis and is addressed subsequently.

Essentially, mindful organizing comprises five principles (Weick et al. 2008). Three principles focus on effective anticipation of unwanted events; the other two concentrate on the repression of such events once they occur. This study elaborates on how 4D can help stakeholders to follow these principles. First, mindful organizations are sensitive to operations, meaning that they continually try to grasp a rich image of how the operational processes interact and develop; 4D tools stimulate this behavior by providing explicit and comprehensive visualizations of construction processes. Additionally, the tool enhances insights into operational processes by integrating parts of the design models and schedules. Second, mindful organizations are pre-occupied with failures that can occur within their organization. This means that they report errors and near failures and try to learn from past mistakes. Four-dimensional tools can increase attention for failures through visual and automated inspection of design details and schedule conflicts. Third, by following the reluctance to simplification principle, organizations spend more time analyzing reality. Instead of categorizing situations and plans as standard or abstract, they prefer to perceive and understand situations in detail. Compared to two-dimensional (2D) drawings and sketches, the traditional artifacts that are used in utility construction coordination, 4D visualizations often model project plans and conditions in greater detail, generating a more comprehensive image of the project's scope and content.

To contain emerging unwanted situations, the fourth mindfulness principle suggests organizations to commit to resilience. According to this principle, organizations contain unwanted events by maintaining resources and developing mental capabilities to cope flexibly with emerging unexpected holdups, and to recover from these situations swiftly. Four-dimensional supports this by allowing stakeholders to develop and evaluate alternative scenarios on-the-fly. This increases managers' understanding of the construction project and thus enhances their commitment to resilience. Finally, the fifth principle of deference to expertise suggests organizations use flexible decision-making structures. According to this principle, decision making follows the hierarchy in an organization except when unexpected situations emerge. Then, decision making migrates to the experts that can adequately respond to the situation. In theory, 4D tools can empower various expert stakeholders with a platform to communicate and integrate their engineering, design, and construction knowledge.

In their exploratory pilot study, the authors first found evidence that 4D fosters behavior alongside the five principles (olde Scholtenhuis et al. 2014). This preliminary study was, however, based on their first observations and contained a less detailed and systematic analysis. It elaborated limitedly on the value of the mindfulness concept as a lens for technology evaluation. This paper advances the pilot study by contributing a more extensive empirical grounding and theoretical integration. The next sections explain how the authors observed 4D coordination in three utility reconstruction works, and presents selected observations on how 4D supported mindfulness.

Research Method

This study used ethnographic-action research (Hartmann et al. 2009) to achieve the objective of testing qualitatively and systematically how 4D influences utility reconstruction works coordination. Ethnography can be used to study implementation of innovations in the full complexity of a local work culture, and to develop rich-thick descriptions of observed phenomena (Phelps and Horman 2010). This approach uses ethnographic techniques, such as participant observation (Jorgensen 1989), to collect data from a real-life context. In addition, action research holistically studies an intervention in an existing work practice. Essentially, this takes place in two steps: (1) a comprehensive analysis of a social situation, and (2) the introduction and study of a collaborative change experiment (Baskerville 1999).

Together, these methodologies culminate into ethnographic-action research (Hartmann et al. 2009). This approach comprises four steps: (1) conducting ethnographic observations, (2) identifying work routines, (3) system development, and (4) system implementation. The methodology uses accepted qualitative methods to build theory (Eisenhardt 1989; Yin 2003). Validation occurs through triangulation (Hartmann et al. 2009). This means that data are collected from multiple sources, such as, for example, documents, observations, and action research experience at different times, in different spaces, involving different persons (Phelps and Horman 2010). During this process, new observations continually confront researchers, and confirm their understandings or present inconsistencies that challenge them (Phelps and Horman 2010). This interpretive method does not search for statistical generalizations, but builds theoretical understanding about a phenomenon by using observations in a particular place or time, such that it also helps understanding the same phenomena in other situations (Whyte 2011). The remainder of this section elaborates on conducted ethnographic-action research.

When starting this study, the research population was defined as utility reconstruction projects that take place in urban space. A sample of three real-life projects in which clients pioneered with 4D technology were purposefully selected. This sample accurately represented the research population; like any other urban utility project, the selected cases involved the reconstruction of street-level infrastructure and the construction of different cables and pipes. The first case encompassed the realignment of utilities in inner-city space. The project duration was about one year and involved a civil works contractor and utilities contractor. Construction activities took place on an inner-city intersection and adjacent bus platform. In this project, the authors implemented 4D models to support six coordination meetings. The second project involved the reconstruction of a 900-m sewer line in a residential area. The research team was involved during the planning phase and construction stage of this five-month project. During the construction stage, 4D models were implemented to support six meetings. Similarly, the third project involved the reconstruction of a 450-m sewer line in a residential area. The project duration was approximately seven months. A 4D model was developed together with the project team and implemented during five multi-stakeholder meetings. Table 1 descriptively summarizes the three cases.

During each case, the research team took the lead in developing and implementing 4D models. To this end, they used a 4D-based method (olde Scholtenhuis, Hartmann et al., in press) to support coordination processes. They collected practitioners' schedules, 2D drawings and sketches, and reformatted these into virtual 3D models and Gantt-charts. The resulting models were integrated into a 4D visualization. Feedback from stakeholders was used to continually improve and adapt the models to practitioners' needs.

Table 1. Descriptive Summary of the Three Cases

Project characteristics	Project 1	Project 2	Project 3
Main construction activities	Moving and replacing subsurface utilities	Reconstructing sewer line (900 m)	Reconstructing sewer line (450 m)
Data collection phase	Planning stage	Execution stage	Execution stage
Estimated duration	Approximately 12 months	Approximately 5 months	Approximately 7 months
Observed meetings	6	6	5
Collected artifacts	7 meeting minutes; 6 2D-maps of current project conditions; 2 phasing drawings; 1 surface level design; 2 design sketch utilities; 1 2D-CAD of surface level design	4 meeting minutes; 2 master schedules; 2 phasing drawings; 2 2D-CAD maps of current project conditions; 2 2D-CAD sewer and surface level design	1 meeting minute; 3 progress reports; 1 master schedule, 1 2D-CAD map of current project conditions; 1 2D-CAD sewer and surface level design
Involved stakeholders	Municipality: project manager, supervisor Civil works contractor: project manager Service provider: 5 work planners Utilities contractor: work planner	Municipality: project manager, supervisor Civil works contractor: project manager, work planner, site manager, consulting engineer	Municipality: project manager, supervisor Civil works contractor: project manager, site manager

Furthermore, the first author moderated parts of the coordination meetings by navigating through the 4D model on request of the stakeholders. To collect data, notes were made about how the 4D-models influenced mindful behavior, and meetings were tape recorded. All the data were assembled and analyzed with support of the qualitative data analysis tool *ATLAS.ti*.

The data analysis comprised open and axial coding (Strauss and Corbin 1990) steps. Open coding is a stage in the qualitative analysis process in which concepts are derived from empirical data in a grounded way. The authors first used open coding to identify actions and statements that described benefits and uses of 4D models. Axial coding then was used to relate these coded observations to the mindfulness principles.

In this study, axial coding was performed by relating observations to mindfulness concepts from measurement instruments such as the Safety Organizing Scale (Vogus and Sutcliffe 2007), Mindfulness Audits, and the Mindfulness Organizing Scale (Weick and Sutcliffe 2007). These instruments are commonly used to assess how established organizational cultures perform mindfully. However, because the coordination processes was observed at an operational level rather than on the organizational level, the existing mindfulness instruments were adapted. To this end, survey items were used that were part of the existing instruments to derive observable mindfulness constructs. This culminated in the overview presented in Table 2.

As a next step, the mindfulness constructs were used to identify instances of mindful behavior in the data. Therefore, the constructs from Table 2 were used to organize the coded actions and statements from the open-coding stage. This resulted in an overview of codes that instantiated mindfulness constructs.

The subsequent example illustrates how the coding process took place. In an observed meeting during Project 1, a stakeholder requested the 4D model and asked: "Can I watch the animation before next meeting? I will then try to identify conflicts or bottlenecks. This can help you to improve the schedule." First, this excerpt was labeled and the open code identifying possible obstacles was created to indicate that 4D created awareness of possible errors. During axial coding, the open code was allocated to 'detect construction process conflicts and try to understand them.' This, in turn, was categorized as a class of the mindfulness principle preoccupation with failure. Table 3 shows the amount of observed actions and statements that relate to the theoretically derived constructs of mindfulness to summarize the outcomes of the coding process.

Results

This section presents selected examples of mindful behavior that were observed during the three cases. The structure of the mindfulness principles were used to explain these empirical findings. The appendix contains a more detailed overview of these examples. It contains a table that presents and explains a selection of coded verbatim quotes that were extracted from the data.

Sensitivity to Operations

The three constructs from Table 2 that were observed and that related to sensitivity to operations were (1) trying to understand operations beyond one's own job, (2) building a clear picture from

Table 2. Breakdown of Mindfulness Principles in Observable Actions and Statements. Adapted from Three Resources: The Safety Organizing Scale (Vogus and Sutcliffe 2007); Mindfulness Audit and the Mindfulness Organizing Scale (Weick and Sutcliffe 2007, pp. 94–103)

Mindfulness principle	Observable actions based on theoretical mindfulness constructs
Sensitivity to operations	Trying to understand work processes beyond one's own job; building a clear picture of the current situation; paying attention to operations from day-to-day
Pre-occupation with failures	Looking for design/schedule conflicts and trying to understand them; investigating why the unexpected occurs and figuring out why expectations were not met; discussing mistakes to learn
Reluctance to simplification	Not taking anything for granted; challenging the status quo; deepening analyses to better grasp nature of the problems; expressing different views of the world
Commitment to resilience	Building response repertoires; having a number of informal contacts to solve problems; discuss alternatives to normal work processes; pooling expertise to solve problems
Deference to expertise	Value expertise over hierarchical rank; knowing who has the expertise to respond to situations

Table 3. Number of Observations Corresponding with the Mindfulness Constructs from Table 2

Mindfulness principle	Constructs representing related mindful actions and statements	Number of observations
Sensitivity to operations	Trying to understand operations beyond one's own job	7
	Building a clear picture from current situation	10
	Paying attention to operations from day-to-day	26
Pre-occupation with failures	Looking for design conflicts and accuracies and trying to understand them	6
	Looking for schedule/process conflicts and accuracies and trying to understand them	14
Reluctance to simplification	Deepening analyses to better grasp natures of potential problems	19
	Expressing and discussing different viewpoints and alternatives	3
Commitment to resilience	Building response repertoires	4
Deference to expertise	Value expertise over hierarchical rank	0
	Knowing who has the expertise to respond to situations	0

current situation, and (3) paying attention to operations from day-to-day.

Regarding the construct *trying to understand operations beyond one's own job* we observed that 4D models helped stakeholders to understand interfaces and relationships between the various concurrent construction processes. This was, for example, observed when a work planner in Project 2 used the 4D model to anticipate an operational situation onsite. The planner used the model in Fig. 1(a) to conclude that the work of the sewer construction crew did not conflict with the parallel process of sidewalk paving. Also, in Project 1, a service provider watched the 4D visualization and argued that it helped him to show that he could execute pipe drilling without disturbing operational bus lines in the public space.

Furthermore, it was found that existing schedules and 2D designs had to be significantly altered to develop a useful 4D model for coordination. Compared to the existing schedules, the schedules in 4D models, for example, broke down the main tasks in greater detail and modeled sequential relations between them. The resulting overview did not only facilitate automated schedule updates, but also helped stakeholders to *build clear pictures from current situations*. This was observed, for example, when the jobsite supervisor in Project 3 used the detailed models to better understand the

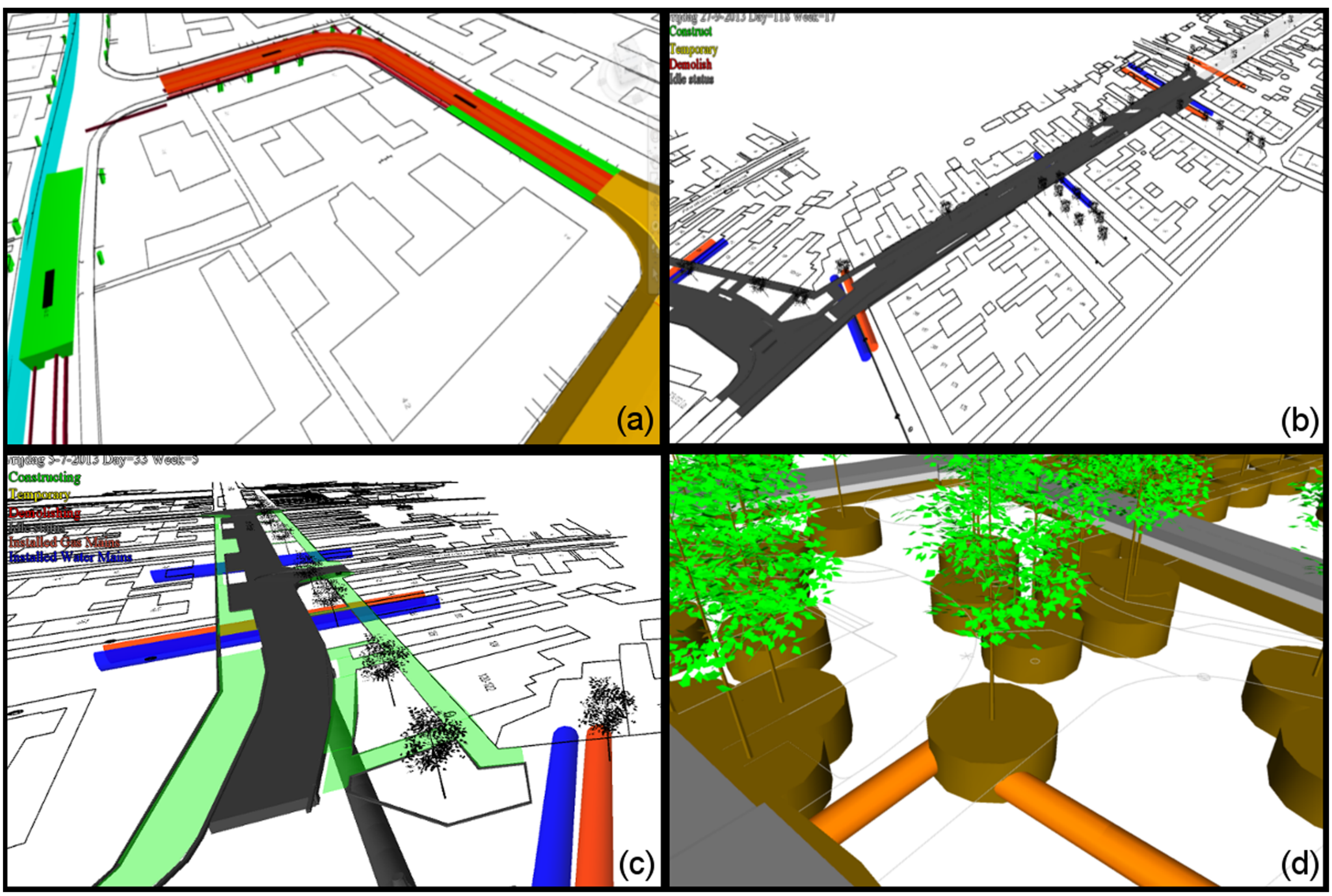

Fig. 1. Selected examples of 4D visualizations that helped to (a) understand interactions between sewer construction and paving operations; (b) build a clear picture of the paving progress of an intersection; (c) create attention on a day-to-day operational decision to alter a construction sequence of sidewalk and road paving; (d) look for a conflict between a designed gas network and the environment

situation onsite on a specific date. The supervisor used the visualization to verify whether an intersection (Fig. 1) was fully paved in a timely manner, and how the paving crew progressed at that given point in time (Fig. 1). Similarly, the leader of Project 2 built a picture from the existing project stage as he compared the project status that was modeled in 4D with the actual paving activities onsite.

Besides understanding ongoing construction processes, the development of 4D models allowed stakeholders to visualize virtually every other moment on the project's timeline. Such *attention to operations from day-to-day* was observed in Project 3, when its manager watched the 4D process visualization in Fig. 1(c) to understand why he deviated from his common sequencing routine a few weeks earlier. He explained that the visualization surprised him because it showed that he paved the road deck before constructing the side walk, whereas he normally did this the other way around. Stakeholders in the first project also paid attention to operational detail when they argued that a more sophisticated 4D model was needed to visualize utility construction work realistically. The water supplier, for example, required that the 4D model differentiated more clearly between the distinctive installation methods for pipes and cables.

Pre-Occupation with Failure

The second principle investigated was pre-occupation with failure. This investigation found instances related to the theoretical mindful constructs looking for design conflicts and trying to understand them, and looking for schedule/process conflicts and trying to understand them. A discussion of a selection of observed examples related to these constructs can be read subsequentially.

First, instances where 3D-design integration and development of 4D-process visualizations were identified to allow practitioners to *look for design conflicts and to better understand them*. In a meeting during Project 1, for example, a service provider noticed that the 4D model did not adequately locate designed utilities in a combined trench. Similarly, the project's utility contractor watched a 3D view that integrated the designs of an urban planner and gas network engineer. He identified a design conflict between gas pipes and tree roots [Fig. 1(d)], and listed the conflict for closer investigation.

Furthermore, the projects' stakeholders argued that they could use 4D process visualizations to *look for construction schedule/process conflicts and to try to understand them*. An observation from Project 1 illustrates this. During this project, a service provider that watched the 4D visualization in Fig. 2(a) stated that utilities [marked by circle in Fig. 2(a)] were not properly and timely removed before the scheduled start of a tunnel construction. A 4D model also was used in Project 3 to identify schedule inaccuracies. In this study, the visualizations showed that sewer construction activities started although soil layers were not yet excavated. The project manager looked at this visualization in retrospect and

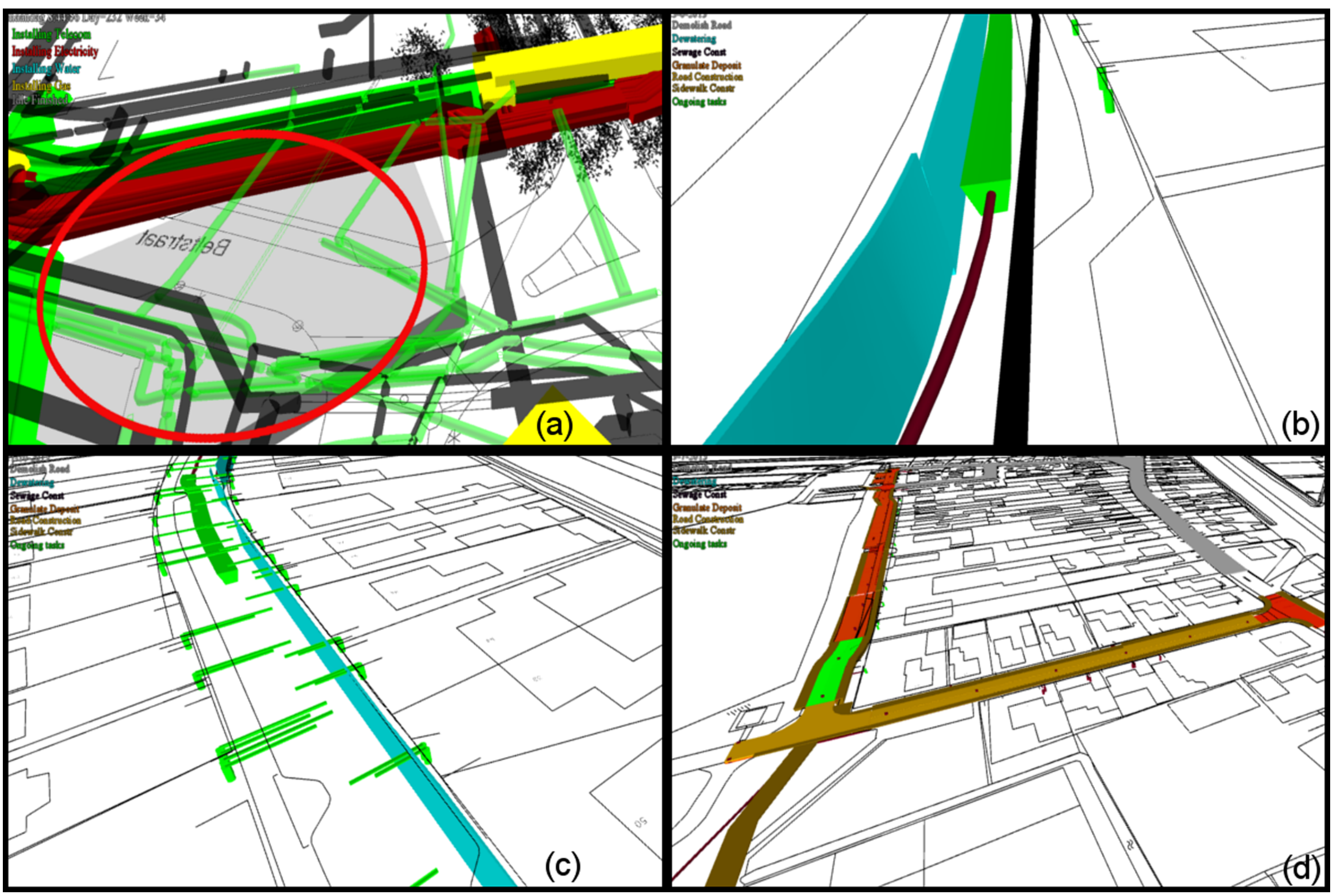

Fig. 2. Selected examples of 4D models that helped to (a) look for a process conflict between utility removal and a tunnel construction; (b) deepen understanding about dewatering installation and the demolition of old sewer pipes; (c) discuss different viewpoints about sequencing sewer line and branch construction; (d) extend response repertoires by evaluating the impact of a delay on paving processes

explained that this unrealistic situation was not formalized in the schedule properly, and that this sequencing problem was solved onsite.

Reluctance to Simplification

The third principle visible in 4D-supported coordination was reluctance to simplification. The subsequent selection of observations relates to the theoretically-derived codes deepening analyses to better grasp nature of potential problems, and expressing and discussing different viewpoints.

The greater detail captured in 4D models stimulated stakeholders to *deepen analysis and to better grasp the nature of potential problems*. Surprisingly, this deepened analysis was often not caused by the content in the 4D models, but by their shortcomings and omissions. Practitioners often argued that the 4D models, which were based entirely on their manual designs and schedules, represented their scheduling logic more accurately when modeling a few additional significant design objects or schedule tasks. During Projects 2 and 3, for example, stakeholders requested the research team to model details such as positioning of dewatering installations, removal of the old sewer, construction of the new sewer lines [all visible in Fig. 2(b)], and the working direction of pavers. Furthermore, a manager in Project 3 tried to obtain a comprehensive understanding about the scheduled construction work by requesting the research team to model sewer construction processes in a more detailed time scale than he initially did himself when developing the original schedule.

Two other instances of observed reluctance to simplification related to the mindfulness construct *expressing and discussing different viewpoints*. The work planner of Project 2, for example, watched the 4D visualization and explained that he had two alternative sequences for the installation of sewer line branches; he either installed them before [as in Fig. 2(c)] or after construction of main sewer lines. After watching the visualization, he elaborated on these two strategies, and explained that the latter alternative is often chosen in situations like Project 3. Further, the work planner in Project 2 explained that the 4D models could help his team align viewpoints by visually inspecting upfront whether their construction plans were commonly understood and agreed upon as feasible.

Commitment to Resilience

In relation to the principle commitment to resilience, it was observed that 4D models *extend stakeholders' response repertoire*. In Project 2, for example, 4D was used during a planning meeting to increase project knowledge by developing an alternative pavement strategy on-the-fly. The first author visualized an alternative paving process, and the work planner subsequently reflected on it by arguing that the visualized option would help prevent heavy weight construction traffic that would deform newly paved road surfaces.

During Project 2, the work planner further argued that 4D could help him anticipate potential delays. His project, for example, was confronted with a delay after his team discovered that the load-bearing capacity of an existing soil layer appeared to be critically low. They therefore had to replace the soil layer completely, causing a few weeks delay. The work planner asked the research team to evaluate the impact of this delay by updating the schedule and visualizing the anticipated onsite situation on a future milestone date [Fig. 2(d) depicts this delayed situation].

Deference to Expertise

No examples of the fifth mindfulness principle, deference to expertise, were observed in the 4D-supported cases. It seemed that the influence of 4D on constructs, such as value expertise over hierarchical rank and knowing who has the expertise to respond to situations (constructs from Table 2), were difficult to observe and inconclusive. The next section reflects upon the results, and also addresses this last surprising finding in more detail.

Discussion

This study confirms the hypothesis that 4D implementation enables mindful behavior in utility reconstruction works. The use of 4D models allows stakeholders in utility projects to follow principles of mindfulness. The findings show that development and implementation of 4D enabled practitioners to schedule more formally and in greater detail. This sensitized them to operational processes. As the tool allowed them to visually grasp and discuss interfaces between parts of the design and master schedule, it also enabled them to become pre-occupied with errors and inaccuracies. Next, 4D helped stakeholders to be reluctant to simplify because it supported the detailed modeling and discussing of construction plans. Further, evidence was provided that showed stakeholders can commit to resilience when using 4D to evaluate alternative schedules. These findings are summarized in Table 4.

The outcomes of this research contribute to the body of knowledge about 4D implementation. Earlier explorative research in this domain primarily discusses the special purposes and benefits of 4D (e.g., Koo and Fischer 2000; Heesom and Mahdjoubi 2004; Hartmann and Fischer 2007; Russell et al. 2009). Although this literature can be used to generate a list of specific benefits and 4D purposes, it does not provide knowledge about how 4D impacts dynamic coordination processes.

This study fills this gap. It is first to synthesize the mindfulness perspective and 4D implementation literature to systematically evaluate the impact of 4D on mindful behavior during utility reconstruction. Existing studies on mindfulness in flight deck crews (Weick and Roberts 1993), aeronautics (Casler 2013), hospitals (Weick and Sutcliffe 2007), and construction organizations (Mitropoulos and Cupido 2009; Brady and Davies 2010) explain that increased mindfulness, in turn, helps to effectively cope with unwanted situations. In this light, findings in this study suggest that utility project stakeholders that use 4D are better able to anticipate and contain coordination issues. Ultimately, this positively influences performance.

This study acknowledges that project performance and project success are complex phenomena that can neither be reduced to coordination nor to mindfulness. Although the correlation between 4D-supported mindfulness, coordination, and performance is explained, this study does not attempt to reduce project performance solely to coordination.

Like any other study, this research is not without limitations. Challenges that should be addressed in future research are discussed subsequently. First, the empirical nature of this study allowed comprehensive investigation of the dynamic interaction between 4D model development, implementation, and coordination. Analysis of the data set revealed detailed chains of events that show that 4D triggered mindful behavior in the observed meetings. As such, this study provides a stepping stone in the generation of knowledge about the causal relation between 4D and mindfulness. It is nevertheless acknowledged that coordination processes are influenced by multiple interplaying factors. Consequently, the possibility that factors other than 4D use also influence mindful behavior is not excluded. The influence of other factors should be minimized when investigating the attributability of mindfulness benefits to 4D even more closely. It is therefore recommend that 4D and mindfulness

Table 4. Summary of Selected Examples of 4D-Supported Mindful Behaviour

Mindfulness principles	Mindfulness-enhancing actions in 4D-based coordination
Sensitivity to operations	*Looking beyond own operations*
	4D visualizations helped practitioners to understand simultaneously executed construction activities
	4D showed how construction activities interacted with processes in surrounding public space (e.g., traffic flows)
	Building a clear picture from current situation
	Practitioners using 4D had to explicate and formulate detailed designs and schedules, increasing their detail of process understanding
	4D was used to assess the onsite progress at time of construction meetings
	Paying day-to-day attention for operations
	4D was used to explain schedule deviations
Pre-occupation with failures	*Enhanced attention for conflicts and inaccuracies*
	4D allowed detection of conflicts in design of utilities and sewer networks
	4D supported detection of errors and inaccuracies at process plan interfaces
Reluctance to simplification	*Deepened analysis*
	4D modeling required explication of significant design and process details
	Omissions in 4D models resulted in focus on construction process details
	Expressing different viewpoints
	4D caused reflections on details that are taken for granted in manual scheduling
Commitment to resilience	*Enhance response repertoires*
	4D facilitated creation of schedule alternatives
	4D was supposed useful in evaluating progress delay
Deference to expertise	No observations were made in relation to use of 4D and this principle

be studied in a controlled setting. Future research could, for example, use an experimental setup that compares mindfulness in 4D-supported (intervention) groups with mindfulness in manually coordinated (control) groups.

The second limitation is that this study did not identify a comparable amount of instances for each of the mindfulness principles. Specifically, behavior primarily related to the three principles for anticipation (i.e., sensitivity to operations, pre-occupation with failure, and reluctance to simplification) were identified and fewer instances of containment-related behavior were observed. Although it was initially assumed that 4D enabled network designers and planners to visualize their knowledge, and empowered them during coordination discussions, this deference to expertise behavior was difficult to observe and inconclusive in this study. This could be because expertise was consulted outside the coordination meetings that were observed. Alternatively, the limited amount of deference to expertise-related observations could be explained by the argument that this mindfulness principle applies less to 4D-based construction coordination than others. It is recommended that future research investigate 4D usages outside official meetings to find out how 4D visualizations empower experts and support deference to expertise.

The third limitation relates to the use of utility work as cases to demonstrate the influence of 4D on mindfulness and coordination. Although this population was purposefully selected because of its coordination complexity and the potential advantages it can receive from 4D adoption, the findings also may be generalized to the construction domain as a whole. To validate the applicability of these claims to projects in the broader civil engineering domain, conducting similar research in more infrastructure projects of different scales and types is suggested.

Fourth, this research involved three utility reconstruction works that pioneered with 4D implementation. Because this tool is new to the domain, it was not expected to be flawlessly adopted. The authors, therefore, took the lead in developing and implementing 4D models. This resulted in a hybrid practice (Whyte 2011) of manual and 4D-supported coordination. Although the findings show that 4D has potential to enhance mindfulness in coordination, practitioners need to develop visualization skills to benefit from this advantage. Literature provides various frameworks and methods that allow practitioners to learn how to visualize collaborative construction project information (e.g., Kuo et al. 2011; Boton et al. 2013; olde Scholtenhuis 2015). Once practice uses these frameworks to establish more mature 4D coordination practices, it is recommended that future research obtain a more detached role and repeat this study to make more definitive claims about the impact of 4D on coordination.

This discussion ends with two practical recommendations. First, implementation of the mindfulness lens shows that the mindful coordination of project stakeholders can be supported by 4D tools. By using 4D to formalize and integrate construction plans, stakeholders enhance anticipation skills as they have more attention for details, conflicts, and operations. It is recommended that practitioners implement 4D to analyze projects plans in more detail, to enhance action repertoires, and, eventually, to deal with coordination conflicts effectively.

Second, inner-city projects often take place within constrained construction space while simultaneously facing significant public pressures and tight deadlines. These projects, therefore, need to be coordinated mindfully to avoid or mitigate overruns. It is suggested that utility construction practices use the observable mindful behavior constructs from Table 2 and instances of 4D-enhanced mindful behavior as a guide to establish such mindful practices.

Conclusions

Utility project stakeholders face significant challenges to manage their subsurface infrastructure projects. Although literature shows that 4D tools can be used for various project management purposes, the amount of 4D-supported projects in practice is limited. In addition, the nature and scale of the different 4D studies differs widely. From a research methodological viewpoint, it is therefore difficult to statistically evaluate the impact of 4D. To date, literature also enumerates various benefits of 4D, but does not holistically evaluate how 4D impacts creative and dynamic coordination processes. To address this, this study's objective was to test qualitatively how 4D influences utility coordination. Therefore, mindful organizing as a lens to systematically test the relation between

Table 5. Selected Examples of Empirically Observed Mindful Behaviour

Construct	Data excerpt of mindful behavior observation	Explanation of observation
	Sensitivity to operations	
Trying to understand operations beyond one's own job	Referring to the green objects in Fig. 1(a) that visualize sewer construction and paving: "At this place, you can see paving and sewer construction nicely aligned. You see that the sidewalk is under construction, while we (simultaneously) start with sewage installation"	A work planner in Project 2 elaborated how the 4D model demonstrated interactions between the pavement crew and sewer installation crew. The model showed him that the activities were synchronized properly
	"At a certain moment, (when your process requires) pneumatic moling to cross the road's subsurface, (4D clearly visualizes) that the bus traffic remains in operation"	The service provider in Project 1 watched the 4D visualization and argued that 4D helps to show how his work interacts with processes in the public space
Building a clear picture from current situations	Referring to grey area at the bottom left of Fig. 1(b): "What's the date? (in the visualization it was 27 September). Well, it (the pavement) was indeed done till there, and the intersection is finished as well"	The increased detail in the design model and schedule allowed the jobsite supervisor in Project 3 to create a clear picture of the planned status at a specific date, and to compare the schedule with the existing situation onsite
	"This (model visualizes) the as-planned situation. The whole road should be finished by this Friday. Currently, we should be working on the parking places, right? And we need to start with the road this week"	The leader of Project 2 built a picture from the existing project stage as he verified the construction status onsite
Attention to operations from day-to-day	Referring to the road (gray) and sidewalk (green) in Fig. 1(c): "Yes, the road must have been paved completely by then (next week). Oh. Not. Only partly (. . .) Normally we first complete the sidewalks, so now I look at the schedule again, and wonder why we first constructed the main road instead (. . .) Probably because the road had to be in operation first"	4D triggered and guided discussions about operational changes in Project 3. The project manager explained how the visualized original plan differed from the activities onsite
	"You cannot install a piece of cable, stop, and continue, so that is a large difference with gas or water . . . . So let's (visualize) this	The water company in Project 1 commented on the detail of the 4D model and started discussing about the distinctive construction methods for pipes and cables
	Pre-occupation with failure	
Looking for design conflicts and trying to understand them	"Some pieces of the gas and electricity (network) that should have been aligned actually have some differences. I noticed that the cables and trenches are not co-located at points where this is actually necessary . . . Probably, you did not align the reference points of the different (3D models) . . . "	During Project 1, service providers discussed the alignment of designs. One stakeholder then argued that utilities had to be located closely together in a combined trench. This was not yet visible in the 4D model
	Referring to the model-view that contained a tree-design plan and the designed gas infrastructure network [Fig. 1(d)]: "Watch over there, at the location of these two trees. We are also connecting gas pipes right there, so this situation will not be possible"	While zooming in on the integrated overview, the utility contractor in Project 1 identified a conflict
Looking for construction schedule and process conflicts, and trying to understand them	Referring to the existing cables (green) and a tunnel (light grey) in Fig. 2(a) (marked by the red circle): "Utilities have not been removed over there! The tunnel is already under construction while the cables are not yet gone. That is not possible; they first have to be dug up"	A service provider in Project 1 noticed that utilities were not properly and timely removed in the model. He noticed that this would cause a conflict with other construction activities
	"This (visualization) might seem strange, but we have to make a temporary connection in the middle of this sewer line. So, although the trench will be excavated in parts in reality, we scheduled the construction of the whole line at once. This explains why all sewer pipes are visualized as under construction, while a part of the trench is not yet modeled as excavated. I did not include this detail in my schedule"	The project manager in Project 3 found a scheduling error as the 4D model showed that sewer construction activities already started, whereas the top soil layer was not even excavated
	Reluctance to simplification	
Deepening analysis to better grasp the nature of potential problems	"If you want to improve the visualization of our initial schedule, you actually need to model the (hourly) production rate of construction tasks, so you can visualize the daily process in minutes or hours. We could then visualize in sixteen seconds (in greater detail) what happens to the sewer during a specific day. You will see this work progressing while pavement activities proceed and cover the sewer"	The manager of Project 3 suggested including more detail in the model to improve the process visualizations accuracy
	Referring to the old sewer (black) and constructed sewer (green) in Fig. 2(b): "It will be best if you can see the existing sewer already at the start of the visualization. And then, if you (. . . run the visualization), you will see this sewer in black or grey. Then, the trench will occur, and if the trench is gone, the existing sewer is still there (. . .) or a new sewer is installed"	A manager in Project 2 requested to increase the detail of the schedule by adding tasks such as the removal of the old sewer and installation of the new sewer. Surprisingly, the original manual schedule did not contain these details either

Table 5. (*Continued.*)

Construct	Data excerpt of mindful behavior observation	Explanation of observation
Expressing and discussing different viewpoints	Referring to the cylinder shaped green sewer pipes and their branches in Fig. 2(c): "Look, these branches will usually be installed as soon as the sewer main is buried. Other projects may schedule branch installation before construction of the mains (just like in the 4D visualization). But in residential areas, you usually try to build the mains first so that people can use their sanitary again"	The work planner of Project 2 explains an alternative for the construction of sewer line branches
	"For the project team, (4D would offer a way to) go through the initial plan once more to check whether it is good, or whether we have completely different views on how it should be realized"	The work planner in Project 2 argues that the 4D model could help to visually check whether their construction plans are feasible
	Commitment to resilience	
Extending response repertoires	"I think they (the crew) will start paving at this end of the street, because starting at the other end would mean that heavy equipment drives over the newly paved street continuously. If you would start at this side, however, you will not do this and reduce damage to your own pavement"	The work planner in Project 2 elaborated and reflected on an alternative schedule for the paving activities
	Referring to the light and dark brown driving lanes in Fig. 2(d): "What you can do when you run three days behind schedule? Just like we did a moment ago: you can evaluate whether your project is ready before a deadline, for example that week. You can find out whether we get it done in time. And in the visualization, you can actually see this really nice: the road should be ready, and it is"	Stakeholders in Project 2 provided an example of where 4D could help them anticipate potential delays, and to come up with mitigation alternatives

Note: Column 2 and 3 represents instances of the mindfulness constructs in column 1.

4D and mindful coordination in utility reconstruction works was introduced.

To achieve this objective, 4D models in three real-life urban subsurface utility projects were implemented and their impacts studied by following an ethnographic-action research methodology (Hartmann et al. 2009). While engaging in six, six, and five 4D-supported meetings, data were collected by taking notes and by tape recording. Outcomes show that development and usage of 4D allows stakeholders to follow four mindfulness principles. For one, stakeholders' sensitivity to operations and reluctance to simplification was enhanced because 4D development required them to explicate scheduled operational processes, to schedule in greater detail, and to analyze project interfaces. In addition, 4D increased pre-occupation with failure by making stakeholders attentive to potential errors and inaccuracies in schedules and designs. Practitioners also increased commitment to resilience by using 4D schedules to evaluate alternative construction processes, which consequently allowed them to enhance their action repertoire and to develop delay mitigation solutions. No examples that indicated that a relation exists between 4D and the fifth mindfulness principle, deference to expertise, were found.

This study contributes to literature as it is the first in combining the mindfulness perspective with 4D implementation literature to show that usage supports mindful behavior in coordination. Because efficient coordination has a positive influence on performance, these findings contribute to debates about the process impact of 4D on project performance. For future research, it is suggested that mindfulness in 4D-supported cases be compared with mindfulness in manually-coordinated cases to obtain additional evidence on the causal relation between 4D and mindful behavior. It also is suggested that whether and why some mindfulness principles apply to 4D-based coordination more than others be more thoroughly investigated, and that the impact of 4D tools on the mindful coordination of other projects in the civil engineering domain be explored. Furthermore, consecutive research should aim to compare mindful coordination in organizations that established more mature 4D practices. This study recommends that practitioners use 4D when they analyze projects plans in detail and attempt to enhance resilience of their plans. Finally, practitioners are encouraged to use the constructs and examples of this study as a yardstick to establish mindful coordination practices. Eventually, this may decrease the likelihood that stakeholder alignment issues occur, reduce the amount of overruns, and improve coordination and performance.

Appendix

Table 5 hierarchically decomposes the mindfulness principles into theoretically derived mindfulness constructs and a selection of verbatim quotes.

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