Enhancing Mindful Coordination in Fragmented Utility Construction Practices

*By developing, implementing and evaluating
Virtual Design and Construction Models*

Léon olde Scholtenhuis

Propositions accompanying the dissertation:

Enhancing Mindful Coordination in Fragmented Utility Construction Practices
By Developing, Implementing and Evaluating Virtual Design and Construction
Models

By Léon olde Scholtenhuis
Defended on October 22nd, 2015

1. Construction project studies obtain benefits from pragmatically using the High Reliability Organising lens (Chapter 2).
2. End-user perspectives are crucial in developing feasible Virtual Design and Construction tools (Chapter 3).
3. VDC models need to be systematically developed and implemented to support the scoping, formalizing and synchronizing of utility construction plans (Chapter 4).
4. VDC tools, such as 4D, enhance mindful behaviour in utility construction coordination (Chapter 5).
5. Tension regarding Construction Management's scientific footing will remain, since CM-scholars unlikely achieve agreement on a monodisciplinary approach.
6. Scientists should keep thinking about the societal consequences of their work by asking the "so what?" question.
7. Tax payer's money is justified particularly when research outcomes do not provide immediately implementable solutions and magic bullets.
8. A science focused on publishing journal papers induces a tendency toward more communication about research, rather than research producing new outcomes.
9. Presenting research findings such as "construction needs better collaboration and more trust" snoozes any constructive debate.
10. Privatization policies have been conveniently reluctant to look beyond short term profits.

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FRAGMENTED UTILITY CONSTRUCTION PRACTICES

BY DEVELOPING, IMPLEMENTING AND EVALUATING
VIRTUAL DESIGN AND CONSTRUCTION MODELS

DISSERTATION

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Prologue

City skylines depict many of the great projects that characterise the construction and civil engineering industry. The impressive bridges, lively quays, busy railways, iconic houses and remarkable high rises evident on such skylines are, however, not the only elements that shape the urban landscape. One absent, yet relevant, element comprises of the vast amount of subsurface utility networks that provide 24/7 services to all premises in urban space. As the age of these networks dates back to over 100 years, they all require reparations and replacements. These construction activities not only seclude citizens temporally from services, but also closedown busy streets and sidewalks, consequently blocking access to public spaces and buildings. Not surprisingly, this public burden results in utility projects being watched closely by local politics and media.

I used my PhD research as an opportunity to explore this context of utility construction and the fascinating dynamics between the stakeholders. I developed and implemented Virtual Design and Construction (VDC) models to test how they could impact on utility construction coordination. This thesis reports about these research efforts and formally concludes my graduate study. I hope reading my work stimulates the readers' thoughts about the need to streamline utility construction and the potential of VDC to support this objective.

Working in the utilities domain made me accept two ironic consequences. One was being nicknamed 'the sewer guy' by friends. Sometimes, this pointed at my seemingly trivial and boring role. I hope I convinced them now how lively the utilities sector can be and how much effort is needed to professionalise it further. Second, I developed a professional deformation characteristic that may be best referred to as 'utility tourism'. When visiting cities, I made a habit out of looking into utility trenches and taking pictures of the remarkable solutions that were created temporally to support existing utility networks that cross the jobsite. This behaviour may look strange, but it definitely provided the most surprising and colourful images.

While writing this prologue, I find myself on the brink of receiving my PhD and can use this moment to reflect and to express how I experienced my PhD-life at the University of Twente. I can say that I look back at a great period in which I had much flexibility and freedom. I visited construction sites, attended congresses, met dozens of companies, followed classes and developed teaching skills. Besides formal PhD

tasks, I received also the chance to develop professionally by organising our CiT department outing; presenting at the UT open days; and, organising a one-week International Academic Writing School.

Stories of peers; the Economists' 'disposable academic' article (December 2010) and many PhD-comics are not always very positive about doing a PhD. Their bottom line seems to be that it requires extreme hard work, provides little reward and, often, takes much longer than anticipated. Looking back, I agree that doing a PhD indeed requires commitment. I agree less, however, with the other two statements: PhD work can be great fun and very rewarding as it provides a chance to deeply understand and improve practice. Furthermore, I strongly believe that finishing a PhD timely also is a matter of wisely spending time off – besides having good supervision and clear focus. I spent plenty of time playing tennis or visiting the Alps to teach snowboarding. These hobbies consumed time which I compensated by working a little longer during my days at the office. This work-life balance helped me to switch effectively between studying with focus, whilst also being able to detach mentally and positively from it.

I would not have been able to deliver this thesis without the support of various organisations. I am grateful to them all and would like to mention some in particular. I thank Stichting Pioneering for providing resources that allowed me to do this research in the first place. I also acknowledge Gemeente Enschede, Gemeente Hof van Twente, Gemeente Hengelo, Van Gelder, TWW, NTP Infra, Reef Infra and ProViel for allowing me to study their work practices.

I would further like to acknowledge my examination committee for the time and effort spent while reviewing and commenting on my work. Specifically, I would like to thank my promotor André Dorée who in the first instant invited me to become PhD-student. André, I found it very comfortable working with you always. At times, I visited to your office to report about an exciting observation, or just to reflect on a personal matter. These short dialogues often were inspiring. I also have a high regard for the way in which you provided feedback and comments. Your critique was always brought forward in a constructive and motivating way, no matter how critical your comments were. I enjoyed your company and learnt about 'research in action' during the multiple times we went out for a 'fact finding mission' to authorities, contractors, utility companies and abroad.

This all would not have happened if my daily supervisor, Timo Hartmann, had not suggested me as a potential PhD candidate. Timo; I realise that already you have been

my major now for eight years (including my undergraduate study). Our collaboration was mostly smooth and often pleasant. You gave me inspiring research ideas; helped me to improve my writing skills significantly; and introduced me to your international research network. I admire you for your work ethos and your drive to develop the construction management as scientific discipline further.

The surrounding context of other good colleagues also made my PhD years joyful. It was an exciting time with the colleagues from HT3.00. We had many discussions and good fun, both in and around the office. I owe a special word of thanks to a few: Jacqueline Nijhof and Yolanda Bosch - dear ladies -thank you for the pleasant coffee breaks and great logistical support that you have given me in the past few years. Frank Bijleveld, Julieta Matos 'Castona', Hendrik Cramer, Frederick van Amstel, Alexander Vasenev, Michiel Loonen, Seirgei Miller, Niels Vossebeld, Diruji Dugarte, and Marc van den Berg; you became good friends. The gatherings and amazing excursions (with many of you) to Madrid, Berlin and Hamburg will stay in my mind for a long time!

I also appreciate a lot the many good moments that I had and have with all my friends from outside academic life. The pleasant day trips, terrace drinks, sports events and holidays have given me plenty of energy to complete this PhD. Dear, friends, thank you all!

As a last word of big-thanks I turn to my family: Mam, Pap; you raised me wealthy and taught me to preserve some modesty always. I am confident that your perseverance, curiosity and inquisitiveness brought me to where I am now. Thanks also to my brother Glenn. It is always nice to see you again back home to have good discussions, simply enjoy a drink, or go out for a trip. Finally, my life companion - Sophie. You are in my life already for eight years. I love every moment being with you and am indebted to you for all the support and room you give me to work, sport and go abroad. I am looking forward to the moment we can be living together.

Summary

Institutional and technological developments in the utilities sector have led to: 1) a change in ownership of utilities from a few public bodies to a myriad of public *and* private organisations; 2) added infrastructure on the existing subsurface; 3) increased numbers of clients and contactors involved in reconstruction works; and, 4) scattered the formal responsibility for a smooth, timely and cost-efficient execution of construction work. As a consequence project level coordination in subsurface utility construction has become much more challenging. Nowadays, coordination processes involve multiple organisations that participate during distinctive moments in the project life cycle and when, often, there is no single organisation that can enforce a hierarchical alignment of inter-related reconstruction plans.

Nevertheless, stakeholders' construction plans still need to be integrated to successfully accomplish reconstruction work. This process becomes more complicated when authorities also impose tight deadlines and spatial constraints on construction activities in urban spaces. It is increasingly difficult to cope with these coordination challenges in today's paper-based 2D design and scheduling practice. These work practices offer limited possibilities, for example, to analyse project interfaces visually; anticipate process conflicts in advance; and, to develop and evaluate design and schedule alternatives quickly.

While coordination complexities have grown, Virtual Design and Construction (VDC) systems have become available more widely. These systems offer the potential to support paper-based coordination processes by capturing construction knowledge to visualise and simulate construction processes. In construction projects, visualisations, such as 4D CAD, are used, for example: to explicate construction plans; to predict schedules; to rehearse construction projects virtually; and, to detect potential conflicts. However, despite the widespread availability of these tools, as yet, they do not seem to be well-tailored to the needs of the utility domain. Consequently, the utility sector cannot reap the benefits from VDC systems. This PhD-study focuses on VDC systems that enhance reliable construction of utilities to address this point with the specific aim to:

Enhance reliable construction of subsurface utilities by developing, implementing and empirically testing VDC systems to coordinate multi-stakeholder construction processes.

An ethnographic action research strategy was employed to achieve the research goal. This methodology combines ethnography with action research to gain in-depth

knowledge about a domain of interest while, at the same time, conducting an intervention. I studied five projects for periods that ranged between six to twelve months. I observed over thirty meetings that took place prior to construction activities and on-site and also collected more than 350 pictures; 20 meeting minutes; 21 2D CAD drawings; and, nine scheduling documents. I took an active role in developing some 70 4D CAD files which were then implemented in eighteen meetings. The qualitative analysis of this data led to: explicated concepts that are used during utility project coordination; identified and validated required steps for development of adequate VDC-systems; and, systematically identified process-benefits that show how VDC-systems impact reliable construction of utilities.

These research activities were conducted to achieve three sub-objectives:

- *To enhance understanding of how end-user perspectives can be involved in development of VDC systems.* This was achieved by ethnographically observing coordination practices in a utility project; deriving and testing a domain-ontology using gained knowledge; and, by explicating the steps that were followed during this process.
- *To increase insights in how VDC models should be implemented to adequately support utility coordination processes.* This was done using action research in four real-life cases. I developed an empirical method for using 4D models in utility projects, and validated it through three design iterations and observation of 4D benefits.
- *To evaluate how VDC models impact mindful utility coordination and project performance.* To reach this goal, I collected data about the interactions with, and discussions about, 4D models that were used during three of the previously studied projects. This data was analysed by using the mindfulness principles from High Reliability Organising (HRO) literature to study the process impact of 4D, and to predict its influence on coordination and project performance.

Altogether, the research activities delivered four main scientific contributions, as follows:

A reflection on the adoption of HRO lens to study performance in the construction management domain: The HRO lens contains five mindfulness principles that help evaluate to what extent processes anticipate effectively and contain unwanted disturbances and events. Anticipation and containment are essential tasks in coordination. HRO can therefore be used as a lens to study coordination processes and to investigate how VDC systems influence these. However, a reflection on the debate surrounding the adoption of this lens, and similar new theoretical concepts in the construction management domain,

shows that reductionist perspectives focus on construction ‘being not a high reliability organisation’. Therefore, it is argued that, sometimes, construction management is not suited as a domain for HRO-studies. An alternative pragmatic perspective focuses on the practicality and productivity of a theory, rather than its permissiveness, regarding the domain. This study helps researchers avoid reductionist categorisation disputes by outlining these distinct viewpoints. Thereby, it contributes to the overall research goal by providing a rationale to study how VDC systems impact mindfulness in coordination and performance.

An approach that spells out steps that are necessary to involve end-user perspectives while developing domain-specific knowledge bases (ontologies) for VDC systems: This approach complements existing desk-based research ontology development methodologies by showing how end-users can be engaged. The approach consists of the following main steps: 1) conducting ethnographic observations; 2) exploring, organising and visualising domain specific concepts and relation; and, 3) developing and implementing a domain-ontology. This inductive approach empirically captures domain-specific knowledge, and supports the development of feasible VDC systems that use this knowledge as a basis. The method can be followed stand-alone as bottom-up approach to ontology development; and can additionally help to validate the end-user-fitness of existing ontologies. The knowledge obtained while applying the method to one case in the utility domain provided another step in achieving the aim of this PhD-study since it created the knowledge base for the VDC models that were developed in successive cases.

An empirically developed method that shows how to develop and implement VDC systems, such as 4D models, to support utility coordination processes: This method was developed during action research in four utility cases. It consists of three phases, these are: scoping, formalisation and synchronisation of construction plans. The models that were developed by following the method helped to detect potential design conflicts, elaborate schedule omissions, understand project interfaces and conduct delay analysis. These examples validate and demonstrate the usefulness of the 4D CAD based coordination method; extend the application domain of 4D VDC tools toward more smaller sized infrastructure projects, such as utilities, and also complement an empirical implementation case to more recent technical 4D studies. All in all, the introduced method and its observed benefits provide the next step on the way to achieving more reliable construction of utilities.

A structured evaluation of the process impact of 4D models on utility coordination and performance:

The mindfulness principles from the introduced HRO lens were mobilised to analyse and explicate the benefits of VDC systems for coordination of utility works. Empirical evidence shows that VDC system elements, such as 4D models, provide a way to behave more mindfully, i.e. to sensitise oneself to planned operational processes; to become pre-occupied with potential process disturbances and errors; to be less tempted to simplify interpretations of reality; and to be more committed to resilience. Furthermore, the study confirms that HRO provides a pragmatic and valuable lens to study processes organisations that are different from classical high-hazard organisations in HRO-literature. In addition, it demonstrates that HRO's domain of application could be enlarged by including studies of processes in multi-organisational project contexts. Finally, the findings contribute to technology implementation literature by showing how the lens serves as a structured framework to guide qualitative assessment of VDC tools.

This last deliverable provides the final contribution to the research goal. It concludes the research efforts on VDC system development, implementation and its empirical evaluation. To continue exploring the development and implementation of VDC systems, consecutive research efforts should extend the sample of cases to generalise findings about the influence of VDC tools on coordination. It is expected that this is possible once practitioners develop more explicit scheduling practices and more mature visualisation skills. In addition, future research could aim to explore how the mindfulness lens supports development, implementation and evaluation of VDC tools that are similar to 4D CAD. It should be acknowledged that VDC systems are just one way to enhance project level coordination in utility construction. Additional governance and project management research is needed to develop a more comprehensive portfolio of tools and methods that help enhancing reliable construction of utilities.

In summary this thesis demonstrates that: 1) tailored VDC systems support performance along mindfulness principles in utility works if: 2) practitioners explicate scope, formalise and synchronise their construction plans by using VDC systems, such as 4D; and, if 3) developers of VDC models involve end-user perspectives when developing the knowledge base underlying such systems.

By demonstrating that end-user tailored VDC systems could support mindful behaviour and, thus, help to anticipate and cope with unwanted events, I believe strongly that VDC systems reduce the likelihood of cost and schedule over-runs and re-

planning. Eventually, this provides great potential to enhance coordination, project reliability and performance.

Nederlandse samenvatting¹

De nutssector heeft in de afgelopen decennia een aantal belangrijke veranderingen doorgemaakt. Liberalisering en privatisering hebben het institutionele speelveld van netbeheerders, operators en aannemers op de schop gegoooid. Verder ontstonden in stedelijk gebied nieuwe infrastructuren zoals glasvezelnetten, warmte-koudeopslag en ondergrondse afvalverwerking. Door deze ontwikkelingen neemt ook vandaag de dag nog het aantal (publieke en private) nutsbedrijven toe en groeit de absolute omvang van ondergrondse infrastructuur. Tijdens binnenstedelijke nutswerkzaamheden² zijn hierdoor een groter aantal opdrachtgevers en opdrachtnemers variërend betrokken over opeenvolgende projectfasen. Hoewel zij een gedeelde verantwoordelijkheid dragen voor een soepel, tijdig en kostenefficiënt uitvoeringsproces, is er meestal géén organisatie die de formele leiding heeft. Een hiërarchische afstemming van de onderling afhankelijke bouwplannen is dus beperkt mogelijk. Projectcoördinatie en zorgvuldige uitvoering van nutswerken zijn hierdoor ingewikkelder en uitdagender geworden.

Tegelijkertijd wordt het belangrijker om nutswerkzaamheden gestroomlijnd te laten plaatsvinden. In veel steden leggen gemeenten daarom ruimtelijke beperkingen en strikte deadlines op aan werkzaamheden in de publieke ruimte. Het publiek en de bedrijven worden kritischer en de eisen van hulpdiensten scherper. Deze randvoorwaarden leggen meer druk op bestaande coördinatiewijzen die veelal plaatsvinden ‘uit het hoofd’ en op basis van papieren 2D tekeningen. Het is met deze coördinatiepraktijk vaak tijdrovend en lastig om raakvlakken tussen werkzaamheden te identificeren; om vroegtijdig op procesverstoringen te anticiperen en om ontwerp- en planningsalternatieven te ontwikkelen.

Terwijl de coördinatielast is toegenomen, hebben ook virtuele bouw- en ontwerp tools (Virtual Design and Construction, afgekort VDC) hun entree gemaakt binnen de grond- weg en waterbouw sector. Deze systemen kunnen bestaande coördinatieprocessen ondersteunen, omdat zij uitvoeringskennis opslaan en gebruiken voor het visualiseren en simuleren van bouwplannen. Bouwprocesvisualisaties, zoals 4D CAD, kunnen bijvoorbeeld worden gebruikt om projectplannen expliciet te maken; om virtueel een repetitie van het bouwprojecten uit te voeren; om verschillende scenario’s te

¹ Deze Nederlandse samenvatting is afgestemd op lezers uit de praktijk. De Engelse samenvatting legt meer nadruk op (onderzoekstechnische) aspecten die met name voor academisch publiek relevant zijn.

² Werkzaamheden aan infrastructuur waarbij ondergrondse riolering, kabels of leidingen aangelegd, onderhouden, of verlegd worden.

verkennen en om procesverstoringen vroegtijdig op te sporen. Ondanks deze potentie lijken VDC-tools momenteel nog niet toegesneden op gebruik in de nutssector. Hierdoor kan er in de praktijk nog nauwelijks voordeel gehaald worden uit de inzet van VDC-middelen. Dit promotieonderzoek onderzoekt daarom de mogelijkheden en beperkingen van VDC. De auteur ontwikkelde en implementeerde hiertoe VDC-systemen die betrouwbaarheid van nutswerkzaamheden vergroten. Het onderzoeksdoel was:

Het vergroten van de betrouwbaarheid van nutswerkzaamheden door het ontwikkelen, implementeren en empirisch testen van VDC-systemen die coördinatie in multistakeholder bouwprocessen ondersteunen.

De stappen uit deze studie zijn uitgevoerd door middel van participatief etnografisch actieonderzoek. Deze methodologie combineert etnografie met actieonderzoek om diepgaande en specifieke kennis over een domein te vergaren. Deze kennis wordt daarna gebruikt om in het domein een interventie te plegen en bestuderen. Om het onderzoeksdoel te bereiken heeft de auteur allereerst potentiële eindgebruikers van VDC-systemen geobserveerd. Hierdoor konden concepten waarlangs nutscoördinatieprocessen worden uitgevoerd in beeld worden gebracht. Op basis hiervan zijn voor vijf praktijkprojecten 4D modellen ontwikkeld en getest. De data die daarbij verzameld zijn, zijn gebruikt om te evalueren welke impact VDC modellen, zoals 4D, hebben op ‘mindful’³ nutscoördinatie en projectresultaat.

De vijf projecten hadden een doorlooptijd van zes tot twaalf maanden. In deze periode zijn dertig vergaderingen bijgewoond die plaatsvonden voorafgaand of tijdens de uitvoeringsfase van de verschillende projecten. De auteur verzamelde 350 foto’s, 20 verslagen, 21 2D CAD-tekeningen en negen planningsdocumenten. Hij had een leidende rol in de ontwikkeling van circa 70 4D CAD bestanden die werden ingezet tijdens 18 vergaderingen. De ontwikkelde modelleerkennis werd door hem gedeeld tijdens twee 4D trainingen waaraan negen stakeholders uit de GWW-sector deelnamen. Het beschreven onderzoeksproces leidde tot de vier wetenschappelijke bijdragen die hieronder zijn beschreven.

Om nieuwe technologieën, zoals VDC-systemen, te evalueren dient men eerst inzichtelijk te maken of deze positieve invloed hebben op coördinatie en procesbeheersing.

³ De term mindful, letterlijk vertaalt opmerkzaam, komt voort uit literatuur over hoogbetrouwbaar organiseren (in het Engels: High Reliability Organizing, HRO). Deze literatuur wordt in dit proefschrift toegelicht en gebruikt om de impact van VDC-systemen te evalueren.

Dit proefschrift mobiliseert daarom als eerst *de High Reliability Organizing (HRO)-lens als een evaluatiekader voor coördinatiestudies in het bouwdomain*. De HRO lens komt voort uit de organisatiewetenschap en leert hoe organisaties op procesverstoringen anticiperen en optredende verstoringen inperken. Hoewel de lens ontstond uit onderzoek in het risico- en veiligheidsdomain, is deze ook bruikbaar in een andere context. Anticiperen op verstoringen en inperken van verstoringen is bijvoorbeeld essentieel bij het beoefenen van coördinatie. HRO kan daarom worden gebruikt als een lens om coördinatieprocessen in de bouw te bestuderen. Toch laten debatten over de adoptie van HRO en andere theoretische concepten zien dat concepten door het academische veld soms bij voorbaat verworpen worden. Tijdens deze debatten heeft een reductionistisch perspectief vaak de overhand. Dit perspectief gaat er vanuit dat een theorie in haar volledigheid wel óf helemaal niet toepasbaar is. Volgens een dergelijk perspectief bestaat de bouw niet uit hoogbetrouwbare organisaties en is de HRO lens dus *helemaal niet* toepasbaar in dit veld. Een pragmatisch perspectief houdt zich niet bezig met dit legitimiteitsvraagstuk, maar focust op de praktische toepasbaarheid en productiviteit van een concept. Het pragmatische perspectief toont hoe reductionistische interpretaties vermeden kunnen worden: HRO reikt verder dan ‘veiligheid’ alleen en heeft bredere relevantie voor procesbeheersing. Volgens dit inzicht blijken HRO’s mindfulness-principes dus praktisch toepasbaar bij het bestuderen van de impact van VDC op projectcoördinatie.

VDC-systemen kunnen dus worden beoordeeld met de HRO-lens. Maar hoe kan je nieuwe technologie – zoals VDC – ontwikkelen die aansluit op de praktijk? De invulling van deze vraag levert de tweede wetenschappelijke bijdrage: *een expliciet stappenplan voor het gebruik van eindgebruikersperspectieven bij de ontwikkeling van een domeinspecifieke kennisbasis (een domeinontologie) voor VDC-systemen*. Het ontwikkelde stappenplan levert voor onderzoekers en ontwikkelaars een methode waarmee belangrijke domeingerelateerde concepten kunnen worden geïdentificeerd. Deze concepten vormen de kennisbasis voor functionele en toepasbare VDC-systemen. Om de concepten te identificeren stelt de auteur voor om de volgende stappen te doorlopen: 1) etnografische observaties uitvoeren; 2) verkennen, organiseren en visualiseren van domeingerelateerde concepten en relaties en 3) ontwikkelen en implementeren van de domeinontologie. Het geïntroduceerde stappenplan is ad-hoc te gebruiken. Tevens dient het als aanvulling op bestaande ontwikkelmethodes wanneer men wil nagaan in hoeverre bestaande domeinontologieën overlap hebben met eindgebruikersperspectieven. Tijdens de ontwikkeling van het stappenplan heeft de auteur domeinconcepten voor coördinatie van

nutswerkzaamheden in kaart gebracht. Deze zijn in vervolgstappen van dit onderzoek gebruikt om functionele 4D modellen te ontwikkelen en in te zetten.

Na ontwikkeling volgt implementatie. Hoe zet je VDC-systemen in om de betrouwbaarheid van nutswerkzaamheden in de praktijk te vergroten? De beantwoording van deze vraag levert de derde wetenschappelijke bijdrage: *een empirisch ontwikkelde methode die laat zien hoe VDC-systemen, zoals 4D modellen, ingezet kunnen worden teneinde coördinatie van nutswerken te ondersteunen*. De methode beschrijft ontwikkeling en gebruik van 4D modellen en bestaat uit drie fases, te weten: afbakening, formaliseren en synchroniseren van bouwplannen. Deze fases zijn gebaseerd op de stappen die tijdens het onderzoek genomen zijn om tot functionele 4D modellen te komen. De observaties van deze projecten laten verder zien dat deze 4D modellen hielpen om potentiële ontwerpconflicten inzichtelijk te maken; omissies in planningen te bespreken; procesraakvlakken in beeld te brengen en om de impact van vertragingen te analyseren. Deze toepassingsvoorbeelden maken aannemelijk dat de 4D coördinatiemethode effectief ingezet kan worden ter ondersteuning van kleinschalige infrastructuurprojecten zoals nutswerkzaamheden.

Hebben de ontwikkelde VDC-systemen een positieve invloed op coördinatie en betrouwbaarheid? De vierde wetenschappelijke bijdrage beantwoordt deze vraag en levert een *gestructureerde evaluatie van de procesimpact van 4D modellen op coördinatie en resultaat van nutswerkzaamheden*. De mindfulness-principes uit de geïntroduceerde HRO-theorie zijn ingezet om de impact van VDC-systemen op coördinatie van drie nutswerkzaamheden te meten. Uit deze analyse komt voort dat VDC-systemen, zoals 4D modellen, stakeholders helpen om de mindfulness-principes te volgen. Met andere woorden; stakeholders die VDC-systemen gebruiken: 1) richten zich in detail op geplande operationele processen; 2) richten zich op procesverstoringen en fouten; 3) zijn minder geneigd om een vereenvoudigde interpretatie van de realiteit te accepteren en 4) kunnen veerkrachtige bouwplannen ontwikkelen. Deze resultaten laten bovendien zien dat de HRO-lens in de praktijk gebruikt kan worden om op een systematische manier te evalueren welke impact VDC tools hebben op coördinatie.

Deze vierde bijdrage levert het sluitstuk van dit empirische onderzoek naar de inzet en evaluatie van VDC-systemen ter ondersteuning van nutscoördinatie. Samengevat tonen de bijdragen dat coördinatie en bouwplannen van nutsprojecten verbeteren als projectstakeholders hun bouwplannen afbakenen, formaliseren en synchroniseren met VDC-systemen, zoals 4D, en als VDC-systeemontwikkelaars eindgebruikersperspectieven betrekken bij ontwikkeling. Door aan te tonen dat toegesneden VDC-systemen

mindful gedrag ondersteunen, en dus helpen om op procesverstoringen te anticiperen en deze in te dammen, is meer dan aannemelijk bewijs geleverd dat VDC-systemen kans op kosten- en tijdsoverschrijding van nutswerkzaamheden verkleinen.

Het ligt voordehand om voor toekomstig onderzoek de methoden verder te ontwikkelen door deze toe te passen tijdens nieuwe projecten. Ook zal aanvullend onderzoek zich kunnen richten op het verscherpen en generaliseren van bevindingen over de impact van VDC op mindful coördinatie. Ter afbakening geeft de auteur mee dat ontwikkelde VDC-systemen slechts één oplossingsrichting beslaan in de weg naar verbeterde projectcoördinatie. Het is daarom zeer goed denkbaar dat onderzoekers in de toekomst een portfolio ontwikkelen van tools en methoden waarmee de betrouwbaarheid van coördinaties kan worden verbeterd. Hierbij dient ook aandacht te worden gevestigd op niet-technische projectmatige en bestuurskundige interventies.

Kortom, gezien de geschetste ontwikkelingen wordt verondersteld dat coördinatie van binnenstedelijke nutswerkzaamheden in het komende decennium niet eenvoudiger zal gaan worden. Geïntegreerde en doordachte bouwplannen worden al maar belangrijker door toename van het aantal netbeheerders en aannemers; groeiende aandacht voor zorgvuldige aanleg en voorkoming van graafschades; verwachte renovatieopgaves en striktere randvoorwaarden. Wil de praktijk de methoden en tools uit dit onderzoek inzetten om deze coördinatieprocessen te ondersteunen, dan dient zij een aantal slagen te maken. Zo raadt de auteur aan om structuur in nutscoördinatie aan te brengen door deelplanningen van verschillende disciplines expliciet te integreren in een hoofdplanning. De planning die hieruit voortkomt, kan worden gebruikt om met VDC-systemen visualisaties te maken van het geplande bouwproces. Om zelfstandig VDC-systemen te kunnen inzetten zullen werkvoorbereiders, tekenaars en projectleiders bovendien modelleer- en visualisatievaardigheden moeten ontwikkelen. Om na te gaan hoe andere VDC-systemen de praktijk ondersteunen, zullen deze stakeholders de geïntroduceerde HRO-lens als evaluatiekader kunnen gebruiken. Uiteindelijk bieden veel van deze systemen, mits toegesneden op de gebruiker, kansen om coördinatie te verbeteren en om projectbetrouwbaarheid te vergroten.

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Record of published papers

Double peer reviewed articles in this thesis

Chapter 2: olde Scholtenhuis, L. L. and A. G. Dorée (2014). High reliability organizing at the boundary of the CM domain. Published in: *Construction Management and Economics* **32**(7-8): 658-664

Chapter 3: olde Scholtenhuis, L. L. and T. Hartmann (2015). Fieldwork-Based Method for End-User Engagement in Domain Ontology Development. Published in: *Ontology in the AEC Industry: A Decade of Research and Development in Architecture, Engineering and Construction*. R. Issa and I. Mutis (Eds). Reston, Virginia, USA, American Society of Civil Engineers (ASCE). ISBN: 978-0-7844-1390-6

Chapter 4: olde Scholtenhuis, L. L., Hartmann, T. and Dorée A.G. A 4D-CAD based method to support coordination of urban subsurface utility projects. In third review round at *Automation in Construction*

Chapter 5: olde Scholtenhuis, L. L., Hartmann, T. and Dorée A.G. Testing the value of 4D visualizations to enhance mindfulness in utility reconstruction works. Being revised and submitted for second review to the *Journal of Construction Management and Engineering*

Peer reviewed papers written during PhD-training, not included in this thesis

Journal articles

Hartmann, T., olde Scholtenhuis, L.L., Zerjav, V., Champlin, C. (2014). Mindfully implementing simulation tools for supporting pragmatic design inquiries. In: *Engineering Project Organization Journal* **5**(1): 4-13

Olde Scholtenhuis, L.L., Hartmann, T. and Dorée, A.G. Coordinating in network project organizations: how utility coordinators bridge voids in project-of-projects constellations. Being prepared for submission

Olde Scholtenhuis, L.L., Hartmann, T. and Dorée, A.G. Using simulations to verify and empirically validate a categorization of sewer construction scheduling knowledge. Being prepared for submission to: *Advanced Engineering Informatics*

International scientific conference papers (published and presented)

Olde Scholtenhuis, L.L., Hartmann, T. and Dorée, A.G. Systems architecture for a virtual construction site to support utility construction management tasks, In: A. Borrmann, P. Geyer, P. de Wilde, Y. Rafiq (Eds.), *EG-ICE 2012 international workshop: Intelligent computing in engineering*, Technische Universität München, Herrsching, Germany, 2012, pp. 1-10

Olde Scholtenhuis, L.L. and Hartmann, T. An object model to support visualizations and simulations of inner city subsurface utility construction activities, In: V. Telichenko, A. Volkov, I. Bilchuk (Eds.), *14th international conference on computing in civil and building engineering*, Moscow State University of Civil Engineering, Moscow, Russia, 2012, pp. 1-7

Olde Scholtenhuis, L.L. and Dorée, A.G. Welcoming high reliability organising in construction management, in: S.D. Smith, D.D. Ahiaga-Dagbui (Eds.), *29th Annual ARCOM Conference*, Reading, UK, 2013, pp. 939-948

Olde Scholtenhuis, L.L. and Hartmann, T. Changing Scheduling Purposes and Evolving 4D-CAD Models: A Study of Planning and Realization in a Utility Project, in: R. Issa, I. Flood (Eds.), *2014 International Conference on Computing in Civil and Building Engineering*, Orlando, Florida, United States, 2014, pp. 299-306

Olde Scholtenhuis, L.L., Hartmann, T. and Dorée, A.G. Comparing Mindfulness in Manual and 4D Supported Coordination Practices, in: J. Irizarry, B. Ashuri (Eds.), *Construction Research Congress, construction in a global network*, ASCE, Atlanta, Georgia, USA 2014, pp. 160-168

Olde Scholtenhuis, L.L., Hartmann, T. and Dorée, A.G. Characterizing coordination in both loose and very tightly coupled utility reconstruction processes, In: T.M. Froese, L. Newton, F. Sadeghpour, D.J. Vanier (Eds.), *5th International/ 11th Construction Specialty Conference*, University of British Columbia, Vancouver, Canada, 2015

National industry conference papers (published and presented)

Olde Scholtenhuis, L.L. and Dorée, A.G., De gordiaanse knoop van kabels en leidingen: hakken we hem door?, *CROW Infradagen 2012*, Papendal, the Netherlands, 2012

Olde Scholtenhuis, L.L. , Meijberg, E., and Boes, J. EMVI en snellere binnenstedelijke rioleringsprojecten: wat te doen met nutscoördinatie?, *CROW Infradagen 2014*, Ermelo, the Netherlands 2014

Meijberg, E., olde Scholtenhuis, L.L. Stop het graven! In 2024 liggen alle kabels en leidingen in goten, *CROW Infradagen 2014*, Ermelo, the Netherlands, 2014.

1. Introduction

Subsurface utilities are part of Western cities' most critical infrastructures. Water pipes, sewers, gas mains, electricity lines and telecommunication cables are buried extensively in public space (McMahon, Burtwell et al. 2005). The complexity of these networks is substantial, not so much in terms of total length (in the Netherlands ~2 million km. (Gemeentelijk Platform Kabels en Leidingen) and in the UK ~4 million km. (Rogers, Hao et al. 2012)), but because of their interconnectedness, the variety of utility types and the different network ages; some dating back even 150 years (Rogers, Hao et al. 2012). Also, in construction, utilities are becoming more significant as is, for example, visible in the emergence of the subsurface utility engineering vocation; a profession which supports construction projects by maintaining utility records, conducting site inspections and localising cables and pipes (Jeong, Abraham et al. 2004).

Given that utilities require maintenance, urban areas are confronted continually with projects to install, repair and replace subsurface networks. Such reconstructions predominantly involve open-cut methods. These methods progressively expose buried infrastructure, damage roadways and disrupt society's functions of public space (Royal, Atkins et al. 2011). Municipalities often put tight deadlines on reconstruction works to minimise this disturbance. Given the short time frames, an increased amount of network owners and contractors need to plan and execute reconstruction work. This results in time pressures and small margins for errors and delay which tend to become even smaller as the frequency and amount of utility works rises and while the pressure on urban space increases.

The construction plans of network owners and contractors need to be adequately integrated to solve the resulting project management puzzle. Achieving a collective set of tasks through alignment of different organizational activities is referred to in literature as coordination (Van de Ven, Delbecq et al. 1976). Coordination is associated with tasks dependencies (Thompson 1967) and the processing of information during execution of uncertain tasks (Galbraith 1977). Based on this seminal work, this study defines *coordination* as follows: the identification, explication and alignment of interfaces – and potential conflicts - between the utility project stakeholders' mutually dependent processes. My thesis reports on how utility coordination challenges can be addressed with Virtual Design and Construction (VDC) systems. *VDC systems* are information systems that explicate project information and construction knowledge to

visualize or simulate construction projects. These models, in turn, enable identification and evaluation of design-construction options (Kam and Fischer 2004, Khanzode, Fischer et al. 2008), therewith supporting multi-disciplinary project management tasks (Kunz and Fischer 2012). *VDC models* are models that VDC systems use as knowledge base, or produce as construction product model. They support tasks such as coordination by communication of construction plans, enabling conflict detection; and, upfront alignment of sequentially dependent construction activities.

My study develops and implements VDC models, such as domain ontologies and 4D-models, to support existing coordination practices. Subsequently, it analyses how VDC impacts coordination, particularly by looking at how these systems influence anticipation and containment of process disturbances.

The sections below consider this objective from a practical and theoretical perspective. Later, the research set-up is explained by elaborating the following: the goals and deliverables; my research philosophy and research efforts; and, the network of organisations that contributed to this PhD study. The chapter ends by outlining the structure of this thesis.

1.1. Practical Context

The practical motivation for developing, implementing and evaluating VDC systems originates from developments such as: the fragmentation of ownership and control over utilities; the growing length and increased amount of subsurface network types; and, the procurement regulations that complicate the formal relations between the growing amounts of contractors involved in *utility works*. This section elaborates how these developments complicate coordination. In addition, it argues that VDC systems have demonstrated their use already during civil engineering projects, other than *utility construction*. This provides a rationale to study how similar VDC systems impact coordination in utility projects (which involve installation, replacement or reparation of cables and pipes that are part of subsurface utility networks).

The root cause for the complicated utility works' coordination is the liberalisation and privatisation of the utility sector. Since the 1990s, many Western countries changed the way in which they provide services to the public (Cropper, Huxham et al. 2009, pp. 147). They relied more heavily on private markets to increase productivity (Kettl 2005, pp. 1). The ways in which utility services are institutionalised vary from country to country. In the Netherlands, for example, electricity networks are completely privatised; drinking water supply is liberalised to a limited degree (Steenhuisen, Dicke et

al. 2009); and, sewer networks are owned by local governments. New service providers entered the utility sector and buried their networks in the ground during liberalisation and privatisation. Since each owner typically constructed their own utility network, the underground became congested. Consequently, cables and pipes moved closer to each other compared to that which would be desirable from an engineering viewpoint (Rogers, Hao et al. 2012). Today, organisations still enter the utility sector and continue to add new systems, such as smart energy grids, subsurface waste collection and fiberglass communication.

Secondly, and partly as a consequence of the privatisation and liberalisation, utility clients are required to conform to various procurement regulations. These regulations determine the ways in which the utility owners can select their contractors and who, independently, often plan and execute construction work. While selecting contractors, each owner needs to comply with different regulations. Public clients, for example, must follow EU and national procurement laws. This means that they often have to run tenders for each separate project. In contrast, private utility owners mostly use framework contracts to select dedicated contractors for a longer time frame. The use of these different regulations prevents utility owners from outsourcing their work collectively to a single contractor. In addition, network owners have long-term maintenance strategies which vary and this complicates the alignment of utility reconstruction programmes even more (van Ravesteijn, Westdijk et al. 2014).

A third motivation for this study concerns the growth in the pressures on project level coordination. Typically, utility projects in urban space disrupt traffic flows (Nguyen, Nguyen et al. 2014), cause noise, and limit accessibility. As a result, local authorities often put tight deadlines and spatial constraints on these construction processes. The multiple stakeholders involved need to effectively align their designs and schedules to deliver projects within such constraints. The industry fragmentation and use of different procurement laws complicates this process since utility works no longer have a main principle that is responsible for overall project coordination. In absence of hierarchy, which is one main coordination mechanism (Martinez and Jarillo 1989, Tsai 2002), the multiple utility owners and contractors involved can no longer enforce an alignment of each other's plans. This highlights the need even more to find practices and ways that support utility stakeholders to understand and integrate one another's construction plans collaboratively.

Construction practice can use VDC systems to deal with this increasingly complex coordination. Although these systems improve coordination in mainstream infrastruc-

ture reconstruction projects, there is no research to date on whether they also help to improve coordination in the domain of utility construction.

The following summarises the practical background chain of developments of this study:

- Fragmentation of ownership and control over utilities construction;
- An increase of both magnitude and types of utility networks;
- Varying procurement regulations and limited overview and control;
- Pressures on coordination: i.e. alignment of construction processes;
- VDC systems potentially support coordination, but have not been investigated to date.

These developments raise the question whether VDC systems enhance coordination in utility works. In the next section, this question is elaborated from a theoretical angle. The section introduces mindfulness; a concept that can be used to evaluate coordination and performance. It hypothesises also that VDC systems contribute to mindfulness. The section explains that well-tailored VDC systems need to be developed and implemented first to test this hypothesis.

1.2. Theoretical context

The mindfulness concept is central to this thesis. According to High Reliability Organising (HRO) literature (c.f. Roberts and Rousseau 1989, Roberts, Bea et al. 2001, Weick and Sutcliffe 2007, Weick, Sutcliffe et al. 2008), organisations follow the mindfulness concept in order to enhance performance as they anticipate unforeseen situations and try to contain disturbances. This study postulates that VDC systems enable mindful behaviour because VDC models are tools that help stakeholders to identify and cope with process disturbances. To test this claim, I used the principles of mindfulness and evaluated how VDC models help practitioners to behave mindfully.

This section first introduces the term mindfulness by explaining its origin in High Reliability Organising (HRO) theory and elaborates on its adoption in the CM research community. Then, I focus on the development and implementation of VDC systems and conclude by explaining these systems may enhance mindfulness. The relations between the points of departure in this thesis are summarised in Figure 1 below.

Figure 1 – relations between the theoretical points of departure in this PhD study.

HRO emerged from grounded studies of error-coping processes in complex and tightly coupled high-hazard organisations. The theory focuses at its core on how organisations cope effectively with errors and unwanted and unexpected situations. It explains how collective processes in organisations can be established to anticipate and contain unexpected events. HRO uses *mindfulness* to explain how reliability can be established on strategic and operational level (Vogus and Sutcliffe 2012). In brief, this concept elaborates the capacity of organisations to focus on the present and to know how to detect anomalies in plans and processes. In turn, this allows them to better anticipate and contain unwanted, unexpected situations. Five *mindfulness principles* capture this behaviour (Weick and Sutcliffe 2007):

1. Be aware of operational processes and how they develop;
2. Be pre-occupied with failures and learn from past mistakes;
3. Resist to over-simplify reality;
4. Develop resilient processes to cope with unwanted events; and
5. Enable experts to make decisions when solving problems.

These principles have been adopted by scholars in mainstream organisational science to study, for example, aviation (Shawn Burke, Wilson et al. 2005); the railway sector (Jeffcott, Pidgeon et al. 2006); health care (Vogus and Sutcliffe 2007); and, operations of electrical and telecommunication grids (De Bruijne and Van Eeten 2007). From a pragmatic viewpoint, HRO's mindfulness principles are of value also to study performance in construction. However, this study experienced differently as its research

presentations and peer discussions were confronted initially with debates about the origin and applicability of HRO to construction management research. It appeared that - in contrast with other theories (e.g. transaction costs (Winch 1989)) that were more fluently assimilated by the research field - the adoption of mindfulness principles was locked in reductionist discussions about HRO's roots and its permissiveness with regard to the construction management domain. Initially this kept HRO concepts at the domain's boundaries. This study first analyses the **HRO legitimacy-debate** to be able to apply HRO's mindfulness principles and, then, provides a solution by clarifying how researchers can use the mindfulness concept more pragmatically.

In essence, behaviour according to the outlined principles enhances **mindfulness** which, eventually, increases reliability (Weick, Sutcliffe et al. 2008). Therefore, it can be argued that construction management performance improves when mindful practices are established. This study hypothesises that **VDC systems** can help establish such practice. This study focuses on the development and implementation of VDC models for utility coordination to test this claim. It uses the mindfulness principles to qualitatively evaluate the impact of VDC on mindful behaviour after introducing methods to develop and implement VDC systems. The theoretical basis for these steps is elaborated below.

To test whether VDC fosters mindful behaviour in a meaningful way requires a VDC system that fits organisational routines (Hartmann, olde Scholtenhuis et al. 2014). Therefore, **developers** need to align their systems with the work practices of end-users. They can do this by developing a knowledge base that captures the key concepts of practitioners that use VDC systems. A domain ontology is such a knowledge base as it formally captures shared end-user views on domain concepts (Studer, Benjamins et al. 1998). Existing methods, such as TOVE (Gruninger and Fox 1995), Enterprise (Uschold 1996, Uschold and Gruninger 1996) and Methontology (López, Gómez-Pérez et al. 1999), can involve end-users in development of domain ontologies using scenarios, expert brainstorm and consultations. Although many methods propose such techniques, they do not spell out explicitly the steps that are required to abstract domain knowledge from end-users. Therefore, this study developed an approach that helps researchers to create a domain ontology that closely matches end-user perspectives.

Information technologies, such as VDC systems, additionally need to be mindfully **implemented** (Swanson and Ramiller 2004) to support effective use. Stakeholders should 1) perceive technologies as useful (Davis 1989, Davis, Bagozzi et al. 1989,

Hartmann 2008), 2) have adequate technical infrastructure, 3) and possess skills to operate VDC systems (Adriaanse, Voordijk et al. 2010, Adriaanse, Voordijk et al. 2010) to successfully implement VDC systems. Furthermore, (4) VDC systems should be tailored to end-user needs. One type of VDC system that likely matches the first three criteria, but is not tailored and tested in the utility sector (criterion 4), is 4D process visualisation. Earlier research shows that 4D VDC models are beneficial to manage high-rise construction and infrastructure projects (e.g. Mahalingam, Kashyap et al. 2010, Zanen, Hartmann et al. 2013). In such projects, these tools supported design reviews; bid preparation (Hartmann, Gao et al. 2008), construction method reviews (Russell, Staub-French et al. 2009); construction planning; workflow planning; and, resource utilisation (Jongeling and Olofsson 2007). The literature review produced no empirical studies on how such VDC systems can be used to coordinate smaller-sized utility works. This study proposes a method that supports utility stakeholder coordination with VDC models, such as 4D.

After implementation, a next step in VDC system development is to **evaluate** its impact on construction management processes. Researchers need to collect and compare construction performance data of both VDC-based and paper based coordinated projects to quantitatively evaluate this. However, since these systems are not adopted widely in practice, statistical data about VDC project cost and schedule performance are hardly available and of limited comparability. Therefore, this study *qualitatively* evaluates the impact of VDC systems on coordination. To this end, it assumes first that mindful behaviour supports coordination. It can be argued further that increased mindfulness contributes to project performance positively as coordination is an antecedent of project performance (Neeraj Jha and Misra 2007). Based on this logic, this study used the mindfulness principles as a lens to show how VDC systems impact mindful behaviour, coordination and project performance.

The theoretical background of this thesis can be summarised as follows:

- HRO and its underlying mindfulness principles show how organisations in complex, tight coupled systems (Dubois and Gadde 2002, Dorée and Holmen 2004) cope with unexpected disturbances and unwanted events. My application of this concept to construction initially faced critique during discussions with peers. This study took a distanced view on the recurring ‘HRO legitimacy debates’ to resolve the debates and to set the stage for the use of HRO as a lens. This clarified the origin of the debate and explained how the HRO lens could be used pragmatically to study coordination and performance.

- Virtual Design and Construction systems have the potential to streamline and structure pressured coordination in utility works. In essence, such systems help dealing with unexpected and unwanted events.
- VDC systems need to be developed in a thoughtful way to support coordination effectively. Developers can do this by matching VDC-knowledge bases, called domain ontologies, with end-user perspectives. This study complemented the literature with a research method for achieving this since existing ontology development methods do not formally spell out the steps required to obtain end-user knowledge.
- Little empirical evidence is available on how VDC systems support smaller scaled project, such as utility works. This study explored how stakeholders can implement VDC models, such as 4D, to adequately support coordination in utility construction to complement to literature.
- Research can use mindfulness principles as an alternative to quantitative statistical analysis of VDC tools. This lens focuses on anticipation and containment of process disturbances and, therefore, helps to evaluate qualitatively and systematically the process impact of VDC systems. This study uses this lens and contributes to literature by evaluating how VDC systems influence mindfulness.

1.3. Research goals & deliverables

The practical and theoretical background in the previous section motivate a need to investigate VDC systems – such as 3D/4D models – more closely to help establish a more reliable coordination practice in the utility sector. These needs are captured in the following research goal:

To enhance reliable construction of utilities by developing, implementing and empirically testing VDC systems to coordinate multi-stakeholder construction processes.

In a more abstract research question:

What is the impact of VDC systems - such as 3D/4D models - on coordination of multi-client, multi-contractor utility reconstruction works?

The next chapters present four deliverables that achieve the research objective and answer the main research question:

1. An explanation and pragmatic solution to the **legitimacy debates** that occur during adoption of theories such as HRO (Chapter 2).
2. An approach to involve end-users in the **development** of domain ontologies for Virtual Design and Construction systems (Chapter 3).
3. A method to **implement** a 4D VDC system that supports coordination in urban subsurface utility works (Chapter 4).
4. An **evaluation** of the process impact of 4D CAD on **mindfulness**, coordination and project performance (Chapter 5).

Figure 2 connects these deliverables in a visual storyline and shows that the thesis essentially covers two themes: 1) development and implementation of VDC-models for utility construction; and, 2) the evaluation of VDC systems in real-life projects, according to HRO.

Figure 2 –visualised relations between the four main research deliverables in this thesis (the banded rectangles indicate the scope of this study).

1.4. Research philosophy

The philosophy that underlies this thesis is that established findings should be theoretically sound; based on empirical data and systematic analysis; and relevant for construction practice. In this light, theories are seen as devices that help to describe, to

explain, and to predict real world phenomena. Researchers observe the real world based on a-priori constructed frames of reference. Besides, although objects and social phenomena may *exist* independent of whether someone observes them (ontological objectivity), their social *meaning* emerges from an individual's perception and shared interpretation (epistemological subjectivity). The understanding about subjects and phenomena can differ between domain insiders and outsiders. Therefore, domain understanding is created and recreated in context and changes over time. When developing VDC tools for a particular domain, such as construction, it is therefore essential to conduct studies in close interaction with the practical context itself.

The research methodology that fits this philosophy⁴ is ethnographic-action research (Hartmann, Fischer et al. 2009). The methodology was used in this study and essentially suggests using ethnography to develop a detailed insider-understanding of work practices. In addition, it uses action research to study the effect of a planned intervention in such practices.

1.5. Research efforts

Based on the outlined philosophy, I have: followed courses; collected and analysed data; and, diffused findings, in multiple ways. While employing ethnographic research in this study, I collected project artefacts, such as schedules, designs and meeting minutes. In addition, participant observation of planning and jobsite meetings were used as a non-intrusive technique to obtain data about coordination practices in utility reconstruction works. Action research techniques were employed to study the effect of implemented VDC systems on existing coordination practices in utilities. I collaborated with practitioners to develop, incrementally improve and implement 4D VDC models in pilot projects. Weekly visits to the field enabled me to develop VDC models that could be customised to the needs of practitioners.

To analyse the collected data qualitatively, this study used open, axial, and selective coding (Strauss and Corbin 1990). First, the open coding technique extracts and marks excerpts of qualitative data (text and audio-visual material) to identify concepts from raw data inductively. Axial coding subsequently relates and prioritises these concepts. Eventually, selective coding identifies the key concepts and variables that explain a study's phenomenon of investigation. Open codes were created in this study to label, for example, VDC coordination steps, and observed VDC benefits. Then axial coding

⁴ The Epilogue contains a more elaborate consideration about science as it describes the author's sense making of the research profession and research processes.

was used to cluster these labels. Selective coding helped to organise the labels around key phenomena of investigation, for example, 4D VDC-implementation, and mindfulness.

Figure 3 depicts a visual overview of the conducted research in a timeline that summarises most efforts related to data collection, teaching, studying and the dissemination of research findings. Figure 3 also depicts additional activities that did not contribute directly to the achievement of the objective in this thesis. These extra activities contributed to my PhD training and gave a more holistic image of the empirical and theoretical endeavour. Chapter 6 provides a more extensive description of this additional work.

1.6. Research Network

While teaching and undertaking research, I evolved a network with industry and academia. Organisations that were involved were municipalities (Enschede, Hengelo, Hof van Twente, Amsterdam and Rotterdam); the Province of Overijssel; service providers (Enexis, Vitens, Reggefiber, our campus facility service department); contractors (a.HAK, NTP, Reef, van Gelder, Dusseldorp); universities (Lulea, Bochum, Birmingham); platform organisations (the utilities platform KLO, the municipal platform for utilities); authorities (land registry office, Dutch Radiocommunications Agency); and, software suppliers (Bentley Systems, Itannex).

Altogether, this research network formed the living lab in which practice-engaged research on VDC systems took place. The network provided cases in which rich empirical data could be collected. In return my visits to industry provided stakeholders the opportunity to reflect and to learn about state-of-the art tools that support existing work routines. Furthermore, a few organisations also hosted BSc. and MSc. students who executed their graduation project in the same domain as in this thesis. A major part of the established research network continues to be involved in the Smart City research programme that has been launched recently, partly as a result of this PhD study.

Figure 3 – the timeline of this PhD study, containing an overview of attended meetings and conferences, peer-reviewed publications, teaching guest lecturing, attended courses and data collection efforts.

1.7. Outline of this thesis

To achieve the research goal, the next chapters address how VDC systems influence mindful behaviour in the coordination of urban utility construction. Chapters 2 to 5 are reformatted versions of earlier research publications (a research note; a book chapter; and, two journal articles respectively) that were written together with my supervisors ⁵. After these chapters, the thesis draws conclusions and reflects on the research outcomes and research process. These chapters are structured as follows:

Chapter 2 focuses on the concepts that help evaluate the influence of VDC systems on coordination performance. HRO is introduced as a lens to study performance in construction. The chapter explains the adoption of the HRO lens in the construction management research field based on my experience in earlier research debates. It elaborates how new theoretical phenomena, such as HRO and its **mindfulness** principles, can become stuck in reductionist **legitimacy debates**. A proposed reinterpretation shows how the construction management domain can adopt an alternative pragmatic perspective to signal diversionary reductionist disputes and, in so doing, redirects focus to the more pragmatic use of concepts for productive construction research. This reinterpretation sets the stage for using HRO's concepts to study how VDC systems influence mindful behaviour during utility project coordination.

Chapters 3 and 4 centre on the development and implementation of VDC systems. They improve the way in which disturbances are dealt with as these systems increase the rigidity and structure of coordination processes which, in turn, increases the ability to anticipate and contain process disturbances. To support coordination processes effectively, developed VDC systems need to capture the domain concepts that end-users commonly use in their work routines. Domain ontologies can be used to capture such concepts formally. The research philosophy section already has argued that viewpoints on domain concepts differ between insiders and outsiders. Hence, it is necessary to investigate practitioners' work routines empirically when developing ontologies for VDC systems. Therefore, Chapter 3 introduces a fieldwork-based ontology **development** approach that spells out steps for the involvement of end-user perspectives. The cyclical approach consists of three iterative steps: first, ethnographic

⁵ The Chapters 2 – 5 therefore contain plural pronouns such as 'we', 'our' and 'the research team'. As individual research paper, these chapters had to be self-standing and required a proper introduction of the project scope. Although this inevitably means that this thesis contains redundancies, I tried to minimize these as much as possible. Further, the language in this thesis varies between UK and US English, but has been used consistently within each chapter.

fieldwork; second, analysis of empirical data; and, third, development of an ontology. To demonstrate the use of the method in practice, chapter 3 additionally applies the method to develop a domain ontology for urban utility reconstruction.

Chapter 4 proposes a method that aligns the development and use of a 4D VDC model with paper-based coordination practices to subsequently use the developed utility domain ontology in an **implemented** VDC system. This method helps to support construction plan scoping, formalising and synchronising. Findings show that the models created with this method support coordination in multi-stakeholder subsurface utility works in three ways: 1) by enabling identification of design and schedule interfaces; 2) by detection of potential conflicts; as well as 3) by supporting evaluation of delays.

Chapter 5 studies VDC based coordination in three utility projects and uses mindfulness as a lens to qualitatively **evaluate** how VDC enables stakeholders to cope effectively with unforeseen situations. It shows that 4D helps stakeholders in a number of ways, e.g. by becoming: sensitive to operational processes; pre-occupied with errors and inaccuracies; attentive to design and schedule details; resistant to simplifying reality; and, resilient and aware of process alternatives. Altogether, these practices enhance mindful behaviour which, subsequently, enhances mindfulness of coordination processes.

Following on after the four chapters that directly contribute to this research' goal, the intermezzo chapter 6 informs the reader about the additional research efforts that took place on a side track of my PhD study. The summaries and conclusions in this chapter do not formally contribute to the research objective of this study, but are meant to provide a global view on the context in which this PhD has been conducted.

Finally, Chapter 7 and 8 conclude this thesis by explaining how utility projects could capitalise on the benefits of VDC systems to, ultimately, enhance mindfulness and performance. These efforts would make unexpected, unwanted events, such as cost and schedule overruns and re-planning, less likely. Finally, these claims are placed in perspective by reflecting on the limitations and assumptions of the research method. Figure 1 summarises the outline of this thesis visually.

Figure 4 – outline of the structure of this thesis.

2. High reliability organising at the boundary of the CM domain

The construction management (CM) domain regularly develops and explores new theories and perspectives. These new insights can shift the existing paradigm radically, they can be assimilated smoothly, or they can stall as they are debated at CM's domain boundary. During our current research, we experience that the concepts from high reliability organizing (HRO) are caught in such a debate. We elaborate this debate from the viewpoint of two distinctive scientific traditions and evaluate the main premises that hold HRO at CM's boundaries. It seems that reductionist scientific traditions underlie much of the critique which currently diverts debate off into an unproductive intellectual cul-de-sac. An alternative pragmatic approach would allow CM's HRO researchers to avoid the confines of the reductionist arguments as it redirects minds and action on productive and practical research to achieving more reliable construction project performance, as well as dealing better with health and safety issues. Above all, the examination of the HRO boundary debate in CM may help other researchers experiencing impasses in their debates to explore whether these debates address the actual notions at stake or are restricted by deeply held views rooted in scientific traditions.⁶

Keywords: academic practice, high reliability organizing, management theory, research paradigm, safety

Identity, theory and theorizing are inherent and recurring topics of discussion in construction management (CM) journals and research communities (cf. Seymour and Rooke, 1995; Weick, 1995; Raftery et al., 1997; Seymour et al., 1997; Cairns, 2008; Dainty, 2008; Green and Schweber, 2008; Chan, 2013; Connaughton and Weller, 2013). In a radical situation these discussions cause Kuhnian scientific revolutions (Kuhn, 1968). A paradigm shift can then reconfigure established scientific rules and standards of practice. In a less radical scenario, theories, concepts and notions can also assimilate and move in and out of domains more fluently. Examples of where this has happened in the CM arena include: transaction costs economics (e.g. Winch, 1989); loosely coupled systems theory (e.g. Dubois and Gadde, 2002; Dorée and Holmen, 2004); supply chain (e.g. Cheng et al., 2001; Love et al., 2004) and trust and partnering (e.g. Wood et al., 2002; Khalfan et al., 2007). Finally, somewhere between radical change and fluent adoption, new theories, concepts and notions can confront CM's

⁶ This chapter has been published as: olde Scholtenhuis, L. L. and A. G. Dorée (2014). High reliability organizing at the boundary of the CM domain. *Construction Management and Economics* 32(7-8): 658-664.

domain boundaries and initiate debates as to whether a new perspective can be allowed to be incorporated legitimately into the existing domain.

Currently, the concepts from high *reliability* organizing (HRO), here defined as cognitive processes and actions directed at actively avoiding seemingly inevitable organizational hold-ups and containing errors (after Rochlin, 1993; Weick Sutcliffe et al., 2008), seem to be caught in such a boundary debate. The application of these concepts to temporal organizations (Lundin and Söderholm, 1995; Packendorff, 1995) and systems (Bigley and Roberts, 2001), such as construction projects, could support studies in current CM research themes, for example: project control; occupational health and safety; and innovation. In our studies of urban infrastructure works we use principles constituting the HRO lens to qualitatively explore and compare planning, coordination and actual construction processes as they unfold. We observe that the HRO lens enhances our analysis and understanding of recurring coordination issues that frequently obstruct overloaded construction projects in meeting their targets.

Surprisingly, we repeatedly face two points of critique to our use of the HRO lens when we present our work to scientific peers. First, some objectors argue that the use of the HRO lens is only permissible in organizations that are already highly reliable and failure free. Evidently, organizations in the construction industry are not. Second, they stipulate that using the HRO lens is only permissible in domains where safety is of prime importance. Again, evidently, this cannot be the case in construction.

Manifestly, therefore, based on these two points, the discussant then suggests that there is no use and no place for the HRO perspective in construction management. In the light of our first findings and observations, these arguments are startling; although the ‘objectors’ logic’ might seem valid, our experience demonstrates the opposite. So, how to proceed? This Note sets out to test and disentangle the ideas that keep HRO outside CM’s boundary debate, and therewith illustrates how new theories, concepts and notions can become restricted in a boundary debate.

This Note starts by introducing HRO concepts and their origin. It then elaborates and dissects the two main premises underlying the debate as to whether HRO is justifiable in the CM domain. Next, we explain that the debate is caught in the confines of reductionist logic. We argue that, beyond this viewpoint, we can explain how the CM domain can use the HRO lens more pragmatically to enhance reliability. We conclude by contrasting the logic underlying these distinctive scientific traditions to show how boundary debates can keep new theories and notions at CM’s boundaries.

2.1. HRO and its key concepts

HRO research focuses on processes and mechanisms that allow some organizations to establish and maintain nearly accident-free performance, while operating at almost peak capacity (LaPorte and Consolini, 1991; LaPorte, 1996). In this research, we define HRO behaviour by following Weick (2011). He observed that such organizations have principles and processes in place to produce dynamic non-events; they focus on avoiding non-goal actions and non-goal results. Although many HRO researchers assume a similar definition, it seems still problematic to find a consensus on the definitions of reliability (Schulman, 1993) and high reliability organizations (Rochlin, 1993; Hopkins, 2007).

One foundation for the development of HRO is Perrow's (1984) normal accidents theory (NAT). This suggests that organizations containing tight couplings and interactive complexities are vulnerable to accidents. Inspired by NAT, a Berkeley-based research group (including LaPorte, Rochlin, Schulman and Roberts) studied how organizations in high hazard environments perform both exceptionally and almost error-free. A range of successive studies on the Challenger explosion (Roberts and Rousseau, 1989), the Mann Gulch forest fire (Weick, 1993) and naval aircraft carriers (Weick and Roberts, 1993) went on to establish the concepts of high reliability organizing.

One key concept drawn from HRO is 'mindfulness' (Weick, Sutcliffe et al., 2008; Weick and Sutcliffe, 2007). In essence, organizational mindfulness is the 'capability to induce a rich awareness of discriminatory detail and a capacity for action' (Weick, Sutcliffe et al., 2008, p.37). It focuses on 'clear comprehension of emerging threads and on factors that interfere with such comprehension' (Weick and Sutcliffe, 2006, p.516). Such mindfulness comprises a set of five principles divided into the categories anticipation and containment (see Figure 1).

Figure 5 - mindfulness principles and heedful interrelating concept in HRO (after Weick, Sutcliffe et al. 2008; Weick and Roberts 1993).

Anticipation focuses on identifying and preventing potential unwanted situations. Containment is about reacting to, and recovering from, such situations. When increasing anticipatory skills, mindfulness principles show that organizations should establish *sensitivity to interdependencies in operational processes*. Additionally, they become *preoccupied with failures* by trying to learn from errors or things that could go wrong. Anticipation further increases through ensuring a *resistance to simplifications* of reality, i.e. by challenging standard assumptions and by deliberately trying to interpret observations in great detail. To effectively contain errors further more reliable organizations *commit to resilience*. To this end, they create backup strategies and flexible decision-making structures for problem-solving. Such organizations promote a *reliance on expertise*. They favour expert judgement in problem-solving, even if there is a strategically or commercially more attractive solution for a problem.

A second key concept central to HRO is *heedful interrelated action*. When interacting in a heedful way, practitioners execute their own tasks and understand how their individual tasks are influenced by, and contribute to, related actions by others within a system (Weick and Roberts, 1993). Together with the concept of mindfulness, we refer to the heedful interrelating concept as the ‘HRO lens’.

The concepts constituting the HRO lens originate from the lively and dynamic HRO domain that hosts debates and promotes a flow of strategic, managerial and technical-system perspectives on reliability (Boin and Schulman, 2008). Our research extends the lens to a CM domain which is notorious for its high rate of overruns, failure costs and accidents, often due to non-goal action and non-goal events. Could the HRO perspective be a key instrument to help deal with these issues? Could this HRO lens make organizations in the construction industry more reliable?

Tempted by these thought-provoking questions, we use the HRO lens in our research (olde Scholtenhuis and Dorée, 2013) to guide the exploration of how multi-stakeholder urban infrastructure project stakeholders *anticipate* in actual planning processes. In studying anticipation, we use mindfulness principles, for example, to conduct field research and direct our attention to observe and explore whether professionals pay attention to significant details when designing and planning interrelated construction tasks. We further focus on the preoccupation with failure by investigating how work planners cope with potential construction site hold-ups. Also, we explore the practices of simplification and complication in project planning. We also use mindfulness principles to study *containment* as we observe whether and how onsite managers and foremen create contingency strategies in situations where construction progress becomes derailed.

In our experience, the HRO lens supports the following: focused data collection during field observations; structured qualitative descriptions of reliability in construction organizations and comparability of reliability processes across construction organizations. Although findings promise pragmatic and valuable insights for both practice and CM researchers, nevertheless, the HRO lens we adopt seems to be questioned frequently by our scientific peers.

2.2. Challenging the major premises underlying the boundary debate

The HRO principles provide a lens to study process flow and processes coping with non-goal events (e.g. accidents and hold-ups) and non-goal results (e.g. overruns). However, it seems that the HRO label, and particularly its initial research setting, complicates diffusion and adoption of the HRO lens in mainstream industries and construction. The main preconceptions and assumptions of the HRO perspective that create legitimacy debates at boundaries of the CM domain are elaborated below.

2.2.1. FIRST PREMISE: THE HRO LENS IS LEGITIMATE ONLY FOR ‘TYPICAL HROS’

Construction processes are certainly not free of failure and, therefore, HRO principles cannot be applied in construction. This first premise centres on the preconception of the necessity of failure-free operation. Once introduced to the principles of HRO, it is often asserted that only organizations characterized as ‘highly reliable’ can use the HRO lens to boost performance. Bourrier (2011), for example, described HRO organizations as high performing, while being bounded by a strict no-failure requirement.

Should one then argue that the HRO label is reserved for error-free organizations only? Will an HRO organization lose its label when an error occurs? How much failure would be acceptable? Not surprisingly, this premise skews any scientific dialogue into a debate that no longer addresses whether the HRO lens can enhance reliability or performance. Instead, the debate concentrates on whether a construction project can attain 'HRO status'. The argument that only 'typical HROs' can apply reliability concepts is disputable and would be similar to restricting quality-enhancing principles only to those organizations that already have a high quality standard.

A less rigid view accepts that high reliability organizations can make mistakes and operate in a nearly error-free (LaPorte and Consolini, 1991). The nuanced interpretation departs from the no-failure constraint and blurs the distinction between 'highly reliable' and 'not so highly reliable' organizations. This allows a broader range of organizations to adopt the HRO lens. The next sections explain that this position is accepted among several acknowledged HRO scholars.

Confusion over the legitimacy of the HRO lens in CM is also created by the term 'organization'. Since reliability is often associated with control, the 'O' in HRO confuses (construction) management scholars, particularly those working in the rational contingency paradigm of organization theory and design. Often, their initial interpretation of organization reflects Morgan's machine metaphor (Morgan, 1997, pp. 11–31) which subsequently directs the focus towards planning and control enforced by structure and prescribed procedures. Control and subsequent reliability are assumed to be the consequence of obedience to such procedures.

An alternative view perceives organization as a domain that is comprised of individuals' communicative events (Dan-Asabe and Radosavljevic, 2009). Similarly, the HRO perspective on organization acknowledges that human beings enact 'organization' within the context of structure and procedures. Reliability is the consequence of this mindful enactment. In HRO, therefore, 'analysis should be at the individual level and at the level of aggregated individual behaviours [emphasis added] that constitute error-reduction processes' (Creed et al., 1993, p.68). Although HRO scholars have tried to avoid misunderstanding by changing organization into organizing, this change has not ended debates defining the structural characteristics of 'an HRO', probably because this change was too subtle to challenge the previously set terminology.

In short, the premise that mindfulness and heedfully interrelated actions apply only to labelled and stereotyped 'high reliability organizations' direct the debate to the identi-

fication of ‘typical HROs’ and their mechanistic control structures. Even though there seems no logical support for these debates, it moves the focus away from actual reliability issues in organizations.

2.2.2. SECOND PREMISE: HRO SHOULD BE CONFINED TO ORGANISATIONS WITH HAZARD AND SAFETY AS PRIMARY FOCUS

With hindsight, the choice of the labels ‘high reliability’ and ‘organization’ seems unfortunate, since they imply that evaluation of high reliability in organizations was ‘based on some absolute, and static, standard of performance, rather than on a relative evaluation of the dynamic management of a difficult and demanding technology in a critical and unforgiving social and political environment’ (Rochlin, 1993, p. 12). Although this partly reiterates the issues described above, it also implicates the rationale for a second premise: HRO labels and concepts should be confined to high hazard industries and, as construction processes do not operate in these types of hazardous environments, so the HRO lens should not apply in the CM domain.

The signature cases of aircraft carriers and nuclear power plants and their focus on ‘safety first’ means that HRO concepts became mostly associated with these hazard and ‘safety first’ domains: so much so that some scholars (e.g. LaPorte, 1996; Boin and Schulman, 2008; Schulman, 2011) even suggested that hazard and safety environments are imperative for organizations in establishing and maintaining HRO behaviour. As Bourrier (2011) observed: ‘the concept of HRO does not apply to a vast category of organizations [...], scholars and experts seem to have forgotten that originally an HRO was primarily defined by its transactions with the institutional environment’ (p.10). However, is reliability an issue reserved just for the hazardous domain? Are organizations in less hazardous domains either reliable spontaneously or inescapably unreliable? The answers are not that evident.

All organizations are driven by goals and invest money and effort to reach targets reliably. It seems that this second premise lumps together and substitutes the term reliable and the safety first goal, due to the fact that ‘HROs’ in high hazard environments strive for ‘reliably safe’. This linguistic contamination of the terms reliable and safe obscures the reasoning and the debate. The fact that classical ‘HROs’ have such a strong focus on safety logically does not imply that reliability should be confined to safety, nor does it imply that the HRO lens should be confined to the high hazard domain. This does not prohibit organizations in less hazardous environments utilizing the HRO lens (albeit to some lesser extent) to become more reliable.

In a word, the premise inherited from HRO signature cases suggests causality between hazardous environments and high reliability. It inextricably bounds hazards, safety and reliable performance, and it confines, unnecessarily, the realm in which HRO concepts are explanatory in enhancing reliability.

Overall, the two premises show how the question of labelling and classification pervade the current debate on the scientific legitimacy of the HRO lens. As a result, they obstruct any progress in researching the intricacies and issues that frequently challenge the daily and practical reality of reliable planning and execution of construction projects.

2.3. Reflection: a debate caught in reductionist logic

The illustrated boundary debate focuses on evaluating whether the HRO lens can be legitimately applied when describing and analysing reliability issues in construction projects. Interpreting this debate from a pragmatic's point of view, the core concern is the practicality and productivity of the HRO lens, rather than the permissiveness of its concepts regarding the domain. This paragraph reflects HRO's practicality and permissiveness in the CM domain from the perspective of jockeying reductionist and pragmatist traditions.

The opposition encountered in our research diverted the discourse into a debate over classification, where categories, labels and labelling became the core concern: viz., are organizations either highly reliable or not highly reliable? Do they either operate in hazardous environments or not do so? Are they either free of failure or not failure-free? Are they either reliable or not reliable? Categorizing HROs, in general, and in construction organizations in particular, seems to be the essence of the reductionist debate encountered. A pragmatist would typically question whether this type of debate helps CM-researchers to understand reliability processes and principles in actual construction projects.

Therefore, instead of confining the HRO label to its original institutional environment and to continue with categorical 'either-or' discussions, a more pragmatic approach would abandon this reductionist perspective and concentrate attention on the actual performance of (construction) organizations. This approach is visible in the work of Weick, Sutcliffe et al. (2008). They argue that HRO concepts are relevant for mainstream organizations because they 'provide a window on a distinctive set of processes that foster effectiveness under trying conditions' (Weick, Sutcliffe et al., 2008, p.31). Similarly, Roberts and Bea (2001) argue that even the sausage maker can learn from

these processes, since such mainstream organizations can also face errors that have far-reaching consequences. These scholars do not bother defining and identifying HROs, but focus rather on the underlying reliability-enhancing processes and characteristics (Lekka, 2011). We provide an overview of the two distinctive viewpoints on HRO in Table 1.

Table 1- overview of reductionist and pragmatic perspectives on HRO.

	Reductionist view	Pragmatic view
Unit of analysis	‘Typical’ High Reliability Organisations	(Construction) organisational processes
Meaning of reliability	Reliability as an absolute status	Reliability as a process
Function of HRO lens	Distinguishing ‘HROs’ from non-HROs based on structure and context	Understanding reliability issues, principles and processes that enhance reliability
Main assumptions	Org’s are either highly reliable or not HRO concepts do not apply beyond safety and high hazards	Org’s can seek to enhance reliability HRO lens applies to common organisational goals

The pragmatic approach becomes more evident as we see HRO concepts crossing their original boundaries, gradually finding their application in mainstream organization science. Recent reliability studies in regular organizations, such as educational institutes, the police, detention centres, theatres and manufacturing were presented, for example, at the 2011 European ProHRO conference. Literature also reports on the application of the HRO lens in aviation, oil production and the railway sector (Roberts, 2009), and in hospitals (Vogus and Sutcliffe, 2007). De Bruijne and van Eeten (2007) analysed how restructuring the utility sector impacted on the performance reliability of large technical infrastructure.

Meanwhile, a small number of HRO-related papers emerged at construction management conferences and in construction-related journals. Mitropoulos and Cupido (2009), for example, looked into the work practices of high- and low-performing residential framing crews and found that a guiding principle of ‘going a little slower to avoid mistakes’ helped crews to finish their work quicker, which also resulted in fewer errors and accidents.

Brady and Davies (2010) also studied HRO processes and argued that the presence of ‘HRO strategies’, such as decentralized working, training and simulation, contributed

to the reliable (i.e. timely and within budget completion) realization phase of Heathrow's Terminal 5, while the lack of these strategies caused contrasting failures in the transition towards its operational phase.

Overall, these exceptional pragmatic perspectives provisionally show how construction benefits from the value of the HRO lens. Using the viewpoint of competing scientific traditions we see how reductionist logic currently fuels 'either-or' HRO classification and labelling debates at the boundaries of the CM domain. Furthermore, it shows that, instead of adopting reliability principles to achieve the goal of absolute safety-reliability, a more pragmatic approach to reliability issues allows a focus on the underlying principles and processes that enhance reliability of a broader set of (mainstream) organizational goals.

2.4. Conclusions

Theories, concepts and notions continually enter and leave the CM research domain. Some assimilate quite fluently. Others struggle and create debate at CM's domain boundaries. This Note elaborates such a boundary debate by focussing on adoption of the HRO lens in construction. It shows that two premises, which focus on labelling and categorizing construction organizations as HRO, cause reductionist 'either-or' debates. We conclude that this hampers a more interesting debate on real reliability issues in everyday construction operations. By releasing the HRO lens from the sidelining consequences of the reductionist classification debates, a pragmatic perspective can bring closure to these legitimacy debates. Ultimately, this allows researchers to integrate HRO concepts in studying project control, performance, and health and safety issues.

In our research, the HRO lens seems productive by its support of a rich and qualitative analysis of reliable and less reliable coordination practices in urban utility construction projects which frequently overrun. For example, we use the lens to guide our study of anticipation and containment processes of planning, coordination and actual construction. By using the HRO lens, we can compare these practices across various cases in a structured way. In future, this will allow us to investigate how technological innovations or strategy changes influence reliable project performance: i.e. more effective anticipation on hold-ups and overruns.

Our own research illustrates and clarifies current CM legitimacy debates and places reductionist premises in the context of understanding different scientific traditions and the way they deal with theories. Although this is unlikely to fully prevent future

reductionist debates, we feel that the Note helps CM's (reliability) researchers to recognize and avoid diversionary labelling and categorization disputes and, thereby, to create the space for more productive and practical construction research.

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References

- Bigley, G.A. and Roberts, K.H. (2001) The incident command system: high-reliability organizing for complex and volatile task environments. *Academy of Management Journal*, **44**(6): 1281–99.
- Boin, A. and Schulman, P. (2008) Assessing NASA's safety culture: the limits and possibilities of high reliability theory. *Public Administration Review*, **68**(6): 1050–62.
- Bourrier, M. (2011) The legacy of the high reliability organization project. *Journal of Contingencies and Crisis Management*, **19**(1): 9–13.
- Brady, T. and Davies, A. (2010) From hero to hubris: reconsidering the project management of Heathrow's Terminal 5. *International Journal of Project Management*, **28**(2): 151–7.
- Cairns, G. (2008) Advocating an ambivalent approach to theorizing the built environment. *Building Research & Information*, **36**(3): 280–9.
- Chan, P.W. (2013) A 'zombie' existence: exploring Ulrich Beck's zombie categories and construction management research, in Smith, S.D. and Ahiaga-Dagbui, D.D. (eds) *Proceedings 29th Annual ARCOM Conference*, Reading, 2–4 September, Association of Researchers in Construction Management, pp. 1059–69.
- Cheng, E., Li, H., Love, P.E. and Irani, Z. (2001) An e-business model to support supply chain activities in construction. *Logistics Information Management*, **14**(1–2): 68–77.
- Connaughton, J. and Weller, S. (2013) Improving collaboration in construction: an opportunity for action research, in Smith, S.D. and Ahiaga-Dagbui, D.D. (eds) *Proceedings 29th Annual ARCOM Conference*, Reading, 2–4 September, Association of Researchers in Construction Management, pp. 1125–34.
- Creed, W.E.D., Stout, S.K. and Roberts, K.H. (1993) Organizational effectiveness as a theoretical foundation for research on reliability-enhancing organizations, in Roberts, K.H. (ed.) *New Challenges to Understanding Organizations*, Macmillan, New York, pp. 55–73.

- Dainty, A.R.J. (2008) Methodological pluralism in construction management research, in Knight, A. and Ruddock, L. (eds) *Advanced Research Methods for the Built Environment*, Wiley-Blackwell, Oxford, pp. 1–2.
- Dan-Asabe, D. and Radosavljevic, M. (2009) Do construction companies need to match employees' expectations?, in Dainty, A.R.J. (ed.) *Proceedings 25th Annual ARCOM Conference, Nottingham, 7–9 September*, Association of Researchers in Construction Management, pp. 1223–32.
- de Bruijne, M. and van Eeten, M. (2007) Systems that should have failed: critical infrastructure protection in an institutionally fragmented environment. *Journal of Contingencies and Crisis Management*, **15**(1): 18–29.
- Dorée, A.G. and Holmen, E. (2004) Achieving the unlikely: innovating in the loosely coupled construction system. *Construction Management and Economics*, **22**(8): 827–38.
- Dubois, A. and Gadde, L.E. (2002) The construction industry as a loosely coupled system: implications for productivity and innovation. *Construction Management and Economics*, **20**(7): 621–31.
- Green, S.D. and Schweber, L. (2008) Forum theorizing in the context of professional practice: the case for middle-range theories. *Building Research & Information*, **36**(6): 649–54.
- Hopkins, A. (2007) *The problem of defining high reliability organisations*. Working Paper 51, National Research Centre for OHS Regulation, Canberra.
- Khalfan, M.M.A., McDermott, P. and Swan, W. (2007) Building trust in construction projects. *Supply Chain Management*, **12**(6): 385–91.
- Kuhn, T.S. (1968) *The Structure of Scientific Revolutions*, University of Chicago Press, Chicago.
- LaPorte, T.R. (1996) High reliability organizations: unlikely, demanding and at risk. *Journal of Contingencies and Crisis Management*, **4**(2): 60–71.
- LaPorte, T.R. and Consolini, P.M. (1991) Working in practice but not in theory: theoretical challenges of 'high-reliability organizations'. *Journal of Public Administration Research and Theory*, **1**(1): 19–48.
- Lekka, C. (2011) *High Reliability Organisations: A Review of Literature*, Research Report RR899, Health and Safety Executive, London.
- Love, P.E., Irani, Z. and Edwards, D. (2004) A seamless supply chain management model for construction. *Supply Chain Management*, **9**(1): 43–56.
- Lundin, R.A. and Söderholm, A. (1995) A theory of the temporary organization. *Scandinavian Journal of Management*, **11**(4): 437–55.

- Mitropoulos, P. and Cupido, G. (2009) Safety as an emergent property: investigation into the work practices of high-reliability framing crews. *Journal of Construction Engineering and Management*, **135**(5): 407–15.
- Morgan, G.K. (1997) *Images of Organization*, Sage, London.
- olde Scholtenhuis, L.L. and Dorée, A.G. (2013) Welcoming high reliability organising in construction management, in Smith, S.D. and Ahiaga-Dagbui, D.D. (eds.) *Proceedings 29th Annual ARCOM Conference*, 2–4 September 2013, Reading, UK, Association of Researchers in Construction Management, pp. 939–48.
- Packendorff, J. (1995) Inquiring into the temporary organization: new directions for project management research. *Scandinavian Journal of Management*, **11**(4): 319–3.
- Perrow, C. (1984) *Normal Accidents: Living with High-Risk Technologies*, Princeton University Press, Princeton.
- Raftery, J., McGeorge, D. and Walters, M. (1997) Breaking up methodological monopolies: a multi-paradigm approach to construction management research. *Construction Management and Economics*, **15**(3): 291–7.
- Roberts, K.H. (2009) Managing the unexpected: six years of HRO-literature reviewed. *Journal of Contingencies and Crisis Management*, **17**(1): 50–4.
- Roberts, K.H. and Rousseau, D.M. (1989) Research in nearly failure-free, high-reliability organizations: having the bubble. *Engineering Management IEEE*, **36**(2): 132–9.
- Roberts, K.H. and Bea, R. (2001) Must accidents happen? Lessons from high-reliability organizations. *Academy of Management Executive*, **15**(3): 70–9.
- Rochlin, G.I. (1993) Defining high-reliability organisations in practice: a taxonomic prolegomena, in Roberts, K.H. (ed.) *New Challenges to Understanding Organizations*, Macmillan, New York, pp. 11–32. Schulman, P.R. (1993) The analysis of high reliability organizations: a comparative framework, in Roberts, K.H. (ed.) *New Challenges to Understanding Organizations*, Macmillan, New York, pp. 33–53.
- Schulman, P. (2011) *There is more than one way to be reliable*. Presented at the ProHRO Conference, The Hague, the Netherlands 15-16 November.
- Seymour, D. and Rooke, J. (1995) The culture of the industry and culture of research. *Construction Management and Economics*, **13**(6): 511–23.
- Seymour, D., Crook, D. and Rooke, J. (1997) The role of theory in construction management: a call for debate. *Construction Management and Economics*, **15**(1): 117–9.
- Vogus, T.J. and Sutcliffe, K.M. (2007) The safety organizing scale: development and validation of a behavioral measure of safety culture in hospital nursing units. *Medical Care*, **45**(1): 46–54.

- Weick, K.E. (1993) The collapse of sensemaking in organisations: the Mann Gulch disaster. *Administrative Science Quarterly*, **38**(4): 628–52.
- Weick, K.E. (1995) What theory is not, theorizing is. *Administrative Science Quarterly*, **40**(3): 385–90.
- Weick, K.E. (2011) Organizing for transient reliability: the production of dynamic non-events. *Journal of Contingencies and Crisis Management*, **19**(1): 21–7.
- Weick, K.E. and Roberts, K.H. (1993) Collective mind in organizations: heedful inter-relating on flight decks. *Administrative Science Quarterly*, **38**(3): 357–81.
- Weick, K.E. and Sutcliffe, K.M. (2006) Mindfulness and the quality of organizational attention. *Organization Science*, **17**(4): 514–24.
- Weick, K.E. and Sutcliffe, K.M. (2007) *Managing the Unexpected: Resilient Performance in an Age of Uncertainty*, John Wiley & Sons, San Francisco.
- Weick, K.E., Sutcliffe, K.M. and Obstfeld, D. (2008) Organizing for high reliability: processes of collective mindfulness, in Boin, A. (ed.) *Crisis Management*, (vol. 3, pp. 31–66), Sage Los Angeles (Reprinted from Research in Organisational Behavior, pp. 81–123, by Sutton, K.M. and Staw, B.M., 1999, JAI Press, Greenwich CT).
- Winch, G. (1989) The construction firm and the construction project: a transaction cost approach. *Construction Management and Economics*, **7**(4): 331–45.
- Wood, G., McDermott, P. and Swan, W. (2002) The ethical benefits of trust-based partnering: the example of the construction industry. *Business Ethics: A European Review*, **11**(1): 4–13.

3. Fieldwork-Based Method for End-User Engagement in Domain Ontology Development

This chapter introduces a fieldwork-based method for end-user engaged ontology development. Our approach complements existing methodologies that, despite their aims to consult end-users and domain experts, have not yet formally spelled out steps for end-user engagement in detail. The method we introduce is based on ethnographic-action research. This grassroots approach allows developers to create feasible ontologies that closely fit end-user needs. Being based on fieldwork, this method extends conventional desk-research and expert-panel methods for data acquisition, conceptualization and validation to more meaningfully derive objects and relations that closely match the work routines of practitioners that eventually use ontologies. This chapter reviews existing post-development methods for end-user involvement and shows how these methods can be complemented with a grounded approach such as ethnographic-action research. We demonstrate the method by developing a semi-formal domain ontology for the subsurface utility construction domain.⁷

3.1. Introduction

Ontologies form the knowledge base of information systems and are defined as formal and explicit specifications of shared conceptualizations (Studer, Benjamins et al. 1998). Conceptualization refers to abstracted and simplified views (Guarino, Oberle et al. 2009) on the reality, or more carefully formulated, the universe of discourse (Turk 2001) we wish to model (the latter term does not imply a real or tangible world, but merely refers to a perceived reality). Shared refers to the multiple views that an ontology should be able to represent. This multi-view representation is necessary, since ontologies that only represent an individual viewpoint are too narrow, being of little relevance to the broader public that eventually uses the ontology. In contrast, too broad and generic ontologies representing concepts beyond a specific domain of discourse might contain redundancies. Redundant concepts unnecessarily complicate an ontology's structure, create ambiguities and make the ontology more difficult to understand by its end-users. Furthermore, ontologies are formal and explicit. These terms refer to the aim of ontologies to describe concepts clearly in a computer interpretable format. More pragmatically, this means that ontologies are comprised of

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objects with time-bounded relations, properties and attributes. Rules and axioms are used to relate various objects that, for example, compose events, instants, processes and states (Chandrasekaran, Josephson et al. 1999).

The scope and purpose of an ontology influence how developers conceptualize various objects, relations and properties. Consequently, ontology developers can represent a single concept in alternative ways. In practice, scopes vary from the general to specific. Most abstract and generic ontologies have a broad scope and are usually called upper-level or top-level ontologies. They have a holistic view on a universe of discourse and use just a few generic concepts to describe this. For some purposes, top-level concepts are too imprecise. Practitioners that, for example, use ontologies in information systems require a more specialized and detailed conceptualization. For this reason, developers often create bounded (Kishore et al. 2004) and more concrete conceptualizations; so called domain ontologies.

This chapter focuses on discussing methods for developing domain ontologies. Such ontologies ideally allow information systems to think and communicate in the language of end-users such as engineers (Katranuschkov et al. 2003). From an interpretive stance, such domain end-users observe, interpret, label and give meaning to phenomena in distinctive ways. So, what is highlighted by one individual might be irrelevant for another. Take, for example, the concept bridge. This seemingly straightforward object can be looked at in different ways. In the context of civil engineering, for example, architects look at this concept using lower-level concepts such as material, colors and shapes, while structural engineers could perceive a bridge in terms of load bearing capacity, materials and construction methods. On the other hand, traffic engineers might highlight concepts such as driving lanes, traffic flows and average driving speed.

The various perceptions of the individuals are incomplete and bounded by rationality (Simon 1976). Due to the bounded cognitive capabilities and varying perspectives on reality, it would be impossible for a modeler to create a conclusive model that perfectly represents all possible viewpoints on a domain. In any model, abstracted concepts hence highlight features that are important for one, but ignore details and complexities for other purposes. At best ontological models therefore only represent a partial understanding of the real world (Turk 2001). What follows from this is that perspectives of developers influence the eventual shape of an ontology as they decide which parts of a domain of discourse they highlight or exclude (Björk 1992). Therefore, develop-

ers need to take due care in investigating the multiple end-user viewpoints on a domain.

Many existing approaches to ontology development acknowledge the need to sufficiently study end-user perspectives. The methodologies, for example, rely on domain expert interviews, panels, brainstorm sessions and end-user boards. One of the problems of these methods is that end-users often have difficulties in verbalizing domain knowledge themselves due to their limited conceptualizing experience. Secondly, domain experts seem distanced from end-user work practices and routines, making it hard to meaningfully conceptualize important domain knowledge. As a result, it becomes difficult to prevent developers from creating comprehensive ontologies that contain more knowledge than needed or miss details for application in a specific domain. To address this problem, we introduce fieldwork-based end-user engagement. Our method provides formal steps for examining and conceptualizing domains through close interaction with the domain.

This chapter is structured as follows: We first summarize how six existing ontology development methodologies formalize end-user engagement for common development steps such as data acquisition, conceptualization and validation. Next, we argue that existing top-down and post development validation methods can be strengthened by using fieldwork. Subsequently, we introduce a formal method—based on qualitative fieldwork techniques such as ethnography and action research—that enables developers to better engage with end-users. Finally, we exemplify how we used this to develop a domain ontology for the urban subsurface reconstruction project domain.

3.2. End-user engagement in ontology development

Ontology developers create models that represent general concepts such as actions, time, physical objects and beliefs (Russell et al. 1995). Steps for creating such abstractions include scoping, data acquisition, concept exploration, definition of terms, structuring and validation. To effectively execute these steps, the process includes the roles of ontology developer, domain expert and end-user. Ontology developers are usually experienced in building models in computer interpretable languages. Further, domain experts are knowledgeable about a domain of discourse. Finally, end-users are practitioners that use information systems of which ontologies are part. Unfortunately, many expert and end-user involvement methods seem to inadequately deliver valuable input in the ontology development process. This section elaborates this point by providing an overview of end-user involvement in the methodologies TOVE, Enterprise, Methontology, DILIGENT, Ontology Engineering Methodology and the

handbook-based ontology development methodology. We summarized our findings in Table 2. We refer to Gómez-Pérez (2004) for more comprehensive comparison of existing methodologies.

In the Toronto Virtual Enterprise (Gruninger and Fox 1995) methodology (TOVE), industry partners provide input for the scope of the ontology. To this end, developers invite end-users to formulate motivating scenarios. To incorporate these in the ontology design, developers create informal competency questions. Answers to these questions define the knowledge that the ontology should be able to provide. Based on the questions, developers identify concepts, requirements, terminologies, definitions and constraints. To validate, developers themselves test whether the ontology, written in computer interpretable language, is technically complete. Additionally, they check whether the ontology answers the competency questions. In sum, TOVE includes end-user's competency scenarios to develop their ontology. However, TOVE misses detailed descriptions of how end-users can convert their knowledge into formulating scenarios effectively.

A methodology that focuses on the creation of an ontology in natural language is Enterprise (Ushold and Gruninger 1996). The approach suggests to first define a scope. Subsequently, it focuses on producing definitions through a middle-out approach. This means that developers move back and forth between identification of higher and lower-level concepts. In the steps that follow, developers review the concepts and devise a meta-ontology. For concept exploration, Enterprise proposes to organize brainstorm sessions with domain experts. Unfortunately, Ushold and Gruninger (1996) do not provide great detail about how end-users and developers could conceptualize in brainstorm sessions. Further, as the developer mainly relies on expert knowledge, Enterprise limits the developer in validating whether conceptualizations are also shared by end-users.

In the last step, the methodology proposes to evaluate the ontology using formal consistency checks and validation interviews. Unfortunately, Methontology does not provide

Table 2 - project characteristics and fieldwork description.

Methodology	TOVE	Enterprise	Methontology	DILIGENT	Ontology Eng. Methodology	'Handbook-based ontology'
Reference	<i>(Gruninger and Fox 1995)</i>	<i>(Uschold 1996; Uschold and Gruninger 1996)</i>	<i>(Gómez-Pérez, Fernández et al. 1996; López, Gómez-Pérez et al. 1999)</i>	<i>(Pinto, Tempich et al. 2009)</i>	<i>(Sure, Staab et al. 2009)</i>	<i>(Hsieh, Lin et al. 2011)</i>
Methods for knowledge acquisition and concept exploration	Competency questions	Brainstorming	Expert meetings, interviews, document analysis	Domain experts involvement, end-users can propose amendments	Ontology re-use, automated document analysis, domain expert consultation	Semi-automatic domain handbook analysis
Validation methods	Formal competency questions	Check model against purpose and user requirements	Consistency and redundancy check, expert inspection	Local adaptations, board reviews	Technical evaluation on consistency, user-focused evaluation	Expert workshops
Expert and end-user involvement	Industry partners formulate 'motivating scenarios'	Domain experts participate in brainstorm	Domain experts verify representational drawings and participate in post-development interviews	Experts, developers, users create initial ontology, end-users and boards suggest and accept adaptations	Experts consultation and interviews, users involved in ex-post evaluation	Domain experts are only involved in upper level concepts definition and review and evaluation

formal steps describing expert’s verification sessions and evaluation interviews. Further, it does not elaborate how developers could check whether the expert viewpoints actually represent the perspectives of the ontology end-users.

Another method for end-user engagement is described in DILIGENT (Pinto, Tempich et al. 2009). The DILIGENT methodology is based on the assumption that ontologies could be developed in a decentralized way—i.e. without developers gathering physically. DILIGENT was developed to address the lack of non-expert software designers in the process of ontology design and allows users to adapt ontologies to their local needs. In the first step of the process that DILIGENT prescribes, a small team of domain experts, end-users and software developers create an initial version of a shared ontology. Then, the team publishes the first shared ontology and allows end-users to adapt the version to their local needs.

Subsequently, a board of developers evaluates local changes and decides whether they also incorporate these in a next version of the shared ontology. The local adaptation and board update can be seen as validation steps that focus on end-user satisfaction and a technical consistency. The steps in the DILIGENT process are iterative: developers go back and forth between development, evaluation and local adaptation. Although end-users can have great input, DILIGENT does not provide detailed steps supporting conceptualizing efforts of developers and end-users.

The next approach is Ontology Engineering Methodology (Sure et al. 2009). This methodology describes how to develop and maintain ontology-based knowledge management applications. It integrates the development of an ontology and the information system in which it will be used. The methodology has five general steps. First, developers set requirements for the ontology (feasibility study). After that they describe a first semi-formal version of an ontology (kickoff) and translate this version in a formal target ontology (refinement). What follows are evaluation, application and evolution steps. For concept exploration, Ontology Engineering Methodology suggests to re-use existing ontologies, conduct automated document analysis or conduct expert interviews. In the validation step, Sure et al. (2009) propose to conduct technology-focused and end-user-focused evaluations. The technology-focused evaluation directs at language conformity, consistency and proper use of formal ontological language, while end-user-focused evaluation aims to validate the ontology from the viewpoint of an end-user. Despite referencing to these end-user engaged methods, this methodology provides little information about how the steps should actually be conducted.

Finally, Hsien et al. (2011) introduce a way to develop an ontology semi-automatically. To this end, they used information systems to extract domain concepts from engineering handbooks. The primary focus of this methodology is to develop a draft earthquake engineering domain ontology. Simultaneously, Hsien et al. (2011) aim to limit time-consuming participation of domain experts. Their methodology therefore uses computers to semi-automatically study engineering handbooks and to develop a glossary of terms. Developers are then proposed to analyze tables of content, definitions and book-indices. From these documents, they extract and organize various concepts and instances. As this methodology's goal is to reduce expert involvement, it implicitly ignores the important task of end-user engagement. The authors admit this by concluding that domain experts were still necessary for post development activities such as revising, weighing and filtering concepts.

The previous ontology development methodologies show various approaches to end-user engagement ranging from motivating scenarios, to re-use of ontologies, brainstorm sessions, interviews and board updates. Although these methods provide relevant input for ontology development and validation, they risk creating inadequate abstractions of end-user domain knowledge. One reason for this might be that existing end-user engagement methods are spelled out only limitedly. Further, it seems that reliance on expert methods does not bring developers close enough to the intricacies within the domain of interest. As experts are often distanced from end-user work tasks and routines, their knowledge seems only partially adequate to create comprehensive domain ontologies. Finally, also end-users have difficulties contributing domain knowledge since these practitioners often have limited experience in verbalizing their own knowledge. Resulting ontologies may contain specification failures, poor conceptualization and consensus problems. Improving representativeness of these ontologies eventually involves consuming validation and rework such as removing redundancies and identifying initially overlooked main concepts.

In reaction to the outlined need to improve representativeness of current ontology development methodologies, this chapter calls for more effective end-user engagement. Therefore, developers need to investigate domains more closely to abstract end-user knowledge. This could be done by applying bottom up strategies (El-Diraby 2012). One such strategy involves fieldwork. When conducting fieldwork, developers step away from their desk to spend a significant amount of time in the domain of study. Here, they learn about practitioners' working culture, practices and routines and find out about domain intricacies. Developers' presence in the field can assist

practitioners in verbalizing their domain knowledge, while they can simultaneously make abstractions based on their own real-life observations.

Another benefit that follows from direct interaction between ontology developers and the domain is that it offers a possibility to implement and validate the ontology (including its information system) directly within the domain: when developers observe this first ontology implementation, they can immediately identify minor changes that are necessary to increase its user-fitness. In contrast with desk-research development, such necessary changes can be identified and addressed quickly whilst ontology developers are actually in the field themselves.

In sum, we argue that fieldwork provides an opportunity to better ground ontological concepts and relations in various end-user perspectives. In our view, this significantly increases user-fitness and representativeness and reduces the likelihood that too-large or irrelevant ontologies are developed. To explain how fieldwork can actually be used in ontology development, the next section spells out our formal steps for a fieldwork-based method.

3.3. Fieldwork-based ontology development methodology

Developers can explore domain practitioners' viewpoints by deploying a fieldwork-based development approach such as ethnographic-action research (c.s. Hartmann, Fischer et al. 2009). This methodology allows ontology developers to adequately conceptualize from an end-user perspective. To this end, it combines explorative and grounded ethnographic research with more engaged action research. We sequentially discuss both research types and integrate these in a formal model for end-user engagement.

Ethnography (Phelps and Horman 2010) originates from cultural studies that aim to grasp socially complex phenomena. Researchers conducting ethnographic studies try to become insiders within a culture as they try to investigate a phenomenon of interest from a close distance during a long-term period of fieldwork. Ethnographers usually join a group, organization or community—e.g. a contractor, project management team, or engineers—to become part of practice and to 'go native'. To discover the concepts and perspectives, ethnographers enter a domain and learn something, try to make sense out of it, verify whether the interpretation made sense in its context, refine the interpretation, and so on (Agar 1996, pp. 62). In contrast with existing desk-research that does not capture detailed end-user knowledge, ethnography allows for

exploration of phenomena that are hard to understand for domain outsiders. In essence, ethnography allows developers to acquire a holistic, end-user-oriented view on a domain, its concepts and language.

Additionally, action research focuses on studying changing practices. In action research, researchers actively participate in a social environment in which they introduce a planned change. Action researchers could, for example, study how an implemented new technology changes work practices by observing a work practice before, during and after the implementation of the technology (Hartmann, Fischer et al. 2009). The researchers investigate these social and technological phenomena by working together with the population of interest, forming “co-participants of enquiry of a change process” (Baskerville 1999). As ontological models are implemented within information systems, developers can use action research to validate an ontology in its domain. Developers can do this by observing how end-users use the information system and, based on this, identify whether additional concepts and relations need to be incorporated in their ontology.

Ethnography and action research complement one another: while the former allows developers to better understand the domain that they model, the latter allows them to implement and evaluate the model in a real-life setting. This subsequently helps developers to adapt ontologies to the needs of practitioners. Hartmann et al. (2009) integrated both approaches and created the ethnographic-action research cycle. They demonstrated it for development of construction management supporting information systems.

We argue that ontology developers can use ethnographic-action research to enhance the feasibility and user-fitness of ontologies. The methodology amends existing desk-research and expert approaches as it provides a more holistic method for domain exploration. As suggested previously, this fieldwork-based approach brings developers closer to the end-user perspective. This subsequently allows them to support practitioners in verbalizing knowledge and to ground conceptualizations in actual observations of practice. Additionally, it offers a way to iteratively validate and improve the domain ontology. Through this, intricate ontology details can be identified while developers can also find out which insignificant generalities to discard.

We adapted the model from Hartmann et al. (2009) for the context of ontology development in Figure 6. In the first step of our adapted ethnographic-action research cycle, developers physically enter a field of study to identify practitioner’s routines and

work practices. They try to learn the local language and then use this language to describe instances, terms and concepts that are part of practitioners' domain perceptions.

Figure 6- ontology development process, adapted from Hartmann et al. (2009).

After the developers arranged these objects, they arrive at a first ontology version, containing various instances, concepts and categories that describe the domain from multiple viewpoints. In subsequent steps, developers can evaluate their ontology by implementing it in a prototypical information system. In the steps that follow, developers use action research to observe how end-users use the prototype in practice. These observations then help to amend or refine concepts represented in the ontology. In the next paragraphs, we elaborate these ontology development steps in detail.

3.3.1. PHASE 1: ETHNOGRAPHIC FIELDWORK

In the first step of our method developers select their population of interest based on the scope and purpose of the ontology. Then they establish first contacts and make practical arrangements in the field. We elaborate on both steps below.

Select Cases for Fieldwork

An in-depth domain study requires developers to work closely together with practitioners. To guide the identification of a project case that meaningfully contributes to the ontology, our method suggests using the ontology's scope and purpose. Additionally, we propose to search for cases representing every day and commonplace situations of a domain. Conceptualizations from this case are assumed to be informative about the domain as a whole (Yin 2003).

As scopes and purposes can vary amongst domain ontologies, this also implicates that different project cases can be studied. For example, narrow scoped ontologies require a selection of cases in a specialized field. Such fields can be unique construction projects, a specific civil engineering discipline, or a type of construction organization. On the other hand, conceptualizing more general domains like 'the civil engineering field' or 'general construction projects,' require a set of participants that have a wider range of expertise.

Establish First Contacts

After identifying case projects, we suggest to establish first contacts with the practitioners that eventually use the ontology. This step aims to align expectations between practitioners and the ontology developer. Here, developers explain the purpose of their fieldwork to gain access to the domain of the end-user. We also suggest developers to make practical appointments about the time frame of their study, the type of phenomena they wish to observe and the expected deliverable.

As developers established contact with practice, they can now start collecting data. For example, developers could ask whether they can observe meetings, conduct interviews and collect documentation. At the start, the fieldwork is nonintrusive: the developer does not yet participate in practice. At later stages, however, the developer increasingly takes an active position and participates in daily tasks and routines.

Conduct Observations

In this step, developers explore practice and try to make sense of practitioners' domains of discourse. To explore the field in a non-intrusive way, we suggest using various methods for observation. Developers could, for example, visit construction sites, stakeholder meetings, or gatherings at offices. At these places, we advise to conduct participant observations (Jorgensen 1989), take out ethnographic interviews (Spradley 1979), study project documentation and have informal chats with practition-

ers. It is important that developers register their first observations in the greatest detail possible. Possible ways to do this are by making field notes, recording meetings on audio or video, taking pictures and collecting meeting minutes. Once the fieldwork started, developers should keep track of their conceptualization ideas. They can do this by writing down unfamiliar words, concepts, instances and terms in a fieldwork-diary. This diary can later guide analysis tasks.

Execute Small Domain Specific Tasks

After the initial exploration of the domain, the next step of the methodology proposes developers to engage with practice more actively. To this end, developers can execute various small engineering or management tasks. This brings developers closer to the insider position and allows them to better reflect on the domain. However, as this active fieldwork is time consuming, developers need to carefully think of how a practical task contributes to the eventual ontology. We therefore suggest developers to continually consider how fieldwork participation fits within the scope of the ontology.

3.3.2. PHASE 2: ANALYZE EMPIRICAL DATA

In this phase, we propose developers to make their first efforts to conceptualize a domain by abstracting and organizing concepts for qualitative field data. This analysis phase should run almost in parallel with fieldwork activities (phase 1) and results in an overview of main concepts and relations within a domain. We base these steps on what is called open coding (step B), axial coding (step C, D) and selective coding (step D and phase 3). Strauss and Corbin (1990) propose to use open coding to examine and conceptualize field data. During axial coding, researchers reorganize and relate the identified concepts. Finally, during selective coding, researchers select a core concept, refine lower-level concepts and systematically relate and validate conceptual relations. We now describe these steps in greater detail.

Assemble Data

We propose to conduct qualitative data analysis to support knowledge abstraction. To this end, this step involves assembling data that has been collected during phase 1. Qualitative data analysis software such as NVivo (2012) and ATLAS.ti (2010) can support this. The packages enable developers to import and store various types of data in a structured way. In the steps that follow, developers can use this to cross-link various document types, and to subsequently extract concepts, terms, instances and relations.

Explore Main Concepts

To extract the main concepts from the vast amount of assembled data, we propose developers to study the field notes, documents, audio files and pictures that have been integrated in the qualitative data analysis software. While reading passages of text, listening back to fragments of audio and studying pictures; we suggest developers to identify and label the ‘pieces of data’ that refer to a concept (open coding, Strauss and Corbin 1990). Once each new concept is created, we suggest continuing identifying additional concepts. It is worth noticing that, during this creative step, developers can create as much labels as they can. There is no need to single out potential concepts in this stage. The list can be seen as the first product that conceptualizes the specific domain through the eyes of practitioners.

Organize and Ground All Concepts

By now developers should have a first idea about the main instances, terms and concepts within the domain. To better organize these, we advise to repeat step B once more. This time, however, we suggest using the list of identified concepts as a guide to label data that was not labeled before. While repeating this coding step, developers can also merge, amend and reformulate concepts that were identified earlier.

Visualize Concepts and Relations

In this step, developers establish conceptual and categorical relations (axial coding, Strauss and Corbin 1990) and start refining all relations concepts, terms and instances (selective coding). Qualitative data analysis tools provide features to visually map these relations. With such tools, developers can map out conceptual relations such as: causes, part-of, property-of, is-associated-with and contradicts with. We suggest visualizing these relations in a tree structure.

3.3.3. PHASE 3: DEVELOP AND IMPLEMENT ONTOLOGY

The provisional insights from the previous steps allow developers to evaluate the first version of their ontology. In this step we propose developers to convert their concepts and relations in a formal model that represents the ontology in computer interpretable language.

As a next step, we propose to implement the draft formal ontology in an information system. This allows developers to validate the ontology in a real-life setting. In this step, developers introduce their information system to its future application domain. They engage with end-users that use the information system as part of their daily rou-

tines. As a first validation step, we propose developers to identify instances of end-users referring to concepts of the draft ontology. Additionally, by observing actual implementation of the information system, developers can identify shortcomings of the information system. These shortcomings feed the identification of additional concepts for the ontology's next version.

All in all, the steps guide developers in gradually creating a valid end-user oriented domain ontology. Although our process model may seem structured in linear phases, we emphasize that several iterations of ethnographic fieldwork, analysis of empirical data and ontology development and implementation are needed to adequately tailor the ontology to end-user needs.

3.4. Developing an inner city subsurface utility domain ontology

This section illustrates how we used the fieldwork-based ontology development method to develop an ontology for end-users in the domain of inner city subsurface utility reconstruction projects. We first describe the domain and elaborate on how an ontology could support its construction management information systems. We then describe the conducted steps and conclude by visualizing our informal ontology.

3.4.1. DOMAIN DESCRIPTION

The modeling efforts for this study took place during two case studies of the urban subsurface utility construction project domain. In this domain, a myriad of authorities, service-providers and contractors work simultaneously on interrelated utility construction activities. Separate contractors work on, for example, street interior renewal, reconstruction of sewer-lines, gas and water pipes, electric grids and fiber-glass cables. To streamline the various construction processes, project managers need to align their construction activities. Information systems can support this challenging coordination task by enhancing managers' understanding of interrelated construction tasks. Additionally, these systems help the managers to create and evaluate alternative construction plans quickly and effectively. Unfortunately, existing information systems lack feasible ontologies that adequately support the end-user viewpoints on inner city utility projects. We therefore conducted two case studies and identified the objects and concepts that professionals use to coordinate utility projects. Based on this, we developed an ontology from scratch.

3.4.2. PROCESS DESCRIPTION

Before we started, we identified our goal and scope: developing an ontology that supports visualizations for the coordination of the inner city subsurface utility construction domain. We limited ourselves to the identification of the main objects that practitioners use to schedule and plan construction projects. We selected two similar multidisciplinary inner city utility projects. Both infrastructure projects took place in a Dutch mid-sized city and comprised reconstruction of a part of the inner city street network. On the first project, one contractor reconstructed an intersection and prepared a connecting main street for future underground construction work. To this end, one main contractor reconstructed street interior and the sewerage system. Additionally, utility contractors renewed and realigned numerous cables and pipes. Finally, a third contractor drilled sheet piles and removed a large amount of contaminated soil.

The second project involved similar construction work: one contractor was responsible for the reconstruction of the sewerage system and street interior, while another contractor reconstructed freshwater tubes, electricity and fiber glass cables, gas pipes and telecommunication lines. Also in this project, existing subsurface infrastructure had to be replaced to prepare future underground construction work. Finally, a contractor of an adjacent hospital project was involved to align construction works on shared public space.

To kick-off the ontology development, we introduced our research to professionals working on the two case projects. Both the project clients and contractors allowed us to study their projects and invited us for their multidisciplinary coordination meetings. In the first project, we mainly used ethnographic research to explore main concepts from the domain. To this end we attended biweekly meetings that took place prior to the actual construction work. We also conducted observations during weekly construction site meetings and additionally observed ongoing construction activities. We tracked our observations as we made field notes. Shortly after each observation event, we processed these notes in a more detailed file. We further audiotaped fourteen meetings, took about three hundred pictures and collected a few designs and meeting minutes.

During the second project, we collected data similarly; we attended multi stakeholder planning meetings and site visits. Additionally, we developed a draft of our ontology and implemented it in a 4D-CAD information system. The system was implemented in a series of real-life multi-stakeholder coordination meetings. We observed the system implementation to validate our ontological concepts for its end-user context. We

summarized characteristics of our fieldwork in Table 3 and provide detailed descriptions of our steps below.

The vast amount of qualitative data that we collected on the first project allowed us to make a first conceptualization of coordination objects in the utility construction project domain.

Table 3 - project characteristics and fieldwork description.

	Project 1	Project 2
Construction work	Replacing sewerage, water and gas pipes, electricity and data cables, and reconstructing intersection to prepare deeper underground construction work	
Stakeholders	Municipality, service providers, civil works contractor, utility contractor, sheet pile contractor, various subcontractors	Municipality, service providers, civil works contractor, utility contractor, hospital contractor, various subcontractors
Ethnographic steps	<ul style="list-style-type: none"> • Observed 3 coordination meetings • Observed 14 onsite meetings 	<ul style="list-style-type: none"> • Observed 4 coordination meetings • Conducted 6 work planner interviews • Observed 2 onsite meetings
Action research steps		<ul style="list-style-type: none"> • Implemented ontology in 4D-CAD model • Evaluated model during 3 additional coordination meetings • Evaluated model during 2 work planner meetings
Taped meetings	14	16
Pictures taken	297	50
Designs and minutes collected	3	8

To do this, we conducted open and axial coding (described in phase two and three of our method). For open coding, we first imported our field notes in the qualitative data coding software ATLAS.ti (2010).

Subsequently, we used this software to mark excerpts from our notes and label each with a string of descriptive text. The following citations show examples of our quoted data (translated from Dutch): *'we have a district station right over there [... and ...] plan to move it over there in the future [...] But can't we do this during our current project?' [utility client]*

'perhaps we need to replace the gas-case from here to there' [utility client]
'we start moving the gas-case at the beginning of next week' [site manager]
'what about the public lightning? [I mean, do we also install] power-supply cables for public lightning?
[site manager] Yes, this will also be incorporated part of your work' [public client]
'the public lightning will also be moved' [public client]
'will we remove the phone booth? I'm not sure, it is not part of the official assignment' [utility client]
'we also have the safety barrier over here. I know, that can also be removed' [contractor]
'do also we need to remove the road signs?' [contractor]
'the container is also located over here, so we have to move it' [public client and contractor]

To abstract these quotes, we grouped them in higher level codes such as *gas district station*, *lightning cable*, *lightning column*, *phone booth*, *safety barrier*, *road marking* and *subsurface waste container*. Subsequently, we used these codes to create a tree-structure that related our codes more explicit. The resulting coarse overview of important concepts, terms and instances helped us to create a first understanding of the utility construction project domain. As these steps increased our domain knowledge and semantic understanding, we could clean the coarse ontology during an axial coding round. In this step, we labeled and coded all data again to provide more detail and find concept relations. For example, our open coding round we derived the concept *gas pipe*. In the successive axial coding round, we identified related lower level concepts and attributes such as *gas pressure*, *gas pipe material*, *welding points* and *pipe protective material*. The resulting list of concepts culminated in our draft ontology.

In a subsequent step, we used the concepts from our draft ontology to guide our ethnographic observations on the second project. Additionally, we conducted action research steps by developing a 4D construction process visualization. We created a project-specific 4D-model incorporating concepts and objects of our ontology. Subsequently, we demonstrated the model during work planner and multi-stakeholder coordination meetings. During these sessions, we validated our draft ontology by observing whether our concepts from the 4D tool were used in discussions. In this coding round, we confirmed earlier identified end-user concepts such as *trees*, *fences* and *welding end-openings*. The observations further provided the additional concept *subsoil*. After two rounds of coding on data from project 1, we conducted selective coding and organized and visualized our draft ontology. Abstractions from project 1 allowed us to further improve our conceptual domain understanding. We used the insights in project 2 to validate and refine concepts. During the 4D implementation, for example, we identified the additional object *foundation block*.

The demonstrated development process continues with various additional iterations between data collection and coding. In essence, we could iterate back and forth continually to refine our domain ontology. As this section is merely illustrative for our method, we decided not to elaborate on these repetitive steps. The final version of our informal ontology comprised 7 high-level concepts, 91 lower-level concepts and 108 concept relations. We depict a selection of this informal draft ontology in Figure 7.

Figure 7 - selection of the informal ontology we developed using our fieldwork-based method.

3.5. Discussion

This study focused on end-user involvement in ontology development methodologies. We analyzed popular methodologies from ontology development and engineering literature and proposed complementary steps for exploration of end-user view on domains. Our fieldwork-based method brings developers closer to the context of the end-user through techniques such as observations, ethnographic interviews and ontology implementation. This inductive conceptualization process allows developers to ground their findings in empirical data. In our field study, for example, the collection of pictures, meeting minutes, audio tapes, ethnographic interviews and observations

of meetings allowed us to ground our concepts in perspectives of end-user in the utility domain. The additional action research we conducted by implementing a 4D-CAD information system further allowed us to validate and further increase user-fitness of our utility domain ontology.

We feel that the presented method can be applied for ontology development in two distinct ways: (1) as in our case study, practitioners could use our method to develop ad-hoc ontologies from scratch, using a bottom up approach. Alternatively, (2) developers can use our approach to involve end-users to further validate and complement ontologies that already exist. In this way, our method helps developers to add ad-hoc, or move out redundant, concepts which contextualize ontologies to domain specificities. In our study, for example, we could have used existing object models such as IFC and CityGML as point of departure for our domain ontology.

One drawback of this latter approach is, however, that developers need to switch continually between top-down and bottom-up conceptualizing as they try to fit ad-hoc concepts in the existing ontology. It can, for example, be difficult to merge ad-hoc concepts with existing top-down-developed concepts as they seem similar, while they actually imply different meanings. Hence, a sound balance needs to be found between top-down and bottom-up approaches to adequately account for user needs of the ontology. Since we could not reveal much about the boundaries of these two distinct approaches, future research is needed to clarify these boundary issues.

One other limitation of this study is that it cannot yet provide conclusive findings with respect to generalizability of identified ad-hoc concepts. This is problematic especially for ontologies that are developed from scratch. Future research should hence focus on developing criteria and steps for distinguishing ad-hoc concepts from the ones that have a high validity for other projects. Such research additionally positions our research better within conceptual modeling debates on reliability of using observational data, reasoning, capturing details, unique views and model generalizability.

Finally, our method assumes frequent stakeholder interaction during concept exploration, validation and evaluation phase. Although this clearly provides benefits with regards to user-fitness and feasibility, we know little about related development costs and resources. Future research should hence compare costs of our approach against traditional post-development methods for user-involvement.

3.6. Conclusion

This study argues that, to be successfully implemented, information systems need ontologies that integrate various end-user viewpoints. Ontologies that fail to do this are of little relevance for practitioners and hamper the adoption of an information system. This chapter shows that various existing ontology development methodologies contain little description of how they aim to address this issue. Current methods for data acquisition, conceptualization and validation suggest, for example, end-user based scope definitions, brainstorm sessions and post development interviews with domain experts. Unfortunately, such steps are often not spelled out formally and limitedly succeed in capturing or verbalizing end-user knowledge. This chapter therefore extends current top-down ontology development approaches and introduces ethnographic-action research. We developed a formal method supporting the creation of ontologies that fit the end-user viewpoints and demonstrated the approach for the domain ontology of the inner city utility construction projects.

Using our method—on its own or in addition to existing methodologies—will allow developers to enhance the user-fitness and representativeness of their domain ontologies. This subsequently customizes information systems more towards end-user needs. In future, this is likely to contribute to more effective information system implementation and adoption processes.

3.7. Acknowledgements

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References

- Agar, M. H. (1996). *The professional stranger: An informal introduction to ethnography*, Academic Press, San Diego.
- ATLAS.ti. Version 6.1. [computer software] (2010). Berlin, Scientific Software Development GmbH.
- Baskerville, R. L. (1999). “Investigating information systems with action research.” *Communications of the AIS*, **2**(19): 2–31.
- Björk, B. C. (1992). “A unified approach for modelling construction information.” *Building and Environment*, **27**(2): 173–194.
- Chandrasekaran, B., Josephson, J. R., et al. (1999). “What are ontologies, and why do we need them?” *Intelligent Systems and Their Applications*, *IEEE*, **14**(1): 20–26.

- El-Diraby, T. (2012). "Epistemology of Construction Informatics." *Journal of Construction Engineering and Management*, **138**(1): 53–65.
- Fernández-López, M. (1999). "Overview of methodologies for building ontologies." In *Proceedings of the IJCAI-99 workshop on Ontologies and Problem-Solving Methods* (KRR5), Stockholm, Sweden.
- Gómez-Pérez, A., Fernández, M., and de Vincente, A. J. (1996). "Towards a method to conceptualize domain ontologies."
- Gómez-Pérez, A., Fernández-López, M., and Corcho, O. (2004). *Ontological Engineering: With Examples From the Areas of Knowledge Management, E-commerce and the Semantic Web*. Springer, London.
- Gruninger, M. and Fox, M. S. (1995). "Methodology for the Design and Evaluation of Ontologies."
- Guarino, N., Oberle, D., and Staab, S. (2009). "What is an Ontology?" in *Handbook on Ontologies*, eds Staab, S. and Studer, R., Springer-Verlag, Berlin Heidelberg: 1–17.
- Hartmann, T., Fischer, M., and Haymaker, J. (2009). "Implementing information systems with project teams using ethnographic-action research." *Advanced Engineering Informatics*, **23**(1): 57–67.
- Hsieh, S. H., Lin, H. T., Chi, N. W., et al. (2011). "Enabling the development of base domain ontology through extraction of knowledge from engineering domain handbooks." *Advanced Engineering Informatics*. **25**(2): 288–296.
- Jorgensen, D. L. (1989). *Participant observation: A methodology for human studies*, Sage Publications Inc. Thousand Oaks.
- Katranuschkov, P., Gehre, A., and Scherer, R. J. (2003). "An ontology framework to access IFC model data." *ITcon* **8**, 413–437, retrieved from <http://www.itcon.org/2003/29> on Aug. 26, 2013.
- Kishore, R., Sharman, R., and Ramesh, R. (2004). "Computational ontologies and information systems: I. foundations." *Communications of the Association for Information Systems*, **14**(1): 158–183.
- López, M. F., A., Gómez-Pérez, and Sierra, J. P., et al. (1999). "Building a chemical ontology using methontology and the ontology design environment." *Intelligent Systems and Their Applications, IEEE*, **14**(1): 37–46.
- NVivo qualitative data analysis software [computer software]; QSR International Pty Ltd. Version 10, 2012.
- Phelps, A. F. and Horman, M. J. (2010). "Ethnographic theory-building research in construction." *Journal of Construction Engineering and Management*, **136**(1): 58–65.

- Pinto, H. S., Tempich, C., and Staab, S. (2009). "Ontology engineering and evolution in a distributed world using DILIGENT." in *Handbook on Ontologies*. Eds Staab, S. and Studer, R. Springer-Verlag, Berlin Heidelberg: 153–176.
- Russell, S. J., Norvig, P., Canny, J. F., et al. (1995). *Artificial intelligence: a modern approach*, Prentice Hall Englewood Cliffs, NJ.
- Simon, H. A. (1976). *Administrative behavior—a study of decision making processes in administrative organisations*, Cambridge University Press.
- Spradley, J. (1979). *The ethnographic interview*, Holt, Rinehart and Winston, NY.
- Strauss, A. L. and Corbin, J. M. (1990). *Basics of qualitative research: Grounded Theory Procedures and Techniques*, Sage Publications, Inc. Newbury Park.
- Studer, R., Benjamins, V. R., and Fensel, F. (1998). "Knowledge engineering: principles and methods." *Data & knowledge engineering*, **25**(1): 161–197.
- Sure, Y., Staab, S., and Studer, R. (2009). "Ontology Engineering Methodology." In *Handbook on Ontologies*. eds. Staab, S. and Studer, R., Springer-Verlag, Berlin Heidelberg, 135–152.
- Turk, Z. (2001). "Phenomenological foundations of conceptual product modelling in architecture, engineering and construction." *Artificial intelligence in engineering*, **15**(2): 83–92.
- Uschold, M. (1996). "Building ontologies: Towards a unified methodology." in *Proceedings of Expert Systems '96, the 16th Annual Conference of the British Computer Society Specialist Group*, University of Edinburgh, Cambridge.
- Uschold, M. and M., Gruninger (1996). "Ontologies: Principles, methods and applications." *Knowledge engineering review*, **11**(2): 93–136.
- Yin, R. K. (2003). *Case study research: design and methods*. Sage Publications, Thousand Oaks, CA.

4. A 4D CAD Based Method to Support Coordination of Urban Subsurface Utility Projects

Coordinators of inner city utility construction works face increasing difficulty in managing their projects due to tight physical restrictions, strict deadlines and growing stakeholder fragmentation. To support their core tasks of scoping, formalizing and synchronizing, this paper presents a 4D CAD based coordination method. We developed and implemented the method by conducting ethnographic action research in four project cases. In these projects, we observed that 4D-models generated with the method allowed practitioners to identify project interfaces and conflicts, identify schedule shortcomings and evaluate delays. In essence, by introducing the method and reporting on its empirical validation we extend 4D CAD's domain of applicability with mid and small-sized utility projects and address a need for 4D implementation studies.⁸

Keywords: subsurface utility projects, coordination, 4D CAD, scheduling, multi-stakeholder

4.1. Introduction

During subsurface utility network reconstruction, service providers install new utilities while simultaneously replacing damaged and aged infrastructure. To minimize the public impact, authorities impose tight temporal and spatial constraints on these works. Within these constraints, multiple service providers simultaneously try to reconstruct their networks. Often, each of them hires a distinctive contractor whose plans need to be aligned with other contractors to finish projects timely and within budget. One great challenge in this tight multi-actor context is to manually align construction schedules. To date, this task is often error-prone since work planners could easily overlook schedule interfaces and details. Such practices of inaccurate scheduling are a major cause of delay in the construction industry (Faridi and El-Sayegh 2006) and negatively affect performance also in utility projects.

One technique that can be used to support this complicated coordination practice is 4D CAD. Despite its potential merit, however, only a few case studies exist that re-

⁸ This chapter has been submitted for a third review to *Automation in Construction* as: olde Scholtenhuis, L. L., Hartmann, T. and Dorée A.G. A 4D-CAD based method to support coordination of urban subsurface utility projects.

port on actual 4D implementation. These studies merely focus on large-scale construction works and limitedly explore 4D CAD usage in smaller infrastructure projects. To fill this gap, this study's goal is to empirically derive an approach that guides development and implementation of 4D in one type of small-sized infrastructure projects: the reconstruction of subsurface utilities. To this end, we empirically studied four utility cases and iteratively developed a 4D CAD based method that supports core coordination tasks of scoping, formalizing project information and synchronizing the master schedule.

This paper is structured as follows: First, we elaborate on how current physical and institutional trends complicate coordination in subsurface utility projects. We then discuss how state-of-the-art 4D CAD tools can support this challenged practice. Next, we describe both our research approach and the four cases that we studied to develop a 4D CAD based coordination method. In the sections that follow, we explain how we validated the coordination method in two complementary ways. The discussion and conclusion finally reflect on how our findings contribute to 4D CAD literature and existing scheduling practices in the utilities sector.

4.2. Coordinating intricacies in urban subsurface utility works

To explain the challenging coordination context that state-of-the-art 4D CAD tools can support, this section describes various physical and institutional trends that complicate project-level coordination of urban subsurface utility works.

From a physical point of view, past decades showed a proliferation of urban utility networks both in number and geographical coverage. This resulted in veritable mazes of utilities, serving buildings in neighborhoods and parts of larger grid systems (Lancaster, Plotkin et al. 2001). Underground space gradually becomes even scarcer nowadays: subsoil that bears light traffic loads already hosts buried utilities such as freshwater pipes, gas pipes, electricity cables and telephone lines, while the remaining underground is often packed with existing sewer lines, water basins, waste disposal containers and abandoned infrastructure. In nearby future, this space will be even further reduced by added new systems such as smart-grids, fiber glass networks, subsurface waste collection and energy storage.

The different material properties of utility networks also cause coordination complexity. Since utility networks have distinctive lifecycles ranging from ten to thirty years, each network would require maintenance on different moments in time. Consequent-

ly, maintenance work of various utility owners should be streamlined to prevent undesirable situations where intersections and roads are being broken up continually.

Furthermore, institutional-level developments such as liberalization and privatization have increased fragmentation in the utilities sector. Previously, utility networks in most democratic countries were owned and maintained by governments. Nowadays, however, governments only own sewer systems while private service providers take care of gas, water and electricity networks. On their turn, these providers hire dedicated contractors to schedule and execute reconstruction work. As a consequence, information about subsurface assets is now distributed over myriads of public and private stakeholders.

The institutional developments have also altered project-level coordination. Due to fragmentation, utility reconstruction works nowadays rarely have a single main project owner. Instead, these projects are comprised of a network of multiple contractors who are hired by distinctive service providers. So, unlike many other infrastructure projects, there is no contractor-subcontractor coordination hierarchy in utility reconstruction works. Consequently, stakeholders can hardly enforce plans and stay individually responsible for managing interfaces with the construction plans of others.

Project-level schedule alignment commonly takes place as contractors and clients manually extract and mentally process scheduling information from one another's project documentation. During coordination meetings, they use sketches, drawings and draft schedules; verbally discuss dependencies between these plans and try to integrate them in a master schedule. The following example about the reconstruction of sewerage underneath an inner city road intersection illustrates how physical and institutional trends have affected coordination practice: To reconstruct an inner city road intersection and sewer network, gas pipes and electricity lines need to be re-aligned as well.

In this case the municipality and her contractor schedule and execute both road and sewer construction activities. Within the same time frame, two service providers and their specialized contractors occupy the construction site to reconstruct gas and electricity networks. In absence of any hierarchical coordination, the three clients and three contractors rely on each other's participation when aligning their construction schedules. To date, this alignment takes place manually, which is often a difficult and cumbersome practice. Time pressures may further complicate the illustrated situation. These pressures are often a cause for the development of too tight and inaccurate

schedules (Koster 2012). Such schedules necessitate re-planning and increase project duration. Alternatively, if tasks are scheduled too loosely, cycle times increase, project expenditures rise and the burden on the public grows. To effectively deal with this trade-off, we assume that three main conditions need to be achieved during construction coordination:

- Clients and contractors *scope* their project parts by identifying relevant project constraints and construction tasks;
- They *formalize* this project information into project artefacts such as designs and schedules; and
- *Synchronize* the master schedule by evaluating interdependencies and interfaces between their scheduled construction tasks.

State-of-the-art 4D CAD technologies offer a way to support scoping, formalizing and synchronizing tasks. The remainder of this paper elaborates on 4D, and introduces a 4D-based method that supports these tasks in practice.

4.3. State-of-the-art and current advancements in 4D CAD research

This paragraph outlines features and research directions in the domain of 3D-4D construction visualizations. 4D CAD tools “link three dimensional graphic images to the fourth dimension of time [...] Such a model allows planners to visualize the construction process as it would be actually built” (Koo and Fischer 2000). By visualizing the actual transformation of a space over time during construction (Webb, Smallwood et al. 2004), 4D helps practitioners to understand a construction plan more realistically (Wang, Zhang et al. 2004). Further, 4D-model elements such as symbols and icons can visually convey a large range of additional contextual project information (Hartmann and Vossebeld 2013).

Literature shows that 4D tools can support multiple construction project management tasks. 4D tools, for example, help to: develop an intuitive understanding of a project (Heesom and Mahdjoubi 2004), to better communicate and review designs (Hartmann and Fischer 2007, Mahalingam, Kashyap et al. 2010), as well as to detect conflicts and review project progress (Mahalingam, Kashyap et al. 2010). The tools also potentially support cost estimating and in-depth analysis of construction operations (Hartmann, Gao et al. 2008). Further, an exploratory study shows that construction stage 4D BIM models can reduce requests for information, rework and change orders and improve

schedule compliance (Fan, Skibniewski et al. 2014). Additionally, 4D has been applied to guide construction planning, resource management and site space utilization (Wang, Zhang et al. 2004) as well as linear task scheduling and workflow scheduling (Jongeling and Olofsson 2007, Russell, Staub-French et al. 2009). More recently, 4D applications were also used for safety and risk management (Hu and Zhang 2011, Hartmann and Vossebeld 2013, Kang, Kim et al. 2013, Zhou, Ding et al. 2013).

Besides exploring these potential purposes, 4D research also focuses on various other themes. One recent theme directs at technical extensions of 4D CAD. Studies focus on developing methods and algorithms that 4D CAD scheduling with integrate remote sensing (Kim, Son et al. 2013) and image processing (Golparvar-Fard, Peña-Mora et al. 2011, Kim, Kim et al. 2013) technologies. Experiments showed that such automatic updating of 4D-models seem to meet or exceed manual progress tracking and monitoring (Turkan, Bosche et al. 2012).

Additionally, last years' research developed methods to connect 4D CAD with cost estimation, schedule and workspace simulations. Object sequencing matrices and genetic algorithms were, for example, used to enrich 3D models with scheduling knowledge to automatically develop cost-time schedules (Feng, Chen et al. 2010). Similarly, Wang, Weng et al. (2014) showed how to use BIM quantity take-offs to feed operations simulation packages and create 4D construction schedules. Further, 3D models have been expanded with automatic workspace generation and schedule simulation systems to support workspace optimized re-scheduling (Moon, Dawood et al. 2014). Another study focused on a special application of 4D CAD and introduced a model that integrates 4D CAD with checklists and assessment templates for quality inspections (Chen and Luo 2014).

Although recent studies have added relevant features to 4D systems, literature provides less attention to implementation issues of existing 4D tools. Applied studies are therefore necessary to develop knowledge about intricate field operations of trade specialties. Without such understanding, modelers might not know which objects to include in their 4D-model or how to depict these properly (Fan, Skibniewski et al. 2014). Botton, Kubicki et al. (2013) partly addressed this by developing a generic business view method that translates information needs of trade disciplines (Botton, Kubicki et al. 2013) into coordinated 4D-model views.

Furthermore, a few studies elaborate on how 4D models can be used to support coordination in real-life projects. These studies report on an intuitive implementation of

4D in larger infrastructure and high-rise construction (Mahalingam, Kashyap et al. 2010), large scale highway projects (Zanen, Hartmann et al. 2013) and metro projects (Zhou, Ding et al. 2013). However, little is known about 4D CAD implementation in smaller infrastructure projects such as, for example, utility reconstruction projects. To address this shortcoming, this research aims to develop and empirically validate a 4D-method that supports coordination of subsurface utility reconstruction works.

Below, section 4.4 describes this study’s ethnographic action research approach. These efforts culminated in the 4D based method that supports coordination tasks of scoping, formalizing and synchronizing (section 4.5). Section 4.6 validates this method by elaborating on the design iterations made while developing the method, and by presenting observed 4D benefits.

4.4. Research approach

This section discusses how we used ethnographic action research (Hartmann, Fischer et al. 2009) to iteratively develop a coordination method for utility projects. We first discuss the methodology, then describe the four case projects and finally elaborate how our analysis enabled the incremental design of a practically applicable coordination method.

Our adopted research methodology integrates ethnography and action research techniques. In ethnography, researchers physically join a cultural domain, such as a construction organization, to experience and identify its intricate routines and practices. In action research, researchers and practitioners collaboratively design, implement and reflect on changes that address a real life organizational problem. In system development both approaches are complementary to each other: ethnography allows researchers to develop a detailed understanding of a domain, while action researcher subsequently allows to customize solutions (methods and systems) to the needs of the domain (c.f. Baskerville 1999).

We used ethnographic techniques such as participant observation (Jorgensen 1989, Agar 1996) to first explore current practices of scoping, formalizing and synchronizing project schedules. To this end, we observed coordination meetings and identified how practitioners manually align construction plans. During subsequent action research (Baskerville 1999) efforts, we worked together with work planners and utility project designers to develop tailored 4D-models. The models were demonstrated during multi-stakeholder coordination meetings. Here, we kept track of discussions about possible uses of 4D for coordination and also observed interactions with the devel-

oped 4D-models. Additionally, reflection sessions were organized to obtain more feedback on the content and value of each projects' 4D-model.

During the course of the study, data was collected in various ways: we kept track of modeling efforts in a written 4D-log; created a field diary to register important observations, and both tape and video recorded practitioners' interactions with, and discussions about, 4D models. We analyzed obtained data with the qualitative data analysis software ATLAS.ti (2010). As outlined in section 4.4.2, our analysis focused on identification of 4D-model elements that practitioners considered to be necessary or redundant for utility coordination. Furthermore, we identified which of the used 4D visualization techniques supported specific coordination purposes.

4.4.1. DESCRIPTION OF STUDIED UTILITY PROJECTS

The first project involved the reconstruction of an inner city road intersection and construction of sewer lines and utilities in an adjacent street. At the execution phase of this project we joined the municipality, civil works contractor and utilities contractor during their site visits and coordination meetings. After observing five coordination meetings, we developed and implemented a 4D-model and reflected on it during two sessions.

The second project involved the reconstruction of utilities at an inner city road intersection. In this project, utilities had to be relocated to facilitate the construction of a tunnel. We joined the project stakeholders— i.e. service providers, the municipality, civil works contractor and utility contractor — during planning stage coordination meetings. Further, we arranged five scheduling sessions with utility companies and one with a utility contractor. Additionally, we organized two separate sessions to reflect on the project's 4D CAD models.

Our third project involved the reconstruction of 450m sewer line and several intersecting utility pipes in a residential area. The team consisted of representatives from the municipality and civil works contractor. We developed a 4D CAD model at the start of the project's execution phase and introduced it during three coordination meetings and a separate reflection session.

On the fourth project, we were involved during the planning and execution phases of 900m sewer line and street interior reconstruction project. The project team consisted of the municipality, an engineering consulting firm and a civil works contractor. We created a 4D-model prior to the construction activities, presented it in three

Table 4 - description of case projects, their stakeholders and the collected project artefacts.

	Project 1	Project 2	Project 3	Project 4
Project description	Inner city intersection reconstruction involving minor sewerage and utilities reconstruction	Sewerage and utilities replacement on inner city road intersection	Sewer and street level reconstruction (450m) in residential area, reconstruction of gas and water pipes	Sewer replacement and street level reconstruction (900m) in residential area.
Project team members	<i>Municipality:</i> Project manager, Supervisor <i>Civil works contractor:</i> Project manager, Work planner Site manager <i>Utilities contractor:</i> Site manager	<i>Municipality:</i> Project manager, Supervisor <i>Civil works contractor:</i> Project manager <i>Service provider:</i> 5 Work planners <i>Utilities contractor:</i> Work planner	<i>Municipality:</i> Project manager, Supervisor <i>Civil works contractor:</i> Project manager, Site manager	<i>Municipality:</i> Project manager, Supervisor <i>Civil works contractor:</i> Project manager, Work planner Site manager <i>Engineering consultancy:</i> consultant
Fieldwork events	3 Site visits, 5 Coordination meetings	6 Work planning sessions, 8 Coordination meetings	3 Coordination meetings	3 Coordination meetings, 1 Work planner intvw.
Reflection sessions and participants	Meeting with contractor foreman, Meeting with municipality's technical designer	Meeting with 4 engineers from energy provider & with utilities contractor's planner	Meeting with municipality's technical designer	Meeting with civil contractor's work planner
Collected artifacts	5 Meeting minutes, 2 2D-CAD maps of current project conditions, 1 Phasing sketch, 3 2D-CAD designs, 1 Master schedule	7 Meeting minutes, 6 2D-CAD maps of current project conditions, 2 Phasing drawings, 1 Surface design sketch, 2 Design sketch utilities, 1 2D-CAD 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	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

coordination meetings and reflected on it during a separate session. Table 4 describes the projects and our research efforts in greater detail.

4.4.2. USING QUALITATIVE ANALYSIS TO DEVELOP THE COORDINATION METHOD

In the first step towards synthesis, we designed a concept of the 4D based coordination method. As a starting point for this method we used the practical modelling experience that we gained during the first project. We refined the concept method during the three subsequent projects by continually analyzing practitioners' discussions and comments about the content of the projects' 4D-models. Some discussions indicated that we correctly modeled project details, while others showed that vital project elements were not represented adequately by our 4D models. Based on these discussions, we could either validate the appropriateness of the steps in our method, or amend the method in such a way that its next version included the missing elements. Updated versions of the method were subsequently tested in successive projects. We repeated these iterative cycles till only a few changes were necessary in the method.

In section 4.6.1, we show how our method evolved during the course of the four utility projects. To maintain readability, section 4.5 first discusses the (final) 4D CAD based coordination method for utility projects that resulted after four iterations.

4.5. Resulting 4D based coordination method for shallow subsurface utility projects

This paragraph describes the final version of the coordination method. As shown in figure 8, the method comprises three main phases: project scope analysis, scope formalization and synchronization of tasks in the master schedule.

4.5.1. SCOPE ANALYSIS

The first phase of the coordination method involves grasping the content and boundaries of all the reconstruction activities that are planned by the multiple stakeholders. As described in construction management literature (Winch 2008), such understanding can be acquired by identifying the project's scope. Our method distinguishes three scope identification steps: analysis of main reconstruction tasks; determining the level of detail, and identifying environmental and utility network constraints.

Figure 8 - the 4D based coordination method for urban subsurface utility construction projects; iteratively developed during four utility projects.

As a first step, the method proposes to identify and analyze the main reconstruction tasks. To this end, one retrieves scheduling information, phasing drawings and meeting minutes from service providers and contractors. If this is not explicitly available,

service providers can also be consulted to obtain sequencing and scheduling knowledge (Hartmann and Fischer 2007). Based on the information delivered by the various stakeholders, we then suggest to identify projects context and, for each separate discipline, establish a first overview of the main reconstruction activities, cycle times, sequential relations, resources and workspace requirements. At the end of this step, the output should be a list with construction activities and stakeholder dependencies. In the successive phase, it is proposed to formalize this information in a multi-stakeholder master schedule.

Furthermore, utility projects involve distinctive disciplines that work with objects of different sizes. The next scoping step hence suggests to collectively defining a level of detail for the schedules and visualizations that they plan to develop. Since 4D visualizations do not require every single project component to be included, we suggest selecting only the objects that are necessary to represent the identified construction tasks. Generally, the level of detail of 4D-models should also depend on the moment in the project's life cycle: while early stage long-term schedules mostly contain abstract task descriptions, short-term schedules usually also incorporate detailed tasks.

For example, one can identify detailed objects such as land boundaries, existing cables, pipes and tree roots at an early project stage. At that moment, the model also includes larger-scaled object sets such as sewer pipes strings and large pavement sections. As the project progresses, more detailed objects need to be modeled as well. These are, for example, ditches, curbstones and utility housing connections. The method finally proposes to segment sewerage in tubes, manholes and joints at even later project stages.

The final scope analysis step identifies utility networks and environmental constraints. Utility network constraints usually stem from network reliability requirements. One such requirement is to minimize network downtime. To achieve this, service providers only allow contractors to plan networks disruptions within specific time frames. For example, telecom providers will not allow construction and maintenance activities to take place during large-scale sports events, Christmas, or national holidays. Further, water suppliers oftentimes try to avoid large-scaled network reconstructions during hot summer days, while energy suppliers do not plan reconstructions during winter. The method proposes to collect all these constraints from involved service providers.

Finally, authorities often define environmental constraints. Such constraints can be, for example, construction deadlines and restrictions related to the accessibility of pub-

lic space. The method suggests identifying constraints that are temporal and spatial, since both aspects can limit the degrees of freedom while drafting reconstruction schedules. Temporal constraints influence possible start dates of construction tasks or limit task durations, while spatial constraints physically restrain available onsite work-space.

4.5.2. FORMALIZING SCOPE INFORMATION

In the second phase of the coordination method, we propose to model the scope information by formalizing project objects into 3D-models and integrating these with a master schedule. One precondition for this step is that stakeholders agree on the meaning of the objects and processes they intend to formalize. This shared ontological understanding is essential since stakeholders in multidisciplinary domains such as utilities may use identical labels to point at distinctive phenomena. For example, a label such as ‘excavating’ seems to unambiguously refer to one set of objects or processes, while stakeholders can actually use this label differently to point at distinctive excavation areas, depths, equipment, methods or sub-process. Shared understanding of used terms is therefore required to formalize a 4D model that represents stakeholders’ intended plans.

A first formalizing step in the coordination method proposes to set up a provisional master schedule based on the identified reconstruction tasks and their sequential dependencies. In this schedule, temporal and spatial constraints can be implemented as a deadline, milestone, or task.

The next formalization steps include modeling the construction objects in 3D. Various object types can be modeled for utility projects. Based on their meaning, geospatial and temporal characteristics the method distinguishes the following categories: (1) *transient accessibility and workspace objects*; (2) *aged utilities, road assets to be removed and other obstructing subsurface objects*; (3) *designed utility networks and road infrastructure* and (4) *non-transient contextual spatial orientation objects*.

First, the method proposes to model *transient accessibility and workspace objects*. The name of this object group is derived from the ‘transient objects’ in the framework of Hartmann and Vosseveld (2013). Such objects represent conditions that temporarily limit construction space. They do not necessarily exist physically. The method suggests two complementary ways to identify these: First, one can use environmental constraint analysis outcomes to find objects that limit the available construction space. Such objects are, for example, active traffic flows, bus routes and occupied public space.

Second, the list of identified construction activities can help to identify objects that temporarily reduce construction site space. Examples are workspaces like excavation trenches, soil deposits, logistical space, drilling areas and dewatering zones.

A next formalization step concerns modeling the aged utilities, *road assets to be removed and other obstructing subsurface objects*. This category consists of objects that will be demolished, moved, replaced or renovated. Available maps of existing subsurface utilities provided by the land registry office can be used to identify removable infrastructure such as pathways, asphalt, foundations, cables, pipes, tubes, road sections, foundations and sewerage networks. Descriptions of such objects can also be found in object libraries such as CityGML Utility ADE (Becker, Nagel et al. 2012) and in the urban civil infrastructure taxonomy (El-Diraby and Osman 2011).

During the next formalization step within in our coordination method, *designed utility networks and road infrastructure* are modeled. These are the objects that will be built during the construction project and can be extracted from clients' designs, sketches and CAD-drawings.

Finally, the method proposes to model *non-transient contextual spatial orientation objects*. The name of this category stems from the 'non-transient' object types that existing literature defines (Hartmann and Vossebeld 2013). These objects represent the environment in which the construction activities take place, and remain unchanged while construction progresses. Examples of such objects are: buildings, street names and private property plots. These objects can be collected from project environment maps provided by land registry offices and local authorities.

Table 2 summarizes the four categories of objects and the sources from which they can be extracted. The first and second columns describe objects types and their corresponding meaning, column three provides examples.

4.5.3. SYNCHRONIZATION OF DESIGN PLANS AND MASTER SCHEDULE COMPONENTS

The coordination method's third phase involves the synchronization of the tasks in the master schedule. At this stage, contractors and service providers can use 4D as a platform to visually explain and discuss relations between reconstruction tasks of service providers. Below, we first outline the grouping and integration of 3D-objects with scheduled tasks. Subsequently, we propose three ways to implement 4D to support

synchronization, these are: timeline snapshotting; process animations and key-date snapshotting.

Table 5- object categories for modelling urban shallow infrastructure projects: types, meaning, examples.

Object type	Semiotic meaning	Example
Transient accessibility and workspace objects	Represents temporal objects that constrain construction space. Objects in this category are not necessarily a physical object	Temporary traffic routes, road signs, available construction site spaces excavation trenches, drilling spaces, dewatering zones
Aged utilities, road assets to be removed, obstructing subsurface objects	Represents existing objects that will be removed, replaced or transformed	Cables, pipes, roads, foundations, sewerage network, tree roots
Designed utility networks and road infrastructure	Represents objects in future situations	
Non-transient contextual spatial orientation objects	Refers to project environments and provide visual cues for virtual navigation through the project	Building, street names, buildings, trees, private property plots

The first synchronization step proposes to create object sets that convey information about each task in the reconstruction project's master schedule. The level of detail in the master schedule can be used as a guide to create these sets. Essentially, we suggest that when the schedule breaks down one large task into multiple smaller tasks, corresponding 3D-objects should be divided or sectioned accordingly. In reverse, to represent one task in the master schedule, multiple 3D-objects should be combined into one single object group. Resulting object sets are, for example, "demolished pavement section 1.2", "sewer pipes 1-4" and "utility connection-2". An alternative way to cluster objects is based on object-contractor relations. This approach is helpful to visualize the activities of the multiple contractors. Examples of such object sets are: "pavement contractor A" and "gas pipe 2.4 contractor B". Next, object sets should be appended to the corresponding tasks in the master schedule. Once this has been done, objects' visual appearance and colors settings (Chang, Kang et al. 2009, Ya-

Hsin, Meng-Han et al. 2013) need to be configured to clearly represent tasks in the planned construction process.

The resulting 4D-model can be used during utility project coordination meetings. For one, the method proposes *timeline snapshots* to support communication of project plans and evaluation of sequencing alternatives. To this end, one extracts images from the 4D-model to visualize the planned status of reconstruction works on start and finish dates of tasks. By sequencing these images, one obtains a step-by-step slideshow of the as-planned reconstruction activities.

Second, the method proposes to use *process animation* videos to generate a detailed overview of the scheduled construction processes. This allows third parties and sub-contractors to quickly grasp the nature of all planned reconstruction work. Additionally, process animation supports a visual rehearsal of the project and allows service providers and utility contractors to analyze project interfaces and to identify physical jobsite conflicts.

Third, the coordination method proposes to use *key-date snapshotting*. When using this technique, one extracts as-planned project visualizations on key-dates such as milestones and deadlines. By comparing the actual project status with these images project managers can monitor and discuss project progress; assess extents of delays and develop delay mitigation plans.

To discuss how the coordination method evolved during the research, the next section outlines our validation outcomes.

4.6. Validation

We validated the 4D based coordination method in two ways: First, iterative development and testing ensured that the method supports actual work practices (Zanen, Hartmann et al. 2013). Second, practitioners' use of 4D-models during coordination meetings allowed us to observe benefits of 4D. This indirectly validates how our method supports the development of a practically applicable 4D-model. We elaborate the results of the two validation approaches below.

4.6.1. ITERATIVE DEVELOPMENT OF THE COORDINATION METHOD

In ethnographic action research, validation can be seen as an ongoing activity during the development and implementation of tools. We illustrate this by providing exam-

ples of how feedback on 4D implementation incrementally improved the coordination method.

Our efforts in the first project focused on the identification and modelling of designed utility and road infrastructure objects. Based on the project scope, we formalized the objects representing designed road infrastructure (figure 9a) and utilities (as in figure 10a).

Figure 9 - modeled designed road infrastructure objects in project 1,2,3,4 (resp. a, b, c, d).

We implemented the model and used process animation videos to support discussions during a stakeholder meeting. While reflecting on the 4D-model, practitioners argued that it adequately visualized the current and future project conditions. However, they also stated that it lacked information about surrounding streets and land plots. Further, practitioners found that visual cues that indicate deadlines and milestones could be added to enhance understanding of the construction progress. The feedback provided in project one eventually resulted in the amendment of the method with the steps ‘model non-transient contextual spatial orientation objects’ and ‘modelling temporal project constraints’.

Figure 10 - modeled designed subsurface infrastructure in project 1,2,3,4 (resp. a, b, c, d).

In the second project we modeled designed infrastructure objects (figure 9b); subsurface utilities (figure 10b) and non-transient contextual spatial orientation objects (figure 12a). Further, we analyzed the additional modelling activities that we conducted during this project. This expanded the method in three ways: First, since the stakeholders had not yet created a schedule when we became involved in the project, we created one from scratch. This step was added to the method by formulating the task ‘assess task dependencies and convert into master schedule’. Second, the project’s reflection discussions revealed that one needs to determine the level of detail for the 4D model in such a way that it captures the relevant tasks and objects of all project stakeholders. To incorporate this, we amended the coordination method with the step ‘level of detail-analysis.’ Third, we also modeled new types of transient objects. These were, for example, utility installation trenches, welding workspaces (figure 11a), signs, and temporary road blocks (figure 11b). To incorporate these in the method, we redefined the step ‘model temporal project constraints’ into ‘model transient accessibility and workspace objects’.

Figure 11 - modeled transient accessibility and workspace objects: (a) cable trenches and (b) traffic rerouting flows in project 2, (c) dewatering zones in project 3 and (d) sewerage trench in project 4.

In the third project we also identified the project scope and modelled street level infrastructure (figure 9d), subsurface utilities (figure 10c), transient accessibility and workspace objects (e.g. temporary dewatering and sewer line bypasses, figure 11c), and non-transient contextual spatial orientation objects (e.g. street names and land contours, figure 12b). One example of how project three expanded our method was the addition of ‘timeline snapshotting’. We used this technique to create understanding of how intersecting construction activities of a facility contractor and civil contractor could be sequenced.

Also during our fourth project, we identified the project scope and formalized the objects to be removed, future street level objects (figure 9d), designed utility infrastructure (figure 10d) workspaces (figure 11d), and contextual objects (e.g. trees, figure 12d). We made only a minor change to the method by relating ‘identified tasks and LOD overview’ to the step ‘create objects sets and attach to schedule’ after we experienced that we often consulted the level of detail in the master schedule while creating 3D object sets. Finally, we moved toward saturation since analysis of fieldwork and reflection sessions did not require other changes to the method.

Figure 12 - modeled non-transient contextual spatial orientation objects: (a) trees and surroundings in project 2, street names and trees in (b) project 3, and (c) project 4.

4.6.2. OBSERVED BENEFITS OF 4D CAD

A second validation took place by observing how project stakeholders experienced benefits from the 4D-models that were generated with the method. This paragraph provides examples of such benefits and discusses how 4D supported tasks such as: detecting potential design conflicts (formalizing), elaborating schedule omissions, understanding project interfaces and conducting delay analysis (synchronizing).

We observed benefits of 4D CAD when practitioners used 3D visualizations to identify potential conflicts between the infrastructure designs of the different clients. In this study 2D-CAD drawings were first converted into 3D-models before they were implemented in 4D process visualizations. Since this enabled 3D inspections of the designs, 3D conflict detection can be seen as a feature of the 4D based coordination practice. During the second project, for example, spatial conflicts were detected once an engineer noticed that a piece of underground foundation of an adjacent building constrained the design space for his utilities. He zoomed in on it and argued (all verbatim quotes are translated from Dutch):

“That’s right. On that side we also have the entrance of the hospital building [...] with several foundation columns. As you can see, we [cannot install our pipes] right underneath that place.”

The visualized situation was in conflict with the company’s design protocol because the building and gas network were not located at sufficient distance. This triggered the engineer to investigate the issue in detail. In another example, 4D supported the utility contractor’s project planner when he studied interfaces and conducted clash analysis. He zoomed in on various places where gas pipes and tree roots intersected and argued as follows:

“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”.

After this observation, the planner wrote down a description of this conflict and addressed it during the next official project meeting.

Additionally, we observed how the 4D model generated with our method helped practitioners to identify shortcomings and omissions in the master schedule. In the fourth project, for example, the work planner explained his construction schedule by making use of 4D visualizations. While doing this, he noticed that his schedule contained an error. He then asked:

“Can you navigate to next week? Pavement activities are probably completed in the visualization by then, right? [In reality, this is not correct] because I forgot to incorporate a week of summer holiday in this [visualized] schedule.”

We also observed that 4D CAD allowed practitioners to integrate drawings and schedules to better understand the interfaces and sequential relations between construction activities. This understanding occurred, for example, when an engineer watched the second project’s animation. He questioned whether the task sequencing was correct when the 4D-model showed him that a telecom line installation was ongoing while gas pipes were not yet installed. He argued:

“This situation is not possible, since a telecom line installation never precedes gas installation activities.”

By using the 4D-model, another engineer realized that electricity lines and gas pipes were not well aligned in the design. He argued that the 4D model did not integrate both utility lines in a single trench, although that would be more cost-efficient.

Further, 4D CAD appeared to be beneficial when discussing project delay. In the third project, for example, practitioners used our timeline snapshots to identify extents and causes of delay at the time of a project coordination meeting. Similarly, in the fourth project they compared the as-planned situation with the actual situation onsite. Then, the work planner argued:

“This is right ... excavations already took place, or not? Look, we are already excavating and preparing [pavement] foundations right there, but our sewer has only been constructed till here.”

Table 6 - summary of the coordination method's iterative improvement (column 1) & observed benefits of its use (column 2).

Iterative improvements of the method (examples)	Observed benefits of 4D based coordination (examples)
<u>Project 1:</u> Created steps: model aged utilities, road assets to be removed, obstructing subsurface objects model utility and road infrastructure design objects Added step: model non-transient contextual spatial orientation objects	Practitioners used 4D based coordination to: Detect potential conflicts between foundation and utilities as well as between gas pipes and tree roots Elaborate omitted holiday week in schedule Discuss scheduled interfaces between telecom cable and gas pipe installation Conduct analysis about root and cause of excavation delay
<u>Project 2:</u> Added step: assess task dependencies and convert into master schedule Added step: level of detail-analysis Redefined step: ‘model temporal project constraints’ as ‘model transient accessibility and workspace objects’	
<u>Project 3:</u> Added step: timeline snapshotting	
<u>Project 4:</u> Added link: Create objects sets and attach to schedule	

Typically, the above quotations exemplify benefits of 4D based coordination. It is shown how 3D models help to gain insight in design conflicts and enhance understanding of project interfaces, while integration of these models with schedules

structures process thinking. In sum, the previous paragraphs show how validation took place while we (1) iteratively developed and implemented the method and (2) observed its benefits in practice. These findings are summarized in table 6.

4.7. Discussion

This study's ethnographic action research approach enabled us to empirically develop and validate a 4D-method that supports scheduling practices in the subsurface utility domain. Findings provide evidence that 4D supports alignment of service providers and contractors involved in utility projects. This section elaborates on these contributions and provides suggestions for future research.

Besides the method as its main contribution, this study extends literature in two ways. First, we bring 4D research and application beyond existing large-scale construction projects (Mahalingam, Kashyap et al. 2010, Zanen, Hartmann et al. 2013, Zhou, Ding et al. 2013). Although one can logically expect that large and smaller projects face comparable coordination problems – yet on a different scale - 4D usage in mainstream infrastructure projects has been limited to date. By developing a method that supports coordination of urban utility reconstruction works, we provide a first case that shows how to achieve benefits from applying 4D tools to more regular construction projects.

Second, most existing 4D literature focuses on system prototype development (c.f. Dawood, Sriprasert et al. 2003, Bansal and Pal 2009, Russell, Staub-French et al. 2009, Mawlana, Hammad et al. 2012) and integration of 4D with technologies such as remote sensing and simulation. These studies are relevant for development of state-of-the-art 4D-tools but often exclude technology implementation aspects. Consequently, fewer attention is given to the argument that understanding of real-life organizational practices is necessary to design information systems that effectively support practice (Boton, Kubicki et al. 2013, Fan, Skibniewski et al. 2014). Implementation studies are needed to gain such understanding. In this respect, our method contributes implementation knowledge and supports integration of current manual coordination practices with 4D coordination techniques.

The remainder of this section addresses suggestions for future research. First, we reflect on the potential value of 4D for coordination purposes that were not observed in this study. Practitioners suggested such 'anticipated 4D benefits' after they had watched the 4D models that we developed during the four cases. 4D was, for example, expected to:

- Help managers communicating construction plans to colleagues, suppliers or third parties: The foreman in the first project, for example, argued that 4D visualizations potentially support him when communicating the sequence of planned construction works to clients. Engineers added that the models also help informing external stakeholders about project plans.
- Support the development of site logistics plans: The municipal designer in the third project, for example, indicated that sewer pipes and soil oftentimes need to be deposited on a small construction site. He found it helpful to use a 4D CAD model in early stages to find suitable storage places for these objects.
- Support identification of conflicts between the planned construction work and its surrounding environment: The work planner on the fourth project saw potential in using 4D when assessing the consequences of delay on availability of public spaces. Similarly, the municipality's designer in this project argued that the 4D-model could be used to check whether a construction plan fits earlier project phasing plans, if it properly reroutes traffic and whether it achieves deadlines.
- Perform a feasibility check for developed schedules: The work planner in project four, for example, argued that it occurs frequently that he reconsiders initial plans after he realizes that they appear not to be feasible. He thought that the 4D-model may be helpful in earlier stages to make sure that his project leaders, foremen and work planners commonly understand and agree on the project's initial schedule.

We suggest future research to analyze how the proposed 4D method needs to be adapted to achieve these anticipated benefits.

Besides studying anticipated benefits, we also suggest future research steps to address the limitations of this study. We elaborate these points below. For one, this study's ethnographic approach enabled us to tailor the 4D based method to its community of practice, and to empirically observe how the 4D models supported real life coordination. From a research methodological perspective, it would however be stronger to test the proposed 4D based coordination method by investigating whether similar benefits would have been observed without the use of the method. We therefore suggest future research to compare coordination in a case in which the proposed method is applied with a similar case in which it is not. This comparison could be extended meaningfully by also collecting data on coordination costs to evaluate the cost-effectiveness of 4D implementation.

Next, one may reasonably assume that the coordination method's scoping, formalization and synchronization phases apply to construction and civil engineering projects in general (such as in Mahalingam, Kashyap et al. 2010, Zanen, Hartmann et al. 2013). However, since we developed and verified the method only for utility projects, we suggest conducting next research steps to explore whether these phases are indeed applicable to a broader domain. This suggested research could also explore how to extend the coordination method with state of the art 4D features such as automated progress monitoring (Golparvar-Fard, Peña-Mora et al. 2011, Turkan, Bosche et al. 2012, Kim, Kim et al. 2013, Kim, Son et al. 2013, Kim, Anderson et al. 2013), schedule simulation (Feng, Chen et al. 2010) and automated quality inspection (Chen and Luo 2014).

Another limitation is that practitioners in this study lacked the skills and facilities to develop and implement 4D-models themselves. The authors therefore had to take on these tasks. Such active involvement is common in engaged research approaches (Van de Ven 2007), but inevitably influences practitioners' uptake and use of 4D CAD. To reduce this effect, researchers could take a more distanced role in future when studying practitioners' abilities to implement the proposed 4D coordination method.

Furthermore, scholars assume that 4D adoption requires new competences (Succar, Sher et al. 2013) and tasks. Although such tasks can be fulfilled by 4D specialists or information model managers (Barison and Santos 2010, Gu and London 2010), it can be argued alternatively that 4D-coordination functions should be integrated within existing organizational roles. Consecutive studies should therefore investigate how tasks in our proposed 4D-coordination method can be allocated to actors in organizations.

Additionally, we propose future research to develop color schemes for 4D visualizations in multi-stakeholder meetings. In our research, different sets of colors were tried and tested. From the iterations it emerged that identifying understandable color sets becomes more difficult as the number of stakeholders involved increases. Unfortunately, existing color schemes are developed for single-contractor projects (e.g. Chang, Kang et al. 2009, Ya-Hsin, Meng-Han et al. 2013). As modelers in multi-stakeholder projects should be cautious in accepting these schemes, future research could devote attention to develop color schemes for multidisciplinary construction projects.

Another point for further research relates to notion of 4D as a BIM tool. Ideally, BIM systems support "parametric modeling and allow new levels of spatial visualization,

simulation of the behavior of the building, as well as more efficient project management” (Miettinen and Paavola 2014). Building information models contain geometric as well as non-geometric design and construction information (Nath, Attarzadeh et al. 2015). In our study, however, 4D model were not parametric in nature, neither were they attributed with meta data. Instead, we developed 4D visualizations by only converting 2D polylines into surfaces and 3D extruded objects, and by linking these objects to manually created schedules. This approach easily integrates with existing 2D-based manual work styles, but delivers 4D models that are less useful during later stages in the project life cycle. Therefore we suggest conducting more research on developing implementation methods for 4D BIM in utility projects. In turn, this work will contribute to the growing amount of BIM studies that conceptually describe models to, for example: integrate building information models with project management data systems during project delivery (Monteiro, Mêda et al. 2014), enable BIM usage in shop drawing creation (Nath, Attarzadeh et al. 2015) and use BIM to obtain a competitive edge (Love, Matthews et al. 2014).

Finally, one stream of literature focuses on project specific arrangements for BIM. This BIM Execution plan literature proposes templates for defining roles and responsibilities of stakeholders, BIM goals and uses and required technical infrastructure (Computer Integrated Construction Research Program 2010, Centre for Construction IT 2013). Although existing BIM Execution plans may be applicable to infrastructure projects as well, they predominantly focus on facility construction. In addition, they limitedly elaborate on how a BIM practice should integrate with existing manual project management styles. Taking our study as a point of departure, future research could address these shortcomings by identifying requirements for Infrastructure BIM Execution plans.

4.8. Conclusions

Shallow subsurface utility projects are, by large, coordinated manually. Utility project clients and contractors often try to align their construction plans through paper-based discussions in construction meetings. Nowadays, these practices become more time consuming and error-prone since public pressures are exerted to minimize project cycle times. More complexity is added by the fragmentation of ownership and control over utilities. As a result, reconstruction schedules are often sub-optimally aligned, causing delays and cost overruns. To support this challenged practice this study’s aim was to empirically develop an approach that enhances coordination of subsurface utility projects. Iterative development and identification of 4D-benefits validated this

method, and show how practitioners can enhance manual practice with 4D based coordination.

To develop the method, we used ethnographic action research in four urban utility reconstruction projects. We identified current coordination practices, iteratively developed 4D-models for four projects and evaluated how these models were used in coordination meetings and reflection sessions. This paper presents the method that resulted after four iterative cycles of 4D model development, implementation and evaluation. Essentially, the method describes:

- Main coordination stakeholders who provide information sources and constraints for utility reconstruction (e.g. service providers, authorities and registry offices). They scope and explicate construction plans;
- Most relevant utility reconstruction objects that need to be formalized in a project's 4D-model (e.g. accessibility objects and workspace, road assets to be removed, subsurface objects, designed utility networks and road infrastructure, and non-transient contextual spatial orientation objects), and
- Application techniques that use 4D-models as a platform to synchronize the master schedule (e.g. timeline snapshotting, key date snapshotting and process animations).

We validated the method by continually testing whether 4D-models - that were created by following the method - matched practitioners' needs. In addition, we observed that the developed 4D models supported coordination tasks such as detection of potential design conflicts (formalizing), analysis of schedule omissions and project interfaces, and investigation of delays (synchronizing).

Besides contributing the method, this study extends literature on 4D CAD in two ways: First, the empirically observed benefits provide evidence of how 4D CAD can be used in a range of utility project coordination tasks. This use in smaller sized utility projects extends 4D CAD's application domain and complements to previous research on 4D in large scale infrastructure and high-rise projects. Second, our empirical examples of 4D implementation enrich recent 4D literature that focuses mostly on technical extensions of 4D systems.

Practitioners' reflections on the use of 4D models resulted in a shortlist of anticipated benefits of 4D. They, for example, indicated that 4D is likely to support coordination tasks such as: communicating construction plans (scoping), developing site logistics

plans (formalizing tasks), evaluating the relation between construction plans and processes in the surrounding the project site, and verifying schedules (synchronization). We suggest future research to explore how the proposed method should be tailored to support these benefits. We also recommend conducting additional research to: compare a case in which the 4D method is used with a case of manual coordination; investigate application of the method to the broader civil engineering domain; study how utility project professionals can gain skills to implement 4D CAD in their organization; develop multi-stakeholder color schemes for 4D visualizations; and finally, integrate the proposed 4D-method with BIM approaches and execution plans.

As a summarizing reflection, we argue that 4D based coordination helps utility project managers to reduce uncertainties and to synchronize reconstruction schedules. Consequently, errors and delays become less likely. This eventually contributes to overall reliability of utility reconstruction works.

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References

- Agar, M. H. (1996). *The professional stranger: An informal introduction to ethnography*. San Diego, Academic Press
- ATLAS.ti (2010). Berlin, ATLAS.ti Scientific Software Development GmbH.
- Bansal, V. and M. Pal (2009). "Construction schedule review in GIS with a navigable 3D animation of project activities." *International Journal of Project Management* **27**(5): 532-542.
- Barison, M. B. and E. T. Santos (2010). An overview of BIM specialists. *Computing in Civil and Building Engineering, Proceedings of the International Conference*, Nottingham, UK, Nottingham University Press, Paper.
- Baskerville, R. L. (1999). "Investigating information systems with action research." *Communications of the AIS* 2(3es): 4.
- Becker, T., C. Nagel and T. H. Kolbe (2012). *CityGML UtilityNetworkADE*. Berlin, Open Geospatial Consortium.
- Boton, C., S. Kubicki and G. Halin (2013). "Designing adapted visualization for collaborative 4D applications." *Automation in Construction* **36**: 152-167.

- Centre for Construction IT (2013). *BIM Essential Guide for BIM Execution Plan*. Singapore, Building Construction Authority.
- Chang, H.-S., S.-C. Kang and P.-H. Chen (2009). "Systematic procedure of determining an ideal color scheme on 4D models." *Advanced Engineering Informatics* **23**(4): 463-473.
- Chen, L. and H. Luo (2014). "A BIM-based construction quality management model and its applications." *Automation in Construction* **46**: 64-73.
- Computer Integrated Construction Research Program (2010). *BIM Project Execution Planning Guide - Version 2.0*. University Park, PA, USA, The Pennsylvania State University.
- Dawood, N., E. Sriprasert, Z. Mallasi and B. Hobbs (2003). "Development of an integrated information resource base for 4D/VR construction processes simulation." *Automation in Construction* **12**(2): 123-131.
- El-Diraby, T. and H. Osman (2011). "A domain ontology for construction concepts in urban infrastructure products." *Automation in Construction* **20**(8): 1120-1132.
- Fan, S.-L., M. J. Skibniewski and T. W. Hung (2014). "Effects of Building Information Modeling During Construction." *Journal of Applied Science and Engineering* **17**(2): 157-166.
- Faridi, A. S. and S. M. El-Sayegh (2006). "Significant factors causing delay in the UAE construction industry." *Construction Management and Economics* **24**(11): 1167-1176.
- Feng, C.-W., Y.-J. Chen and J.-R. Huang (2010). "Using the MD CAD model to develop the time-cost integrated schedule for construction projects." *Automation in Construction* **19**(3): 347-356.
- Golparvar-Fard, M., F. Peña-Mora and S. Savarese (2011). "Integrated sequential as-built and as-planned representation with D 4 AR tools in support of decision-making tasks in the AEC/FM industry." *Journal of Construction Engineering and Management* **137**(12): 1099-1116.
- Gu, N. and K. London (2010). "Understanding and facilitating BIM adoption in the AEC industry." *Automation in Construction* **19**(8): 988-999.
- Hartmann, T. and M. Fischer (2007). "Supporting the constructability review with 3D/4D models." *Building Research & Information* **35**(1): 70-80.
- Hartmann, T., M. Fischer and J. Haymaker (2009). "Implementing information systems with project teams using ethnographic-action research." *Advanced Engineering Informatics* **23**(1): 57-67.
- Hartmann, T., J. Gao and M. Fischer (2008). "Areas of application for 3D and 4D models on construction projects." *Journal of Construction Engineering and Management* **134**(10): 776-785.

- Hartmann, T. and N. Vossebeld (2013). "A semiotic framework to understand how signs in construction process simulations convey information." *Advanced Engineering Informatics* **27**(3): 378-385.
- Heesom, D. and L. Mahdjoubi (2004). "Trends of 4D CAD applications for construction planning." *Construction Management and Economics* **22**(2): 171-182.
- Hu, Z. and J. Zhang (2011). "BIM-and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials." *Automation in Construction* **20**(2): 167-180.
- Jongeling, R. and T. Olofsson (2007). "A method for planning of work-flow by combined use of location-based scheduling and 4D CAD." *Automation in Construction* **16**(2): 189-198.
- Jorgensen, D. L. (1989). *Participant observation: A methodology for human studies*, Sage Publications, Inc.
- Kang, L. S., S.-K. Kim, H. S. Moon and H. S. Kim (2013). "Development of a 4D object-based system for visualizing the risk information of construction projects." *Automation in Construction* **31**: 186-203.
- Kim, C., B. Kim and H. Kim (2013). "4D CAD model updating using image processing-based construction progress monitoring." *Automation in Construction* **35**: 44-52.
- Kim, C., H. Son and C. Kim (2013). "Automated construction progress measurement using a 4D building information model and 3D data." *Automation in Construction* **31**: 75-82.
- Kim, H., K. Anderson, S. Lee and J. Hildreth (2013). "Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology." *Automation in Construction* **35**: 285-295.
- Koo, B. and M. Fischer (2000). "Feasibility study of 4D CAD in commercial construction." *Journal of Construction Engineering and Management* **126**(4): 251-260.
- Koster, I. W. (2012). *Hardlopen, doodlopen?* Verkenning van urgentie en procesoplossingen voor tijdsdruk in de infrastructurele bouw, CROW.
- Lancaster, P. J., E. S. Plotkin and J. N. Lerner (2001). *Construction in Cities: Social, Environmental, Political, and Economic Concerns*. Boca Raton, CRC Press.
- Love, P. E., J. Matthews, I. Simpson, A. Hill and O. A. Olatunji (2014). "A benefits realization management building information modeling framework for asset owners." *Automation in Construction* **37**: 1-10.
- Mahalingam, A., R. Kashyap and C. Mahajan (2010). "An evaluation of the applicability of 4D CAD on construction projects." *Automation in Construction* **19**(2): 148-159.

- Mawlana, M., A. Hammad, A. Doriani and S. Setayeshgar (2012). Discrete event simulation and 4D modelling for elevated highway reconstruction projects. *International Conference on Computing in Civil and Building Engineering V*. Telichenko, A. Volkov and I. Bilchuk. Moscow.
- Miettinen, R. and S. Paavola (2014). "Beyond the BIM utopia: Approaches to the development and implementation of building information modeling." *Automation in construction* **43**: 84-91.
- Monteiro, A., P. Mêda and J. P. Martins (2014). "Framework for the coordinated application of two different integrated project delivery platforms." *Automation in Construction* **38**: 87-99.
- Moon, H., N. Dawood and L. Kang (2014). "Development of workspace conflict visualization system using 4D object of work schedule." *Advanced Engineering Informatics* **28**(1): 50-65.
- Nath, T., M. Attarzadeh, R. L. Tiong, C. Chidambaram and Z. Yu (2015). "Productivity improvement of precast shop drawings generation through BIM-based process re-engineering." *Automation in Construction* **54**: 54-68.
- Russell, A., S. Staub-French, N. Tran and W. Wong (2009). "Visualizing high-rise building construction strategies using linear scheduling and 4D CAD." *Automation in Construction* **18**(2): 219-236.
- Succar, B., W. Sher and A. Williams (2013). "An integrated approach to BIM competency assessment, acquisition and application." *Automation in Construction* **35**: 174-189.
- Turkan, Y., F. Bosche, C. T. Haas and R. Haas (2012). "Automated progress tracking using 4D schedule and 3D sensing technologies." *Automation in Construction* **22**: 414-421.
- Van de Ven, A. H. (2007). *Engaged scholarship: A guide for organizational and social research*, OUP Oxford.
- Wang, H., J. Zhang, K. Chau and M. Anson (2004). "4D dynamic management for construction planning and resource utilization." *Automation in Construction* **13**(5): 575-589.
- Wang, W.-C., S.-W. Weng, S.-H. Wang and C.-Y. Chen (2014). "Integrating building information models with construction process simulations for project scheduling support." *Automation in Construction* **37**: 68-80.
- Webb, R. M., J. Smallwood and T. C. Haupt (2004). "The potential of 4D CAD as a tool for construction management." *Journal of Construction Research* **5**(1): 43-60.
- Winch, G. M. (2008). *Managing construction projects*, Wiley-Blackwell. United Kingdom

- Ya-Hsin, C., T. Meng-Han, K. Shih-Chung and L. Chin-Wei (2013). Selection and evaluation of color scheme for 4D construction models, *ITcon* **18**.
- Zanen, P., T. Hartmann, S. Al-Jibouri and H. Heijmans (2013). "Using 4D CAD to visualize the impacts of highway construction on the public." *Automation in Construction* **32**: 136-144.
- Zhou, Y., L. Ding and L. Chen (2013). "Application of 4D visualization technology for safety management in metro construction." *Automation in Construction* **34**: 25-36.

5. Testing the value of 4D visualizations to enhance mindfulness in utility reconstruction works

This paper reports about an ethnographic-action research study of 4D-based coordination in three utility projects. We show that development and use of 4D models in planning meetings for urban utility construction work enhances mindful behavior, making stakeholders: (1) sensitive to operational processes, (2) pre-occupied with errors and inaccuracies, (3) attentive to design and schedule details, resistant to simplifying reality as well as (4) resilient and aware of process alternatives. By demonstrating that 4D enhances mindfulness and, in turn, improves coordination, we contribute to literature with a first step in the analysis of the causal relationship between 4D, coordination and project performance. We provide a practical contribution by showing that stakeholders in utility projects can use 4D to better anticipate and contain unwanted situations. This helps them to tackle coordination issues effectively and may eventually reduce overruns and rework in utility construction planning.⁹

Subject headings: 4D visualization, Coordination, High Reliability Organizing, Mindfulness, Project Management, Scheduling, Underground Construction, Utilities

5.1. Introduction

Urban subsurface utility projects have an adverse impact on life in surrounding public space (Nguyen, Nguyen, Tran and Villiers, 2014). Reconstructions of, for example, sewer tubes, electricity cables and gas pipes often obstruct traffic routes and public spaces, and create disturbing noise and 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, service providers and municipalities organize multidisciplinary coordination meetings. In these meetings, stakeholders are involved at different moments in time. In addition, they use distinctive formats to explicate their construction plans. Eventually, the goal of the coordination meetings is to integrate these different components of the overall construction plan in both a feasible design and reliable master schedule that anticipate on design errors and process conflicts. Such scheduling efforts are already extensive and time consuming in current manual coordination practices (Kim, Anderson, Lee and Hildreth, 2013).

⁹ This paper is currently being revised. It will be submitted for a second review to the *Journal of Construction Management and Engineering* as: olde Scholtenhuis, L. L., Hartmann, T. and Dorée A.G. Testing the value of 4D visualizations to enhance mindfulness in utility reconstruction works.

Throughout the past two decades, two developments further complicated utility project coordination: First, liberalization and privatization policies gradually shifted responsibility for construction, operation, and maintenance of subsurface networks - and network information - from a few public organizations to myriads of private utility companies (e.g. Steenhuisen, Dicke and de Bruijn, 2009). Second, the accelerated roll out of smart grids (EU, 2010, pp.14) and introduction of other network technologies such as fiber glass, subsurface waste collection and energy storage systems, increased the density of our cities' subsurface networks; adding more organizations to the utility sector.

Although the proliferation of utility networks and stakeholders further increased the need to align (re)construction plans, existing time pressures often provide little room for stakeholders to analyze interrelated design details and process interfaces. This may result in over-simplified construction plans and tight schedules. Consequently, errors that could have been anticipated upfront 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 overruns and frustrates the public.

To support such complex coordination processes, literature suggests that practitioners can adopt 4D instruments (e.g. Khanzode, Fischer and Reed, 2008, Trebbe, Hartmann and Dorée, 2015). These tools integrate parts of the overall 3D design with their corresponding master schedule, resulting in an integrated animation of a planned construction process. Although literature reports about the specific purposes and benefits of 4D (e.g. Kang, Kim, Moon and Kim, 2013, Russell, Staub-French, Tran and Wong, 2009), there is, however, limited knowledge available about the relation between 4D implementation and overall project performance. One main reason for this might be that it is difficult to statistically analyze this relation due to the limited uptake of 4D in construction projects, the variety between the nature of 4D-projects as well as the difficulties to obtain reliable performance information. To address this gap, this study introduces the mindfulness concept as a lens to test in a qualitative way how 4D influences utility project coordination and performance.

The results from this ethnographic-action research study of 4D implementation in three utility reconstruction cases shows that 4D allows stakeholders to follow mindfulness principles such as (1) being sensitive to operational processes and their interactions, (2) reluctant to simplify, (3) focused on inaccuracies and failures, and (4) committed to resilience. Since stakeholders that follow these principles operate more

mindfully, they can more effectively detect and manage accumulating small errors and derailing processes (c.f. Weick and Roberts, 1993, Weick, Sutcliffe et al. 2008). The positive relation between 4D and improved mindfulness suggests, in turn, that the tool also helps to enhance coordination. Since coordination is a determinant of project success (Neeraj Jha and Misra, 2007), these results eventually also demonstrate that 4D contributes to enhanced project performance.

The remainder of this paper is structured as follows: The next paragraph elaborates existing research on 4D and explains how the concept of mindful organizing helps to evaluate the impact of 4D on coordination. The paper continues by elaborating how the authors implemented 4D to support and observe coordination in three utility reconstruction cases. The next section then relates the observations to the principles of mindfulness. Finally the discussion and conclusion elaborate on the implications of our findings and suggest steps for future research.

5.2. Theoretical points of departure

The construction sector is known by its large degree of subcontracting and fragmentation (Eccles, 1981). Multiple organizations hence need to collaborate to align their plans and achieve their shared goals. Also in the utility sector, growth in both amount of stakeholders and increased heterogeneity of actor constellations resulted in institutionalized fragmentation (Steenhuisen, Dicke and de Bruijn, 2009). Such fragmented contexts create significant challenges to achieve effective anticipation and containment of potential obstructions (De Bruijne and Van Eeten, 2007, Vogus and Sutcliffe, 2012).

To address these challenges, utility reconstruction works could implement technologies such as 4D. This tool integrates geometrical 3D-CAD models with time-plans as fourth dimension (Koo and Fischer, 2000) and visualizes the transformation of space over time (Webb, Smallwood and Haupt, 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, for example, support managers to develop detailed understanding of operational complexities and to identify potential problems (Heesom and Mahdjoubi, 2004).

Literature shows that 4D tools provide various benefits: they support project management tasks such as communication, design review, and bid preparation (Hartmann, Gao and Fischer, 2008), evaluation of construction methods and scheduling strategies (Russell, Staub-French, Tran and Wong, 2009), constructability reviews (Hartmann

and Fischer, 2007), construction planning, workflow planning and resource utilization (Jongeling and Olofsson, 2007, Wang, Zhang, Chau and Anson, 2004), risk management (Kang, Kim, Moon and Kim, 2013), and safety management (Zhou, Ding and Chen, 2013). Additionally, empirical 4D literature provides guidelines for 3D design and 4D construction coordination (Staub-French and Khanzode, 2007) and elaborates use of 4D in mechanical, electrical, and plumbing coordination (Khanzode, Fischer and Reed, 2008). In addition, real-life case studies show how 4D supports infrastructure projects with environmental impact visualizations (Zanen, Hartmann, Al-Jibouri and Heijmans, 2013), collaborative planning and scheduling (Kang, Anderson and Clayton, 2007) and trades coordination (Trebbe, Hartmann and Dorée, 2015).

Although literature provides evidence about specific purposes and benefits of 4D, little is known about the impact of the tool on overall project performance. One main reason for this is that 4D technologies are not implemented yet in mainstream construction practice. In addition, the few existing 4D projects vary to a great extent in both nature and scale. As a result, it is difficult to collect and compare statistical evidence about the relation between 4D and project performance. To address this need, 4D research can focus on coordination, which can be seen as antecedent of project success (Neeraj Jha and Misra, 2007) and performance. The concept of mindfulness helps to systematically assess coordination practices. This, in turn, helps to test the relation between 4D, coordination and performance.

The concepts mindfulness (Langer, 1997, Sternberg, 2000) and collective mindfulness (Vogus and Sutcliffe, 2012, Weick and Sutcliffe, 2007) were first adopted by High Reliability Organizing scholars. These scholars originally 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, n/a), business schools (Ray, Baker and Plowman, 2011), and construction organizations (Brady and Davies, 2010, Mitropoulos and Cupido, 2009) anticipate on disruptions and errors, and contain emerging unwanted situations. Such unwanted situations are referred to in literature as dysfunctional momenta (Barton and Sutcliffe, 2009) and arise when derailing processes are not re-evaluated and uninterrupted. When organizations behave mindfully, they identify the subtle cues that allow for such a re-evaluation. 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). This mindful practice seems relevant for the analysis of anticipation and containment processes that are present in every construction planning practice.

Essentially, mindful organizing comprises of five principles (Weick, Sutcliffe et al. 2008) that support coordination. Three principles focus on effective anticipation of unwanted events, the other two concentrate on the repression of such events once they occur. Here, we elaborate 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 in operational processes by integrating parts of the design models and schedules. Second, mindful organizations are *pre-occupied with failures* that occur within their organization. This means they stimulate stakeholders to report errors and near-failures and try to learn from past mistakes. 4D tools can increase attention for failures through visual and automated inspection of task dependencies as well as design 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 reality in detail. In theory, 4D tools should support this behavior by delivering a rich virtual integration of detailed design and schedule components.

To also 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. 4D supports this by allowing stakeholders to develop and evaluate alternative construction 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 to use flexible decision making structures. According to this principle, decision making follows the hierarchy in an organization except when unexpected obstructions emerge. Then, decision making migrates to the experts that can adequately and 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.

The next paragraphs explain how the authors implemented and observed 4D usage in three utility reconstruction works and elaborate how 4D contributes to behavior along the

5.3. Research Method

To study how 4D technologies support coordination in utility reconstruction works, we used ethnographic-action research (Hartmann, Fischer and Haymaker, 2009). Essentially, this approach uses ethnographic methods to study existing work cultures and practices, and integrates this with action research methods to develop information systems and evaluate their impact in a practical context. The authors used the ethnographic-action research approach to develop, implement and evaluate 4D-models during three real-life utility projects.

Table 7 - descriptive summary of the three utility reconstruction cases.

	Project 1	Project 2	Project 3
Project tasks	Realigning inner city utilities	Reconstructing sewer line (900m)	Reconstructing sewer line (450m)
Main time focus	Planning stage	Execution stage	Execution stage
Scheduled Duration	~1 year	~5 months	~7 months
Observed meetings	6	6	5
Collected artefacts	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	<i>Municipality:</i> Project manager, Supervisor <i>Civil works contractor:</i> Project manager <i>Service provider:</i> 5 Work planners <i>Utilities contractor:</i> Work planner	<i>Municipality:</i> Project manager, Supervisor <i>Civil works contractor:</i> Project manager, Work planner Site manager <i>Engineering consultant</i>	<i>Municipality:</i> Project manager, Supervisor <i>Civil works contractor:</i> Project manager, Site manager

The first case is comprised of the realignment of utilities in inner city space. The project duration was estimated 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 developed and implemented 4D models to support six coordination meetings. The second project involved the reconstruction of a 900 meter sewer line in a residential area. In this five month-project the

research team was involved during the planning phase as well as the construction stage. During the construction stage, 4D models were developed to support six meetings. Similarly, the third project involved the reconstruction of 450 meter of sewer line in a residential area. The project duration was approximately seven months. Here, we also developed a 4D model together with the project team and implemented it during five multi-stakeholder meetings. Table 7 descriptively summarizes the three cases.

In the three cases, the research team took the lead in developing and implementing 4D models. To create these models, the team followed a 4D visualization method for utility projects (olde Scholtenhuis, Hartmann and Dorée, in revision). To this end, they collected practitioners' schedule files, 2D drawings and sketches, and reformatted these into formal 3D models and explicit Gantt-charts. The resulting models were integrated into a 4D visualization. Feedback from stakeholders was used to continually improve and adapt the model to practitioners needs. Furthermore, the first author moderated parts of the coordination meetings by navigating through the 4D model on request of the stakeholders. We made notes and tape-records of these meetings to collect data about how the 4D-models influenced mindful behavior. All the data was assembled and analyzed with support of the qualitative data analysis tool ATLAS.ti.

The analysis comprised of open and axial coding (Strauss and Corbin, 1990) steps. Open coding is a stage in the qualitative analysis process where concepts are derived from empirical data in a grounded way. From the raw data, the authors first used open coding to identify actions and statements that described benefits and use of 4D models. Axial coding was then used to relate these observations to the mindfulness principles. In axial coding, one relates observations to one another by using, for example, existing constructs. In this study, we used theoretical *mindfulness constructs* derived from measurement instruments such as the Safety Organizing Scale (Vogus and Sutcliffe, 2007), Mindfulness Audits and the Mindfulness Organizing Scale (Weick and Sutcliffe, 2007 pp. 94-103). Originally, these instruments are used to assess how organizations perform mindfully on a meta-level. However, since our study focuses on activities at operational level, we used these instruments to derive observable mindful operational activities and statements. This resulted in a list containing mindful constructs. This list is presented in table 8 and structures observable actions and statements based on the five mindfulness principles.

Table 8 - breakdown of mindfulness principles in observable actions and statements (derived from Safety Organizing Scale (Vogus and Sutcliffe, 2007), Mindfulness Audits and the Mindfulness Organizing Scale (derived from 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

As a next step, we used the constructs from table 8 as a guide to categorize the identified actions and statements from the open coding stage. The following example illustrates how we conducted open coding, and how we subsequently related identified codes to constructs from table 8 (axial coding): 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, we labelled this excerpt and used the code ‘identifying possible obstacles’ to indicate that 4D created awareness of possible errors. During axial coding, we then attributed the open code to ‘detecting construction process conflicts and inaccuracies and trying to understand them.’ This, in turn, was categorized as part of the mindfulness principle ‘pre-occupation with failure’.

5.4. Results

This paragraph presents our findings. Table 9 shows the amount of observed actions and statements that relate to the theoretically derived constructs of mindfulness. Below, we elaborate a selection of our observations to show how 4D increased mindful behavior in our three cases.

Table 9 - observed constructs and instances of 4D-enhanced mindfulness.

Mindfulness principle	Derived actions and statements (selective codes derived from theory)	Number of related 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 nature of potential problems	19
	Expressing and discussing different viewpoints and alternatives	3
Commitment to resilience	Building response repertoires	4
Deference to expertise		0

5.4.1. SENSITIVITY TO OPERATIONS

For the principle of sensitivity to operations we observed actions and statements mainly related to the theoretical constructs ‘trying to understand operations beyond one’s own job’, ‘building a clear picture from current situation’, and ‘paying attention to operations from day-to-day’. **Regarding trying to understand operations beyond one’s own job** we observed that 4D models helped to understand interfaces and relationships between the various processes at the construction site. This was, for example, observed when a work planner in project 2 elaborated how the 4D model demonstrated the interactions between the pavement crew and sewer installation crew. He verified that these activities were synchronized properly by pointing at the green objects in the model in figure 13a (representing sewer construction at the left; and paving at the right). He then stated:

“At this place, you can see paving and sewer construction nicely aligned. You see that the sidewalk is under construction, while you [simultaneously] start with sewage installation here.”

Similarly, service provider in project 1 watched the 4D visualization and argued that 4D helped to show how his work interacted with processes in the public space:

“At a certain moment, [when your process involves a] directional drill or pneumatic mole to cross the road’s subsurface, [4D clearly visualizes] that the bus traffic remains in operation.”

Other sensitivity enhancing actions we observed related to the theoretically derived code **building a clear picture from current situations**. We found that the process of developing 4D models stimulates the explication and formalization of plans with greater detail. This subsequently led to the development of schedules containing a higher breakdown of tasks in multiple smaller activities. Furthermore, to facilitate an automated 4D-update of changed schedules, stakeholders also increased their detail focus by modelling the sequential relations between tasks.

Figure 13 - selected examples of 4D models that helped to enhance sensitivity to operations (a, b, c) and preoccupation with failure (d).

Such resulting detailed models were, for example, used by the jobsite supervisor in project 3 (figure 13b) to create a clear picture of the actual progress. He compared the schedule with the current situation onsite and referred to the road intersection (in grey; at the left bottom) when asking:

“What’s the date [in the visualization]?[This is 27 September]. Well, it [the pavement] was indeed done till there, and the intersection is finished as well.”

Similarly, the leader of project 2 built a picture from the existing project stage and stated:

“This [the visualization] is as-planned, so the whole road should be finished by this Friday. Currently, you should be working on the parking places right? And you need to start with the road this week.”

Besides understanding ongoing construction processes, the development of 4D models allows stakeholders to visualize virtually every other moment on the project’s timeline. In project 3, for example, 4D created **attention to operations from day to day**, since it triggered and guided discussions about operational changes. When the project manager watched the 4D process visualization (figure 13c), he referred to the road (in green) and sidewalk (in red) and explained how the visualized original plan differed from the activities onsite:

“Yes, the road must have been paved completely by then [next week]. Oh. Not. Only partly.” After a moment of silence and reflection, he continued: “Normally we first complete the sidewalks, so now I look at the schedule again, and wonder why we first constructed the main road instead” After a moment of deliberation: “Probably because the road had to be in operation first [before the holidays] ...”

In the first project, stakeholders also paid attention to operational detail by arguing that they require a more sophisticated 4D model to depict day-to-day utility construction work. For example, while watching the visualization, the water supplier commented that the 4D model had to differentiate more clearly between the installation of pipes and installation of cables. He told that pipes can be installed in sections, while cables have to be deposited in one piece:

“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.

5.4.2. PRE-OCCUPATION WITH FAILURE

The second principle we investigated is pre-occupation with failure. Below, we elaborate selected examples 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’.

We found that integration of designs in 3D and the development of 4D process visualizations allowed practitioners to **look for design conflicts and to try to understand them**. In project 1, for example, we implemented the 4D model during a

meeting with service providers. While discussing the alignment of designs, a stakeholder then argued that utilities had to be located closely in a combined trench. According to him, this was not visible in the 4D model, so he claimed:

“Some pieces of the gas and electricity [network] that should have been aligned actually have some differences. I noticed that the locations of cables and trenches are not integrated at points where this is actually necessary...Probably, you did not align the reference points of the different [3D models]...” Then his colleague provided an alternative explanation: *“or you have modelled the pipes a bit different from how they ideally should be.”*

In another selected example, the utility contractor in project 1 identified a conflict while watching the 4D model. He requested the first author to create an overview that integrated a tree-design plan and the gas infrastructure network. While zooming in on this (figure 13d) the contractor argued:

“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”.

Furthermore project stakeholders argued that they could use the 4D process visualizations to **look for construction schedule/process conflicts and to try to understand them**. An observation from project 1 illustrates this. Here, a service provider that watched our 4D visualization noticed that utilities were not properly and timely removed. Since this would cause a conflict with other construction activities, he pointed at the screen (figure 14a; the area marked with red circle indicates existing cables (green) and the tunnel (grey) in construction) and argued:

“Existing utilities have not been removed over there! The tunnel is already under construction while the utilities are not yet removed. That is not possible; the utilities first have to be dug up.”

Further, 4D allowed identification of schedule inaccuracies during project 3. Here our visualization showed construction activities taking place on a sewage system, while its top soil layer was not even excavated yet. By looking at this unrealistic situation, the project manager explained:

“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 modelled as ‘excavated’. I did not include this detail in my schedule.”

Figure 14 - selected examples of 4D models that enhanced reluctance to simplification and commitment to resilience (a, b, c) and preoccupation with failure (d).

5.4.3. RELUCTANCE TO SIMPLIFICATION

The third principle visible in 4D-supported coordination is reluctance to simplification. To show how this principle was followed in the three projects, we discuss a selection of observations related 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, for example, argued that the models that were based entirely on their own manual designs and schedules could represent reality more accurately when increasing the level of detail, and while adding specific objects and schedule tasks. These omissions triggered discussions about implicit schedule assump-

tions and work practices that are normally not explicitly addressed during coordination.

While developing a 4D model for project 2, for example, implicit common details such as locations for dewatering installation and working direction of pavers were visualized and discussed. Similarly, the following selected example shows that the manager in project 3 suggested to include more detail in the model to improve the process visualization:

“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 [i.e. in greater detail] what happens to the sewer during a specific day. You will see this work progressing while pavement activities grow and cover the sewer.”

Similarly, a designer from the municipality in project 3 asked whether the removal of the old sewer and installation of the new sewer could be visualized separately in the project’s 4D model. A manager in project 2 also made a request to include these details in the 4D visualization (figure 14b; old sewer in black, constructed sewer in green), although his original manual schedule did not contain these details either. He stated the following:

“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 either still there - if we did not do anything with it - or it is removed and a new sewer is installed.”

Further, our observations showed that 4D helped stakeholders **to expresses and discuss different viewpoints** on construction plans. This is demonstrated in the next example, where the work planner of project 2 explains an alternative for the construction of sewer line branches (figure 14c, referring to the cylinder shaped green sewer pipes and their branches):

“Look, these branches will usually be installed as soon as the sewer main is installed. Although 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.”

In a similar way, 4D visualizations helped to express and synchronize different viewpoints of project stakeholders. For example, they argued that 4D models can help to

visually check whether their construction plans are feasible. The work planner from project 2, for example, argued:

“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.”

5.4.4. COMMITMENT TO RESILIENCE

This paragraph discusses selected observations that relate to the fourth mindfulness principle, commitment resilience. The examples below show how 4D helps stakeholders to **extend their response repertoire**. In project 2, for example, an alternative pavement plan was developed on-the-fly during a planning meeting. While the first author visualized the alternative paving process, the work planner reflected on this option and argued:

“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.”

Moreover, it was argued by the work planner that 4D could help him to anticipate on potential delays. It stimulates practitioners to think about delay mitigation alternatives, and can therefore be seen as a way of enhancing response repertoires. The following two expressions from stakeholders in project 2 also illustrate this:

“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.” (See figure 14d; the light and dark brown objects represent lanes.)

“But if you won’t make it in two weeks, what will happen then? Often, you are then at an intersection and you need to evaluate whether you proceed work to the left, right, or straight on.”

5.4.5. DEFERENCE TO EXPERTISE

For the fifth mindfulness principle, deference to expertise, we did not find any examples in three 4D supported cases. It seemed that constructs such as ‘value expertise over hierarchical rank’ and ‘knowing who has the expertise to respond to situations’ (constructs from table 8), were not influenced by the use of 4D.

5.5. Discussion

The previous section shows that 4D models enable stakeholders in utility projects to follow principles of mindfulness. More specifically, development and implementation of 4D enabled practitioners to: sensitize toward operational processes by scheduling formally and in greater detail; to become more pre-occupied with failures and inaccuracies by visually grasping and discussing interfaces between parts in the design and master schedule, and to be more reluctant to simplifications by modelling and discussing these construction plans. Further, we provide evidence that 4D models enabled stakeholders to increase commitment to resilience when it is used to evaluate alternative schedules. These findings are summarized in table 10.

Table 10 - findings of 4D enhanced mindful behavior

Principles	Mindfulness enhancing actions in 4D-based coordination
Sensitivity to operations	Looking beyond own operations 4D visualizations allowed practitioners to understand simultaneously executed construction activities 4D was considered to support creation of mutual understanding of stakeholders' construction work 4D showed how construction activities interacted with processes in surrounding public space (e.g. traffic flow) Building a clear picture from current situation Practitioners using 4D had to explicate and formulate detailed designs and schedules, this increases progress insight 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 4D was used to estimate a project's status on future dates
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 modelling required explication of more 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 to be useful in evaluating progress delay
Deference to expertise	No observations related to this principle

The outcomes of this research contribute to 4D implementation literature. Earlier explorative research in this domain mainly discusses the special purposes and benefits of

4D (e.g. Russell, Staub-French, Tran and Wong, 2009, Koo and Fischer, 2000, Heesom and Mahdjoubi, 2004, Hartmann and Fischer, 2007). Despite this, however, we found no literature that systematically

assesses the impact of 4D on project performance. This study therefore makes a first effort in conducting this assessment by evaluating the impact of 4D on mindfulness. The results indicate that 4D development and implementation cause mindful behavior. Existing studies on mindfulness in flight deck crews (Weick and Roberts, 1993), aeronautics (Casler, 2013), hospitals (Weick and Sutcliffe, 2007), and construction organizations (Brady and Davies, 2010, Mitropoulos and Cupido, 2009) explain that increased mindfulness, in turn, helps to effectively cope with unwanted situations. In this light, our findings suggest that utility project stakeholders that use 4D are also better able to anticipate and contain coordination issues - and ultimately enhance performance.

This study further contributes to construction practice by demonstrating the use of 4D in utility project coordination. Our empirical examples from the domain of utility construction show that development of 4D models stimulates project stakeholders to explicate schedules and designs. This increases their anticipation skills by enhancing attention for details, conflicts and operations.

Furthermore, we provide empirical evidence that 4D enhances action repertoires of project teams by supporting discussions of alternative schedules and work plans. These practical benefits show that stakeholders can use 4D to contain emerging holdups and conflicts. On a more general level, this supports practitioners to establish effective coordination and likely reduces overruns and increases public satisfaction.

Since this research is not without limitations, the remainder of this section addresses challenges for future research. For one, the different number of observations related to each principle shows that the five mindfulness principles were not observed to the same extent. We collected data through observation of coordination meetings which often focused on construction tasks scheduled in future. Consequently, we identified behavior mainly related to the three mindfulness principles for anticipation (i.e. sensitivity to operations, pre-occupation with failure, and reluctance to simplification). Since we did not implement 4D during planning discussions outside these meetings, we were not able to identify more instances of containment-related mindful behavior. The chosen data collection approach might therefore explain why the authors identified only a few instances of 4D-enhanced commitment to resilience, and why none of

the observations relate to deference to expertise. Alternatively, a more simple explanation is that some mindfulness principles apply less than others to 4D-supported construction coordination. To investigate these presumptions, we suggest future research to study 4D usage during coordination activities that take place outside official meetings. To further explore whether 4D enhances deference to expertise, we also suggest that consecutive research investigates whether 4D visualizations empowers experts with a platform to communicate their knowledge and solutions.

Second, the utility works in this study were used as cases that demonstrate the influence of 4D on mindfulness and coordination performance. To generalize the validity of our claims for the broader civil engineering domain, we suggest conducting this research in more infrastructure projects of different scales and types.

Third, we use the richness of the examples in our obtained data to show that observed mindful behavior was caused by 4D visualizations. Although this rich data increases the plausibility that 4D practices are more mindful than manual coordination, this study did not explicitly compare the 4D cases with cases of manual coordination. To make a claim about whether 4D-based coordination is more mindful than manual coordination, future research efforts hence need to contrast the findings in this research with an analysis of mindfulness in manually coordinated utility projects.

Fourth, our research involved three utility reconstruction works that pioneered with 4D implementation. Since this tool is new to the utility reconstruction domain, we could not expect practice to flawlessly adopt it at once. The authors therefore took the lead in developing and implementing 4D models. This resulted in a hybrid practice of manual and 4D-supported coordination. So, although our findings show that 4D has potential to enhance mindfulness in coordination, we stress that practitioners need to develop 4D experience 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. olde Scholtenhuis, Hartmann and Dorée, in revision, Botton, Kubicki and Halin, 2013, Kuo, Tsai and Kang, 2011). When practice is more acquainted with 4D, we suggest researchers to obtain a more detached role and repeat this study to make more definitive claims about the impact of 4D on coordination.

5.6. Conclusions

Liberalization policies, growth of network technologies and tight deadlines create a significant challenge to align the myriads of stakeholders involved in subsurface utility

reconstruction works. Often, this results in suboptimal schedules, overruns and hinder for the public. Literature shows that 4D tools can be used for various construction management purposes to enhance such scheduling and coordination. Despite this explorative evidence, however, the amount of 4D-supported projects in practice is limited, and the nature and scale of 4D project studies differs widely. Since it seems difficult to statistically evaluate the impact of 4D on overall performance, this study instead focuses on its antecedent: coordination. More specifically, we introduce mindful organizing as a measure to evaluate coordination. To this end, we test the relation between 4D and mindfulness in utility reconstruction works.

To examine how 4D-supports mindful organizing in utility reconstructions, we implemented it in three real-life urban subsurface utility projects. We conducted an ethnographic action research study (Hartmann, Fischer and Haymaker, 2009) to both engage in coordination processes and to support practice by implementing tailored 4D models. While engaging in respectively six, six, and five 4D-supported meetings, we collected data by taking notes and by tape-recording. Outcomes show that development and usage of 4D allows stakeholders to follow mindfulness four principles: For one, stakeholders' *sensitivity to operations* and *reluctance to simplification* was enhanced because 4D development required stakeholders 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. In addition, practitioners 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. Finally, no observations were made regarding the relation between 4D and a fifth mindfulness principle - *deference to expertise*.

The results of this study contribute to existing literature about applications and benefits of 4D by showing that 4D improves coordination. Since we consider increased performance to logically follow from enhanced coordination, these findings provide a step further in the evaluation of the process impact of 4D on project performance. For future research, we suggest to extend the sample of this study with additional utility project cases, and to explore the impact of 4D tools on mindful coordination of projects in the broader civil engineering domain. Further, we suggest observing more thoroughly whether and why some mindfulness principles apply to 4D-based coordination more than others. Also, consecutive research should aim to compare coordination in organizations with more mature 4D practices. Finally, we contribute

to practice by showing that the development and implementation of 4D tools helps utility coordinators to enhance their mindfulness. This decreases the likelihood that coordination issues occur, reduces overruns and may eventually increase overall project performance.

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References

- Barton, M. A. and K. M. Sutcliffe (2009). "Overcoming dysfunctional momentum: Organizational safety as a social achievement." *Human Relations* **62**(9): 1327-1356.
- Boton, C., S. Kubicki and G. Halin (2013). "Designing adapted visualization for collaborative 4D applications." *Automation in Construction* **36**: 152-167.
- Brady, T. and A. Davies (2010). "From hero to hubris—Reconsidering the project management of Heathrow's Terminal 5." *International Journal of Project Management* **28**(2): 151-157.
- Casler, J. G. (2013). "Revisiting NASA as a High Reliability Organization." *Public Organization Review* **14**(2): 1-16.
- De Bruijne, M. and M. Van Eeten (2007). "Systems that should have failed: critical infrastructure protection in an institutionally fragmented environment." *Journal of Contingencies and Crisis Management* **15**(1): 18-29.
- Eccles, R. G. (1981). "Bureaucratic versus craft administration: the relationship of market structure to the construction firm." *Administrative science quarterly*: 449-469.
- EU (2010). *Communication from the Commission Europe 2020 A strategy for smart, sustainable and inclusive growth*, Brussels.
- Gebauer, A. and U. Kiel-Dixon (n/a) "High Reliability Organizing; Managing the Unexpected by Building up Organizational Capabilities."
- Hartmann, T. and M. Fischer (2007). "Supporting the constructability review with 3D/4D models." *Building Research & Information* **35**(1): 70-80.

- Hartmann, T., M. Fischer and J. Haymaker (2009). "Implementing information systems with project teams using ethnographic-action research." *Advanced Engineering Informatics* **23**(1): 57-67.
- Hartmann, T., J. Gao and M. Fischer (2008). "Areas of application for 3D and 4D models on construction projects." *Journal of Construction Engineering and Management* **134**(10): 776-785.
- Heesom, D. and L. Mahdjoubi (2004). "Trends of 4D CAD applications for construction planning." *Construction Management and Economics* **22**(2): 171-182.
- Jongeling, R. and T. Olofsson (2007). "A method for planning of work-flow by combined use of location-based scheduling and 4D CAD." *Automation in Construction* **16**(2): 189-198.
- Kang, J. H., S. D. Anderson and M. J. Clayton (2007). "Empirical study on the merit of web-based 4D visualization in collaborative construction planning and scheduling." *Journal of Construction Engineering and Management* **133**(6): 447-461.
- Kang, L. S., S.-K. Kim, H. S. Moon and H. S. Kim (2013). "Development of a 4D object-based system for visualizing the risk information of construction projects." *Automation in Construction* **31**: 186-203.
- Khanzode, A., M. Fischer and D. Reed (2008). "Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing." *ITcon* **13**: 324-407.
- Kim, H., K. Anderson, S. Lee and J. Hildreth (2013). "Generating construction schedules through automatic data extraction using open BIM (building information modeling) technology." *Automation in Construction* **35**: 285-295.
- Koo, B. and M. Fischer (2000). "Feasibility study of 4D CAD in commercial construction." *Journal of Construction Engineering and Management* **126**(4): 251-260.
- Kuo, C.-H., M.-H. Tsai and S.-C. Kang (2011). "A framework of information visualization for multi-system construction." *Automation in construction* **20**(3): 247-262.
- Langer, E. J. (1997). *The power of mindful learning*, Addison-Wesley / Addison Wesley Longman.
- Mitropoulos, P. and G. Cupido (2009). "Safety as an emergent property: investigation into the work practices of high-reliability framing crews." *Journal of Construction Engineering and Management* **135**(5): 407.
- Neeraj Jha, K. and S. Misra (2007). "Ranking and classification of construction coordination activities in Indian projects." *Construction Management and Economics* **25**(4): 409-421.

- Nguyen, L. D., T. K. Nguyen, D. Q. Tran and C. Villiers (2014). "Productivity in Daytime and Nighttime Construction of Urban Sewer Systems." *Journal of Construction Engineering and Management* **140**(7).
- olde Scholtenhuis, L. L., T. Hartmann and A. Dorée (in revision). "A 4D-CAD based method to support coordination of urban subsurface utility projects."
- olde Scholtenhuis, L. L., T. Hartmann and A. G. Dorée (2014). Comparing Mindfulness in Manual and 4D Supported Coordination Practices. *Construction Research Congress, construction in a global network*, Atlanta, Georgia, USA ASCE.
- Ray, J. L., L. T. Baker and D. A. Plowman (2011). "Organizational mindfulness in business schools." *Academy of management learning & education* **10**(2): 188-203.
- Russell, A., S. Staub-French, N. Tran and W. Wong (2009). "Visualizing high-rise building construction strategies using linear scheduling and 4D CAD." *Automation in Construction* **18**(2): 219-236.
- Staub-French, S. and A. Khanzode (2007). "3D and 4D modeling for design and construction coordination: issues and lessons learned." *ITcon* **12**: 381-407.
- Steenhuisen, B., W. Dicke and H. de Bruijn (2009). "'Soft' Public Values in Jeopardy: Reflecting on the Institutionally Fragmented Situation in Utility Sectors." *International Journal of Public Administration* **32**(6): 491-507.
- Sternberg, R. J. (2000). "Images of mindfulness." *Journal of Social Issues* **56**(1): 11-26.
- Strauss, A. L. and J. M. Corbin (1990). *Basics of qualitative research: Grounded Theory Procedures and Techniques*, Sage Publications, Inc.
- Trebbe, M., T. Hartmann and A. Dorée (2015). "4D CAD models to support the coordination of construction activities between contractors." *Automation in Construction* **49**: 83-91.
- Vogus, T. J. and K. M. Sutcliffe (2007). "The safety organizing scale: development and validation of a behavioral measure of safety culture in hospital nursing units." *Medical care* **45**(1): 46-54.
- Vogus, T. J. and K. M. Sutcliffe (2012). "Organizational mindfulness and mindful organizing: a reconciliation and path forward." *Academy of Management Learning & Education* **11**(4): 722-735.
- Wang, H., J. Zhang, K. Chau and M. Anson (2004). "4D dynamic management for construction planning and resource utilization." *Automation in Construction* **13**(5): 575-589.
- Webb, R. M., J. Smallwood and T. C. Haupt (2004). "The potential of 4D CAD as a tool for construction management." *Journal of Construction Research* **5**(1): 43-60.
- Weick, K. E. and K. H. Roberts (1993). "Collective mind in organizations: Heedful interrelating on flight decks." *Administrative Science Quarterly* **38**(3): 357-381.

- Weick, K. E. and K. M. Sutcliffe (2006). "Mindfulness and the quality of organizational attention." *Organization Science* **17**(4): 514.
- Weick, K. E. and K. M. Sutcliffe (2007). *Managing the unexpected: Resilient performance in an age of uncertainty*, Jossey-Bass Inc Pub.
- Weick, K.E., Sutcliffe, K.M. and Obstfeld, D. (2008) Organizing for high reliability: processes of collective mindfulness, in Boin, A. (ed.) *Crisis Management*, (vol. 3, pp. 31–66), Sage Los Angeles (Reprinted from Research in Organisational Behavior, pp. 81–123, by Sutton, K.M. and Staw, B.M., 1999, JAI Press, Greenwich CT).
- Zanen, P., T. Hartmann, S. Al-Jibouri and H. Heijmans (2013). "Using 4D CAD to visualize the impacts of highway construction on the public." *Automation in Construction* **32**.
- Zhou, Y., L. Ding and L. Chen (2013). "Application of 4D visualization technology for safety management in metro construction." *Automation in Construction* **34**: 25-36.

6. Prior and complementary work

The four previous chapters constitute the main research work that was employed to achieve the objective of this PhD. I also worked on eleven other (smaller) research projects dealing with utilities and VDC. This intermezzo chapter provides an overview of these additional projects. From the eleven projects, six do not formally contribute to the objective of this thesis. The other five studies consist of prior work that provided the basis for the studies in chapters 2 to 5. Section 6.1 below summarises the research projects related to utility coordination. Section 6.2 elaborates on the studies related to VDC.

6.1. The domain of utilities and utility reconstruction

One part of these complementary studies focused on how privatisation, liberalisation and new procurement regulations influence coordination of construction work in the utilities sector. The studies elaborate the main cause of institutional problems and introduce the HRO-lens to study construction performance issues. Furthermore, other additional work explored how the utility sector addresses existing coordination issues by introducing physical solutions (cable ducts) and organisational solutions (utility coordinators). The different projects are elaborated below.

The first study¹⁰ in the domain of utilities formed part of my MSc thesis. During this study, I evaluated the coordination of a sewer project that overshot its initial budget and schedule by conducting two rounds of eight and seven semi-structured interviews respectively. The outcomes of the interviews show that factors, such as mutual dependencies between network owners and contractors, created a “Gordian Knot” of coordination in which too many different stakeholders were responsible for distinctive tasks in an inner city infrastructure project. According to an ancient Greece metaphor, a Gordian Knot is too complicated to unravel and needs to be cut instead. , Untangling the Gordian Knot in the context of utility reconstruction projects requires re-centralisation of project control. My study argued that this could be achieved by ‘deprivatising’ the utilities sector. However, this is not likely to happen in the short term. Nevertheless, this article proposed using information and knowledge exchange platforms to support the increasingly complex coordination of utility works.

¹⁰ olde Scholtenhuis, L. L. and A. G. Dorée (2012). De gordiaanse knoop van kabels en leidingen: hakken we hem door? *CROW Infradagen 2012*. Papendal, the Netherlands.

This previous study inspired me to write another paper¹¹ that elaborated in detail how the lens of High Reliability Organising could support studies of construction management issues. The article explained HRO's five mindfulness principles that can help practitioners to anticipate and contain unwanted events effectively. Then, it elaborated the reductionist-debates that, initially, delayed me from using HRO concepts to study construction management. This study argued that a pragmatic focus would help construction management researchers to adopt and use the HRO lens in a more meaningful way; for example, to study utility coordination issues. An advanced version of this paper resulted in the Note presented in chapter 2.

I investigated in a different research project¹² how public projects that are tendered based on innovative procurement criteria may perform worse than anticipated due to third party utility works. This study was motivated by a change in procurement law. This law prescribed authorities to use Economically Most Advantageous criteria (EMA) to score tenders on qualitative aspects, such as, accessibility; project duration; and, nuisance. However, the problem in urban construction projects is that authorities' and their contractors often are not the only stakeholders in urban infrastructure works. In many situations these works also involve utility providers and utility contractors. Since these organisations are legally distinct, authorities' contractors cannot formally influence utility construction works. Consequently, achievement of EMA criteria by the authorities' contractor also depends on the performance of the utility contractor. Public works contractors are unlikely to achieve their targeted performance criteria in case where public clients underestimate the complexity of subsurface conditions, *and* use project duration as the EMA criterion. This article demonstrated this from two cases and proposed a revision of procurement strategies in such projects, for example, by using elements of Best Value Procurement.

Another complementary study looked at the role of coordinators in utility reconstruction projects (in Dutch: nutscoördinator). Utility companies and public organisations in various regions in the Netherlands shaped this inter-organisational function in order to cope with coordination problems that emerged after the Dutch utility sector

¹¹ olde Scholtenhuis, L. L. and A. G. Dorée (2013). *Welcoming high reliability organising in construction management*. 29th Annual ARCOM Conference, Reading, UK.

¹² olde Scholtenhuis, L. L., E. Meijberg and J. Boes (2014). EMVI en snellere binnenstedelijke rioleringsprojecten: wat te doen met nutscoördinatie? *CROW Infradagen 2014*. Ermelo, the Netherlands.

was privatised. A peculiar characteristic of this function is that the coordinator works between chains of command, without having any hierarchical or any formal decision power. I noticed during the fieldwork that coordinator roles were executed in distinctive ways. Therefore, I conducted seven interviews to explore what coordinators actually do and wrote the results up in two articles: The first article¹³ focused on characterising the distinctive styles of coordinating using the concept of loosely coupled systems (Dubois and Gadde 2002, Dorée and Holmen 2004) and explained that coordination prior to utility works execution is often loosely organised. As a result, many coordination tasks are postponed to the execution stage. This means that activities were more tightly coupled onsite. The findings revealed that two styles characterised the coordinators work in practice. They were either 1) more reactive, accepting the loose planning stage couplings and spent significant time on troubleshooting onsite; or they were 2) trying to tighten early stage couplings by pro-actively pursuing stakeholder to make early stage design and schedule commitments.

The ideas from this paper were developed further into a related article¹⁴. This paper investigated the actually performed activities of utility coordination by elaborating the various coordination roles evident in the literature and concluded that most theoretical roles assumed a hierarchy of formal decision power. Generally, such roles can be categorised as interpersonal, informational and decisional (Mintzberg 1973, Mintzberg 1990). The same seven interviews identified and allocated utility coordinator roles that evolved an overview of activities that matched traditional categorisations of management roles. However, some traditional roles that assume hierarchy, such as 'figurehead', 'entrepreneur' and 'spokesperson' were not identified. The interviews led to the definition of non-traditional interpersonal, informational and decisional roles for inter-organisational collaboration. Such roles encompass activities such as: shaping coordination process conditions; supporting and executing plan; updating information; functioning as (collective) memory; and, catalysing formal processes. I expected that such roles could be supported by VDC systems.

¹³ olde Scholtenhuis, L. L., T. Hartmann and A. G. Dorée (2015). *Characterizing coordination in both loose and very tightly coupled utility reconstruction processes*. 5th International/11th Construction Specialty Conference, University of British Columbia, Vancouver, Canada.

¹⁴ olde Scholtenhuis, L. L., T. Hartmann and A. Dorée (Unpublished manuscript). "Coordinating in network project organizations: how utility coordinators bridge voids in project-of-projects constellations."

The final additional utility study focused on how coordination issues can be improved more fundamentally by constructing ducts that physically structure subsurface cables, tubes and pipes. I conducted a scenario building session together with a contractor and wrote a short article¹⁵ that describes potential strategies for implementing cable ducts. The systems integrator (Winch 1998, Rutten, Dorée et al. 2009) concept subsequently was used to develop scenarios that addressed technical issues related to network design and safety, as well as organisational aspects, related to investment and exploitation costs.

6.2. Developing and implementing Virtual Design and Construction system elements

In addition to studying management and coordination complementary to this PhD, I also conducted extra work in the domain of Virtual Design and Construction. I considered at the outset of this PhD to build a Virtual Construction Site for sewer projects. A series of papers (elaborated below) show the steps taken to tackling this goal. The first paper designed a system architecture and knowledge taxonomy. The second paper studied how a selection of VDC-elements (discrete event simulations and 4D construction process visualisations) could be implemented to support scheduling practice.

The first theoretical VDC paper concluded my MSc.-graduation project and designed the architecture of the virtual construction site¹⁶ for utility projects. This design comprised of elements such as a discrete event simulation, construction process visualisation, 3D viewer, performance indicator panel and a productivity database. The paper prototypically tested a discrete event simulation and critical path calculator. While the PhD-study progressed, my focus shifted from *developing* a complete virtual construction site toward *implementing and testing* VDC models in real-life practice. For practical reasons, this meant that only parts of the systems architecture (the knowledge base, simulations, and 4D construction process visualisations) were researched and developed in further detail.

A first step to support the development of VDC models is to obtain an overview of the domain-related knowledge and relevant aspects that should be captured in the vir-

¹⁵ Meijberg, E. and L. L. Olde Scholtenhuis (2014). Stop het graven! In 2024 liggen alle kabels en leidingen in goten. *CROW Infradagen 2014*. Ermelo, the Netherlands.

¹⁶ olde Scholtenhuis, L. L., T. Hartmann and A. Dorée (2012). *Systems architecture for a virtual construction site to support utility construction management tasks*. EG-ICE 2012 international workshop: Intelligent computing in engineering, Herrsching, Germany, Technische Universitaet Muenchen.

tual construction tool. To do this I included in my MSc.-thesis project a study¹⁷ of the actual coordination discussions in meetings of inner city utility projects. I used ethnographic-action research (Hartmann, Fischer et al. 2009), derived coordination concepts, and developed a domain ontology for utility projects coordination based on this. These objects were implemented in a 4D model for a real life utility project as a first validation. The method to develop this taxonomy culminated in chapter 2 of this thesis.

A discrete event simulation comprised another part of the systems architecture for utility project coordination. The actual programming work for the discrete event simulation was done by Simon Hoitema, a MSc.-graduate, who executed his thesis work within the same domain as this PhD dissertation. Simon conducted an empirical study¹⁸ on sewer construction processes and captured these processes in a simulation model. I abstracted this captured knowledge in categories related to project constraints, construction methods and resource allocation. Defined rules were formalised as instances of these knowledge categories and these were subsequently implemented in simulations of a prototype case and real-life project to validate the knowledge categorisation. The study demonstrated that discrete event system development enabled knowledge explication, and allowed contractors to establish a systematic and analytic work practice.

Another piece of research explored the use of 4D models to study the next element of the VDC systems architecture. This study¹⁹ reported the preliminary results from an analysis of how 4D tools enhance mindful behaviour. These principles were used to make a structured comparison between paper-based and 4D-supported coordination in real-life pilot projects. This paper was extended after more data collection and thorough iterations of data analysis and resulted in chapter 4 of this thesis.

¹⁷ olde Scholtenhuis, L. L. and T. Hartmann (2012). *An object model to support visualizations and simulations of inner city subsurface utility construction activities*. 14th international conference on computing in civil and building engineering, Moscow, Russia, Moscow State University of Civil Engineering.

¹⁸ olde Scholtenhuis, L. L., S. Hoitema, T. Hartmann and A. G. Dorée (Submitted). "Using simulations to verify and empirically validate a categorization of sewer construction scheduling knowledge."

¹⁹ olde Scholtenhuis, L. L., T. Hartmann and A. G. Dorée (2014). *Comparing Mindfulness in Manual and 4D Supported Coordination Practices*. Construction Research Congress, construction in a global network, Atlanta, Georgia, USA ASCE.

The last VDC study²⁰ took place as a complementary piece of research and evaluated how the nature of 4D models changed during the life cycle of a utility project. Retrospectively I analysed how a 4D model evolved during one of this study's pilot projects. The outcomes showed that 4D was used for coordination purposes related to process orientation, construction plan communication and process improvisation. These purposes demand different setups of 4D models during the project life cycle. Early stage 4D models, for example, were based on bar charts, clusters of 3D objects, and coarse work breakdown structures. It seems that in execution stages this model needed to expand with elements, such as task predecessor relations, as-built schedules and objects including curb stones, pipes and manholes. Managers can better maintain the practical applicability of their models by understanding how 4D-CAD models change during a project. This, in turn, helps them to create VDC models that can support adequately the changing coordination needs during utility projects.

6.3. Conclusions of additional work

Although these complementary research products summarised above do not form an integrated whole, they do give a broad overview of the coordination challenges, industry initiatives and technical opportunities to improve alignment in utility projects. They provided the following conclusions:

- Past institutional developments - which are the root cause of intricate coordination in the utilities sector – have complicated control over utility construction projects, and are unlikely to be reverted on short notice.
- Procurement innovations, such as the use of EMA criteria, are used by public authorities to gain more control over quality of construction processes. In practice, this procurement innovation enlarges coordination issues, particularly if public infrastructure projects contain a significant component of utility works.
- Initiatives that the utility sector has initiated – e.g. the mobilisation of utility coordinators and use of cable ducts – seem to offer ways toward more streamlining coordination and planning. There are various strategies, styles and roles for stakeholders to implement such solutions.

²⁰ olde Scholtenhuis, L. L. and T. Hartmann (2014). *Changing Scheduling Purposes and Evolving 4D-CAD Models: A Study of Planning and Realization in a Utility Project*. 2014 International Conference on Computing in Civil and Building Engineering, Orlando, Florida, United States.

- Another significant contribution can be provided by development, implementation and evaluation of tailored Virtual Design and Construction systems. Since these tools assist in explicating utility construction knowledge, they could capture construction knowledge in simulation, and should be tailored to the coordination needs that change during a project lifecycle.

This additional work, taken together with chapters 2-5, provide many new threads for exciting future research.

7. Conclusions

This chapter formally concludes this thesis by listing the main conclusions; recapturing the motivation to do this study; and, summarising conclusions of each chapter. The chapter ends by addressing the key theoretical and practical contributions.

In brief, the **main conclusions** of this thesis are as follows:

- *High Reliability Organising (HRO) offers a pragmatic and practical lens to study how interventions influence mindfulness in coordination practice.*
- *VDC systems support mindful behaviour in utility coordination. Tailored VDC systems are needed that match the work routines in the utility construction domain to test this empirically. This study therefore introduces a research approach that helps developers to involve end-user perspectives as they create a VDC system knowledge base (i.e. a domain ontology).*
- *The domain ontology developed with this research method was used to design and validate a method to implement 4D VDC models for utility coordination.*
- *Implementation of the 4D VDC method in real-life cases provided empirical data to evaluate the impact of 4D VDC models on mindfulness. The analysis confirms that VDC solutions help stakeholder to follow HRO's mindfulness principles when performing utility coordination.*
- *Utility project organisations ultimately enhance mindful performance by capitalising on the benefits of VDC solutions. This, in turn, makes unexpected, unwanted events, such as cost and schedule overruns, forced improvisation and re-planning, less likely to occur. Eventually, this can contribute positively to reliability in utility construction.*

7.1. Motivation

This research and its conclusions are in sync with developments in practice and theory. From the practical perspective, the experience of past decades' technological developments, privatisation, and liberalisation has caused a significant growth of sub-surface networks and a proliferation of utility owners. They can construct their utilities in a timely fashion and safeguard accessibility of public space by streamlining their work. However, over recent decades this objective has become more difficult to achieve as the responsibility for the alignment of construction processes had spread out across myriads of utility owners and their contractors who all have their own strategies and policies regarding network maintenance. Coordination of stakeholders' construction plans in this changed context requires significant time and effort. Often, the available time for schedule preparation is limited by tight deadlines. Consequently, there is little room to plan, analyse and integrate the interfaces between distinctive

schedules and designs. Some conflicts become overlooked and need to be resolved during the execution stage.

Another practical aspect that motivated this study was the lack of formal project hierarchy between most stakeholders in utility reconstruction works. Instead, clients and contractors work in network-structures to coordinate the interfaces between their schedules and designs. Projects may be sub-optimal in their preparation when there is no single organisation formally in charge. The consequences of the resulting unwanted, unexpected events force project managers to re-plan and lead to delays, increased expenditures and a proliferation in burdens on the public. Such burdens can be relieved by reducing the effort that stakeholders need to understand, analyse and integrate one another's construction plans. This study started by hypothesising that VDC systems support this task as they seem to offer ways to explicate stakeholders' construction plans; to integrate construction plans; and, to support identification of potential design and process disturbances.

Although the literature has reported benefits of VDC systems for management tasks, such as project communication, design review (Hartmann, Gao et al. 2008), construction method and scheduling evaluation (Russell, Staub-French et al. 2009), and work flow planning (Jongeling and Olofsson 2007), their adoption and testing has been limited in the smaller-sized infrastructure projects, such as utility works. Therefore, this study developed and implemented VDC systems for the utilities domain to test the impact of VDC empirically. In particular, it used the mindfulness lens to study how VDC systems help people to cope more effectively with unexpected process disturbances. This main motivation is based on the following theoretical points of departure:

- VDC systems can integrate construction plans to study how unwanted process disturbances can be prevented or dealt with and, thereby, support coordination. The lens of High Reliability Organising (c.f. Weick and Sutcliffe 2007, Weick, Sutcliffe et al. 2008) – and its underlying principles of mindfulness, in particular – offers a perspective to guide the analysis and evaluation of such systems. HRO concepts stemming from studies in high-hazard industries show how organisations anticipate and contain processes disturbances. This behaviour is described in five mindfulness principles: 1) sensitivity to operations; 2) pre-occupation with failure; 3) reluctance to simplification; 4) commitment to resilience; and, 5) deference to expertise. Mainstream organisations also face unwanted events to a lesser degree and, therefore, can benefit from establishing mindfulness principles. Although organisation studies acknowledge this and are gradually applying

mindfulness principles to study processes, my PhD study was confronted initially with various legitimacy debates that challenged the permissiveness of the HRO lens regarding the construction domain. This study provided a reflection upon these debates to explain why they occur during theory adoption and how such debates can be resolved.

This theoretically drafted argument provided a rationale for me to apply the HRO notion while studying how VDC solutions impact mindfulness. Therefore, I developed methods to tailor VDC systems' knowledge base, as well as to implement VDC models in practice. These steps were based on the following theoretical points of departure:

- Information system adoption studies (Swanson and Ramiller 2004, Adriaanse, Voordijk et al. 2010, Adriaanse, Voordijk et al. 2010, Hartmann 2011) show that inadequate alignment of technological features and user demands limits effective implementation. Developers are therefore required to tailor VDC systems to end-user needs. One way to do this is by developing domain ontologies, i.e. VDC's knowledge bases that reflect the domain knowledge of end-users. Ontologies represent knowledge by using concepts, objects and relations. Ontology development methodologies, such as TOVE (Gruninger and Fox 1995), Enterprise (Uschold 1996, Uschold and Gruninger 1996) and Methontology (López, Gómez-Pérez et al. 1999), use motivating scenarios, expert brainstorming and expert consultations to involve such viewpoints. The methodologies agree that ontology development outcomes should match end-user requirements. Nevertheless, none of these methodologies formulate how this should be done explicitly. Therefore, this study introduced a research method that spells out formally the steps needed to involve end-users during the development of domain ontologies.
- With a knowledge base developed the next step is to implement this in VDC systems in practice. Mindful implementation (Swanson and Ramiller 2004) requires that these systems are developed in accordance with work practices and routines of practitioners. However, VDC literature on 4D mostly addresses its technological advancements (Golparvar-Fard, Peña-Mora et al. 2011, Kim, Kim et al. 2013, Kim, Son et al. 2013), and its implementation in projects, such as facility, high rise and highway construction. In contrast, the implementation of 4D VDC systems in smaller civil engineering projects, such as utility construction, has received less attention. Therefore, I introduced a method to complement the literature that

shows how VDC models can be implemented to meaningfully support coordination in smaller scaled civil engineering projects, such as utility works.

- The functionality of VDC systems to date is tested in literature most frequently by using prototype cases (e.g. Mikulakova, König et al. 2010, Scherer and Ismail 2011, Scherer and Schapke 2011, Benevolenskiy, Roos et al. 2012). A limited uptake of VDC systems and the restricted availability of statistical utility project data make it difficult to compare performance in paper-based and VDC-based coordination quantitatively. My study investigates how VDC technologies impact mindfulness qualitatively; i.e. how VDC helps to anticipate and contain process errors and disturbances. Its systematic use of the HRO-lens contributes to literature by showing that 4D VDC models support mindfulness behaviour in coordination.

The practical and theoretical points of departure motivated research that answered the main research question:

What is the impact of VDC systems - such as 3D/4D models - on coordination of multi-client, multi-contractor utility reconstruction works?

Furthermore, it contributed to the achievement of the following objective:

To enhance reliable construction of utilities by developing, implementing and empirically testing VDC systems to coordinate multi-stakeholder construction processes.

The objective was reached by providing the following deliverables:

5. A reflection on the adoption and pragmatic use of HRO's **mindfulness** principles to qualitatively study mindfulness in construction (Chapter 2)
6. An approach to **develop** and validate a practically relevant knowledge base (ontology) for VDC systems (Chapter 3)
7. A method that supports **implementation** of VDC models for the coordination of urban subsurface utilities projects (Chapter 4)
8. Structured **evaluation** of the impact of VDC models on mindfulness in coordination practices based on the HRO lens (Chapter 5).

7.2. Conclusions per chapter

This section elaborates on the main conclusions provided earlier in this chapter. It summarises the findings for each chapter and elaborates its contribution to the over-

arching goal to develop, implement and evaluate VDC systems for utility works coordination.

7.2.1. CONCEPTS TO GUIDE EVALUATION OF VDC SOLUTIONS: THE HRO LENS, A REFLECTION ON ITS ADOPTION DEBATES AND VALUE FOR CM-RESEARCH

VDC systems for utility project coordination should support anticipation and containment of unwanted disturbances and events. To evaluate developed VDC systems one needs a framework that helps explicate whether the tool supported anticipation or containment. High Reliability Organising (HRO) literature offers such a framework. It provides five mindfulness principles (Weick and Sutcliffe 2007, Weick, Sutcliffe et al. 2008) that help evaluate to what extent organisational processes effectively anticipate and contain unwanted disturbances and events. HRO's adoption in my study was delayed initially by legitimacy debates with peers. These had to be clarified and resolved before this study could apply the HRO-lens to evaluate developed and implemented VDC systems. Chapter 1 reflects on these debates by looking more generally at theory adoption in construction management.

Chapter 1 reflects on a series of debates that I personally encountered during research peer meetings and manuscript reviews. A recurrent theme in these debates was whether the HRO lens was applicable for the construction management domain. These reservations regarding the use of the HRO-lens were unexpected and did obstruct further publication and discussion of research results. A higher-level perspective on the recurrent rebuttal of HRO resulted in a more general reflection on theory adoption in the construction management field.

Theories, concepts and notions seem to find their way to the domain of construction management in different ways: Some metaphors and theories are being adopted fluently without much debate and resistance. Examples of this include: the use of transaction costs (Winch 1989); supply chain (Cheng, Li et al. 2001, Love, Irani et al. 2004); and, trust and partnering (Wood, McDermott et al. 2002, Khalfan, McDermott et al. 2007). On the other hand, theories and notions can stall at the boundary of the construction management domain, as happened with my HRO phenomenon. A primary reason for this can be traced back to the dominance of reductionist perspectives.

Reductionism is considered as a perspective that 'reduces' the interpretation of reality by its heavy use of classification and the creation of artificial boundaries. It classifies phenomena in categories. This frequently results in discussions about whether phe-

nomena fit either into one or into another category. From this perspective, High Reliability Organising does not apply to construction basically for two reasons: 1) the construction Industry is not a classical High Hazard industry (such as power plants, aircraft carriers or fire departments). Thus, it may be concluded that its concepts are not applicable; 2) the term Organising seems to refer to an organisational entity when construction projects comprise of multiple organisations. Although HRO-scholars had clarified earlier that they did not intend to refer to an organisational entity, but rather to focus on organisational processes instead, the ‘organisation term’ still creates debate in reductionist circles. So, solely based on interpretation of the term, and without detailed attention for the pragmatic value of HRO’s underlying principles, construction is then disregarded as ‘not-reliable, not high-hazard’ and, hence, not suited for use in HRO’s concepts.

This view of the reductionist approach explains why new concepts, theories and notions can sometimes face resistance and get stuck at a research field’s boundary without clear reasons. An alternative pragmatic’s point of view argues that the core concerns with regard to any theory and their adoption should be the resulting practicality and productivity, rather than its ‘theoretical permissiveness’ in regard to the domain. A more fruitful alternative to the reductionist question would be how a new theory might best guide and evolve research. This pragmatic perspective is far more likely to support theory adoption and allow cross-fertilisation between scientific domains.

Eventually, the pragmatic viewpoint supports an evaluation criterion more suited for novel perspectives in the construction management domain. Although this viewpoint is unlikely to prevent future reductionist debates fully, it can help researchers to recognise and avoid diversionary labelling and categorisation disputes and, thereby, to create the space for more productive and practical construction research. In relation to the research objective, this viewpoint provides a rationale for using HRO to study how VDC supports mindful behaviour during coordination of utility works.

7.2.2. DEVELOPING A VDC-SYSTEM KNOWLEDGE BASES IN INTERACTION WITH END-USERS

With the setting of HRO’s framework in place, the next step is to develop utility coordination VDC systems that can be tested empirically for their influence on mindfulness. The first logical step in this process is to create a VDC system that supports real-life utility coordination processes. Developers need to tailor VDC systems and models to the needs of practitioners (Davis 1989, Davis, Bagozzi et al. 1989,

Hartmann 2008, Adriaanse, Voordijk et al. 2010, Adriaanse, Voordijk et al. 2010) if they wish to represent reality with sufficient detail and accuracy in simulations and visualisations. Chapter 3 introduces an approach that helps to adapt VDC systems' knowledge bases (domain ontologies) to these needs. The approach complements existing desk-based ontology development methodologies by formally spelling out steps for how end-user viewpoints can be included in ontology development.

The research method introduced uses fieldwork to conduct iterative cycles of ethnographic observations; empirical data analysis, and, ontology development and implementation. This method contributes to the system development literature by explicating steps for a bottom-up, end-user-based ontology development. This inductive approach for concept identification allows developers to explore the work context of the end-users and ground their product in empirical data. This, in turn, is expected to increase the feasibility of any VDC systems that are built from these.

To show how the methodology worked in practice, it was applied to the domain of this thesis: field observations of two utility reconstruction works were used to identify commonly-used concepts and objects and to formalise these subsequently in an ontology that matches end-users' language and needs closely.

The fieldwork-based method for end-user involvement in domain ontology development can be used in two distinct ways: 1) its steps can be followed stand-alone as bottom-up approach to ontology development; for example, when creating a utility domain ontology from scratch. 2) In addition, system developers can use the fieldwork-based steps also to validate existing ontologies. The specific knowledge obtained while applying the method to the utility domain provided a next step in achieving the overall goal of this study since it created the knowledge base for the VDC models that were developed later to study how VDC-based coordination impacts mindfulness utility works.

7.2.3. IMPLEMENTING 4D VDC MODELS TO SUPPORT UTILITY COORDINATION PRACTICE

The next step to study the use of VDC systems for enhanced reliability of utility works was to propose a method that supports system implementation. Such a method comprises steps that show people how to tailor VDC models to support adequately coordination in practice. This chapter explores how 4D VDC systems can be successfully integrated in existing utility work practice by describing how practitioners helped to develop and implement 4D in four cases. These insights further enabled an exploration of benefits that 4D VDC models offer to practice.

The pilot projects consisted of two medium-sized and two smaller-sized urban utility reconstruction works. These works involved: the reconstruction of a road intersection; a sewage network refurbishment; and, the realignment of gas, water, energy and telecommunication utilities. Stakeholders, such as authorities, service providers and different contractors, had to align their schedules to schedule and execute these tasks. I obtained insights in their scheduling practices as I collected schedule documentation, converted existing 2D CAD designs and maps into 3D models and integrated these in a 4D model. Then, I used off-the-shelf 4D software to develop and implement 4D VDC during coordination meetings and evaluated these during reflection sessions.

Retrospective analysis of the tracked modelling efforts and obtained feedback on the VDC models demonstrates how the method improved iteratively during the projects. Chapter 5 introduces the final results of this method and provides examples of the iterations made to arrive at this method. In brief, the method consists of three phases: In the first phase, stakeholders scope their plans by collecting project information and defining VDC model details. In the second formalising step, stakeholders model four object types to represent design and schedule components visually. In the third synchronisation phase, stakeholders align parts of the master schedule by using techniques, such as timeline snapshotting, process animation and key date snapshotting.

Validation of the method occurred during its iterative development and by observation of the actual use of the developed 4D models. First, four pilot projects provided feedback from observed meetings which helped to add, validate or change the method's steps. Second, observations of the meetings allowed me to observe the actual benefits of 4D VDC models and to identify practitioners' anticipated benefits of such models in the future. Chapter 5 demonstrates that 4D VDC models provided benefits, such as the detection of potential design conflicts (formalising); triggering discussion of schedule omissions; creating understanding about project interfaces; and, supporting delay analysis (synchronising). These examples validated and demonstrated the usefulness of the VDC-based coordination method.

All in all, the 4D-based coordination method for utility construction coordination contributes to the body of knowledge by providing explicit, empirically supported steps for VDC model implementation in the utility domain. Furthermore, chapter 3 provides two other main contributions: First, it shows the domain of application of 4D VDC models can be extended from larger-scaled infrastructure and high rise projects (e.g. Mahalingam, Kashyap et al. 2010, Zanen, Hartmann et al. 2013) to smaller sized and mainstream projects, such as utilities. Second, the chapter adds to earlier prototypical 4D

case studies and contemporary studies about the technical extensions of 4D systems (Golparvar-Fard, Peña-Mora et al. 2011, Kim, Kim et al. 2013, Kim, Son et al. 2013) by adding empirical cases of 4D CAD use. This addresses a need for more VDC system implementation. After all, the introduced method supports mindful implementation by aligning work practices and VDC model development closely. This result put in place the next step toward evaluation of a VDC system that supports reliable coordination of utility works.

7.2.4. EVALUATING THE INFLUENCE OF VDC SYSTEMS: THE IMPACT OF 4D MODELS ON MINDFUL BEHAVIOUR IN UTILITY COORDINATION

Finally, the evaluation of a VDC system is the last step in establishing systems that can enable more reliable coordination practices. To do this the study mobilised the HRO's mindfulness principles to analyse the process-impact of 4D VDC models on mindful behaviour during utility works coordination. I observed empirically in chapter 5 coordination in three utility projects that received support from 4D VDC. I attended coordination meetings and supported some of them with 4D models. Some of the data in chapter 5 was collected during the study reported in chapter 4. However, the data set was extended and used subsequently to evaluate how VDC supports behaviour aligned with mindfulness principles.

While evaluating the process impact of 4D VDC models I first used open coding (Strauss and Corbin 1990) to identify actions and expressions that occurred during the observed coordination meetings. Next, axial coding was used to refine the identified codes. Codes were related to theoretical constructs that operationalised mindful behaviour. These constructs described observable mindfulness actions and were derived from theoretical instruments, such as the Safety Organising Scale (Vogus and Sutcliffe 2007) and Mindfulness Audits (Weick and Sutcliffe 2007, pp. 83-102). Examples of constructs describing mindful behaviour are as follows: building a clear picture of the prevailing situation (an activity related to the mindfulness principle sensitivity to operations); looking for design/schedule conflicts and trying to understand them (related to pre-occupation with failure); deepening analyses to better grasp nature of the problems (reluctance to simplification); discussing alternatives to normal work processes (related to commitment to resilience); and, knowing who has the expertise to respond to situations (related to deference to expertise). This thesis eventually shows that 4D VDC models provide a way to enhance behaviour along mindful principles in utility project coordination by connecting empirical observations to the theoretically derived mindfulness constructs.

The findings reported in chapter 5 contribute to the literature in four ways. First, the application of the mindfulness principles in real-life projects provided empirical evidence that 4D VDC models can be used to enhance mindful behaviour in coordination practices. Second, the study confirms for organisation science that the HRO lens provided a pragmatic and valuable lens to study processes in less high-hazard and more mainstream organisations. Third, the study supports the argument that the HRO lens should not necessarily be bounded to research on single organisational entities, but also can be used to study processes (i.e. focus on organising, instead of organisations) between organisations. Fourth, findings contributed to VDC system implementation. This study shows that the HRO's mindfulness perspectives served well as a framework guiding qualitative assessment of VDC tools, such as 4D, complementing earlier studies of mindful technology design (Hartmann, olde Scholtenbuis et al. 2014) and implementation (Swanson and Ramiller 2004).

7.3. Theoretical contributions (recap)

Chapter 5 concluded by evaluating how VDC systems impacted on mindful behaviour. This deliverable, together with the motivation for applying the HRO lens to study mindfulness (chapter 2) and the system development methods (introduced in chapter 3 and 4), provide the following answer to the main research question: End-user tailored VDC systems contribute positively to mindful behaviour during coordination of multi-stakeholder utility works. This answer should be considered in the light of the key theoretical contributions which are as follows:

- An explanation of how reductionist perspectives, which focus on the permissiveness of a theory regarding a domain, can stall new concepts at the construction management research domain's boundary. An alternative pragmatic viewpoint focuses on productiveness and practicality of a new theory and was used to justify the applicability of HRO's mindfulness principles to study how VDC supports mindful coordination in utility construction.
- An explication of the steps required to involve end-user viewpoints in domain ontology development. The explicated steps could be used on their own or in addition to existing ontology development methodologies such as TOVE, Methontology and Enterprise (Gruninger and Fox 1995, Uschold 1996, Uschold and Gruninger 1996, López, Gómez-Pérez et al. 1999). This thesis also developed a domain ontology for utility projects to demonstrate the methodology's steps. The ontology was used during subsequent research steps to guide development of 4D VDC models for utility projects.
- A method which demonstrates how 4D VDC models can be used meaningfully to support coordination in utility works. The method extends the application area of

4D from existing domains, such as larger infrastructure and high rise projects (e.g. Mahalingam, Kashyap et al. 2010, Zanen, Hartmann et al. 2013), to smaller infrastructure projects, such as utilities. The empirical study complements to existing technical and prototypical VDC studies.

- An empirical test of the relation between 4D VDC systems and mindful behaviour in utility project coordination. This thesis also contributes to studies of mindful technology development (Hartmann, olde Scholtenhuis et al. 2014) and implementation (Swanson and Ramiller 2004) by delivering an evaluation framework to analyse the process impact of VDC systems qualitatively. Chapter 5 further shows that the mindfulness principles also support research in mainstream and inter-organisational, as opposed to high-hazard intra-organisational, processes.

Overall, this thesis provides a holistic approach to studying how VDC impacts mindfulness as it has developed, implemented and evaluated VDC models empirically. This study's proposed methods and empirical findings showed that thoughtful development of VDC systems adequately supports mindful behaviour and that this is likely to enhance coordination and overall performance of utility works.

7.4. Practical contributions

The ethnographic-action research approach used in this study is characterised by close interactions with practitioners. This resulted in useful contributions to practice. In brief, these were:

1. An approach that allows VDC developers to tailor the knowledge base (ontology) of their systems to the needs of their end-users. Application of the method to practice also resulted in a domain ontology for utility coordination.
2. A method that explained how 4D VDC models can be used meaningfully to coordinate utility works.
3. Explicated benefits of 4D VDC models for coordination in utility projects.
4. A demonstration of how HRO's mindfulness principles helped organisations evaluate the process impacts of their process interventions.

These points above are elaborated in greater detail below: the fieldwork-based ontology development method introduced in chapter 4 contributed to the practices of system development. The steps provided by the approach can be used by developers - on their own or in addition to existing methodologies - to enhance the user-fitness and representativeness of the knowledge base (domain ontologies) they use in their

systems. While many software developers often use a mere top-down approach as they try to create generic VDC tools, they often neglect the specific end-user needs for the system. Developers can tailor a VDC knowledge base to end-user needs if they use the approach introduced by this study. This could lead eventually to more effective VDC adoption processes in the construction domain.

Chapter 5 (4D method) shifted the focus from the knowledge base development to VDC model development by providing a method for 4D VDC based utility project coordination. The method was developed iteratively with practice and, therefore, provided utility project professionals with a tailored guideline for 4D-supported coordination. Overall, it structured scope information exchange, formalised steps and helped create early-stage process commitments. These benefits, in turn, can be expected to reduce uncertainties and to synchronise stakeholders' reconstruction schedules, thus, making the occurrence of errors and delays less likely.

Furthermore, the evaluation of the process impact of 4D VDC models demonstrated that VDC can support practices along the principles of mindfulness. It can result in a lower likelihood of incurring unwanted events and, eventually, improve coordination and increase reliable performance. The use of the lens in chapter 5 provides further evidence of how construction organisations could use the HRO lens to guide evaluation of implemented process interventions.

Finally, prior and additional complementary work also delivered several practical contributions. This work, for example, explicated various challenges and issues in utility coordination; explained how applied EMA procurement criteria can negatively influence project performance; and, identified styles and rules that practitioners use to coordinate utility works. The VDC system perspective showed additional work that led to a categorisation of scheduling knowledge types and provided insights in how VDC models should be adapted to support coordination effectively during a utility project life cycle.

7.5. Concluding remarks

Overall, the development and implementation of VDC models, as well as the mindfulness lens introduced, can help in the practice of assessing systems that potentially reduce the amount of process conflicts. Ultimately, these contributions enable utility project organisations in becoming more reliable.

Finally, this PhD-research also provided several indirect contributions to practice. For example, during the course of this research, I established a research network comprising of: local authorities; service providers; platform organisations; contactors; utility contractors; and, technology suppliers. I communicated my observations to practitioners, and reflected on existing work practices together with them at various assemblies, conferences and dialogues with industry (GPKL, KLO, Bentley, CROW). The research project further facilitated requests to mobilise BSc. and MSc. students for graduation projects (e.g. at Gemeente Enschede, Gemeente Hengelo, Provincie Overijssel and Dura Vermeer, Agentschap Telecom, Kadaster). These collaborations have helped students to gain experience and knowledge about the field of utilities and inner city construction.

8. Discussion and reflection

Personal integrity and scientific credibility are of paramount importance in research. Besides being clear and open about the research methods one employs, being credible also demands a critical reflection on the research process. The following two sections therefore elaborate the research methods and concepts used. The chapter concludes by providing suggestions for future research.

8.1. Reflection on the method

As with any research, the use of one methodology excludes others. This section reflects on the methodological decision to use fieldwork as a main data collection mode. This discussion follows from a trade-off between lab experiments and more empirical engaged research. This section then elaborates on how case selection may influence observations in regard to the benefits of new technologies. It addresses also practitioners' perceptions on the presence of researchers in the field.

An experimental setup ideally has high internal validity as it creates a setting well-suited to studying the causality between an intervention and its influence on a dependent variable (Leedy and Ormrod 2010, pp. 223). In my study lab setups could have been used to evaluate the causal relation between use of VDC systems elements and mindful behaviour in utility works coordination. This would have involved a comparison between a control group (in which traditional paper-based coordination takes place) and an intervention group (that uses VDC systems to support coordination). This type of an experimental setting offers the means to control the influence of external variables (the *ceteris paribus* principle). As a result, observed differences between the two groups are highly likely to be attributable to the use of the technology. Even though the internal validity of this setup is high, these types of lab experiments are cumbersome to set up; they compress the durations of real life processes significantly; and, their ability to capture real-life project dynamics is limited.

My research was conducted with real-life practice rather than in a lab. The decision for a more representative practice-engaged setup followed logically from this study being rooted in, and initiated by, a construction industry innovation foundation (Stichting Pioneering) that had defined that the assignment should address real-life utility coordination problems. This foundation requested me specifically to develop VDC solutions and study how they support utility coordination in practice. As such, I could identify real-life coordination issues and select VDC tools that properly addressed them. My close involvement during the implementation of VDC systems provided

detailed empirical insights about their benefits. On the other hand, this study also required a significant investment in time to obtain a sound base of empirical data, for example, in preparing 3D/4D VDC models for meetings; attending meetings; and, conducting site visits. This resulted in a set of rich empirical data which probably was more specific and realistic than that which could have been obtained from surveys, interviews or lab studies. After all, I considered these efforts to be worth the investment.

Notwithstanding these benefits, the research approach adopted also has its limitations. For example, VDC systems were found to provide positive process contributions. Despite this, utility construction stakeholders in practice have not yet adopted VDC widely which might be caused by an optimism bias. This means that technologies could have been evaluated by me in more positive ways than they were in fact. This positive conclusion could be result from the way in which pilot cases were selected: most cases were, for example, purposefully selected from municipalities that were members of the innovation foundation; Stichting Pioneering. Although it cannot be validated easily, it is likely that this sample consisted of practitioners with a more-than-average positive attitude toward technological innovation. This could have led to an over-estimation of VDC benefits. I tried to reduce the influence of optimism biases during the pilot projects by not expressing my knowledge and personal view on VDC benefits and shortcomings.

A last reflection point with regard to fieldwork is that my role and presence in the field was perceived by practitioners differently. Their view on the researchers' role changed with time and ranged from someone who: 'observes practice'; 'teaches industry how to do things'; 'critiques practice'; or, more negatively: 'creates only impractical abstract knowledge'. My presence in the field repeatedly involved explaining a researcher's neutral position in order to minimize the influence of these perspectives on practitioners' opinion, for example, about VDC. This demanded patience and management of expectations.

8.2. Reflection on the use of the HRO-lens

This study is pioneering the use of HRO concepts to evaluate the impact of technology interventions on construction projects. It has provided insights also into the possibilities and restrictions of its use. Therefore, this chapter discusses how the use of HRO impacts data collection, causality building and temporal validity of findings.

Various surveys exist in the HRO literature that try to measure organisational mindfulness. However, such surveys are not very useful for the purpose of evaluating the impact of VDC on mindfulness in utility construction. One reason is that surveys at least require a population to sample from in order to draw relevant and generalizable conclusions. Since VDC systems have been adopted by utility stakeholders only to a limited extent, such a population has not yet been established. Furthermore, existing HRO surveys have investigated practices and logic in *established* organisations. Since utility construction projects are temporal by nature, common practices and logic are redeveloped gradually during each project. Consequently, dominant common practices may not evolve or may become much harder to identify. As a result, there is little sense in determining ‘mindfulness of a utility project’ by using a survey. Therefore, mindfulness was investigated *in vivo*, for example, by observing mindfulness at the local level of operational processes, rather than studying it in the organisational as a whole.

Furthermore, HRO-literature (e.g. Weick and Sutcliffe 2007, Weick, Sutcliffe et al. 2008) argues that mindful behaviour helps people anticipate and contain unwanted events and, thereby, enhance process performance. This study uses the HRO’s mindfulness principles to show how VDC supports mindfulness. Consequently, it is logical to assume that VDC also improves coordination and performance. Although I have provided rich empirical evidence and theoretical arguments to support this argument, this study does not absolutely prove that 4D VDC based coordination is *more* mindful than paper-based coordinated projects. Researchers would need to study reference cases (i.e. paper-based coordinated cases with similar coordination issues and environmental conditions) to make that point and compare these with performance outcomes of identical VDC supported projects. Since practical performance data were and are limited in their availability, this cross-case comparison was considered not feasible to conduct within the scope of this PhD.

One last aspect related to the adoption of HRO is that mindfulness is a temporal state of being. It changes from moment to moment. Therefore, the reported findings about the contribution of VDC systems to mindful behaviour should be seen as ‘snapshot of HRO behaviour and being subject to change as practitioners develop their coordination skills and use of VDC systems further.

8.3. Suggestions for future research

This section addresses the shortcomings of this thesis. It discusses how research on development, implementation and evaluation of mindfulness-supporting VDC systems can be improved, refined or extended as a stepping stone for future research.

This study takes the example of the HRO lens to describe the boundary debates that take place in construction management research. Although chapter 2 acknowledged that such discussions may be unproductive, as they keep attention away from actual research outcomes, academic debates about the validity of a novel theory are both necessary and inevitable. This thesis suggests evaluating novel theories using pragmatic criteria (e.g. applicability, usability) to help researchers prevent themselves being derailed by these often diversionary legitimacy debates. This enables substantive discussions about construction management issues, rather than either-or debates about permissiveness of phenomena regarding a domain.

This thesis also introduced methods that are mostly grounded in data collected during field research. Since these may also be complementary to less empirical methods for VDC system development, future research should focus on how the fieldwork-based methods for VDC development and implementation can be integrated effectively with traditional desk-based development approaches. Further, the methods have been developed in a bottom-up way, creating the VDC models from scratch by aggregating ad-hoc derived objects and concepts. To increase the validity of the methods in this thesis, consecutive research efforts should develop criteria that allow distinguishing ad-hoc steps from the ones that have a high validity and generalizability for other projects.

Another suggestion for future research relates to the costs of employing fieldwork. For example, it can be argued that fieldwork-based development of VDC system elements requires developers to spend significant time in the domain of interest. Although it seems more time consuming and expensive compared with traditional desk-based system development; desk-based development very likely has higher redesign costs since it involves end-users only during final system design stages. One suggestion for future research is to study these cost differences between the implementation of the proposed methods fieldwork-based system development and implementation and traditional post-development user involvement. Similarly, implementing VDC systems to support coordination may be more expensive than traditional paper-based coordination. On the other hand, paper-based coordination in multi-stakeholder utility projects seems to have become more complicated, more

prone-to-error, and less cost efficient. Future research could focus on the differences between expenditures made to coordinate respectively with and without VDC systems to evaluate cost differences.

In addition, this PhD studied on only two VDC system elements (domain ontologies and 4D models) in just a few subsurface utility works. To test the developed methods and justify the claims related to application benefits of VDC further, future research should: 1) test whether the developed methods can be extend or re-used for VDC models other than 4D; and, 2) identify VDC benefits on a larger scale by studying additional multi-stakeholder utility projects. These points pose a challenge for researchers to teach practitioners how they can develop and implement VDC tools in their work practice.

Further, the focus of this study was on the utilities domain. The developed, implemented and evaluated VDC systems were investigated in this context, so conclusions regarding the impact of VDC system elements should be considered valid for this context alone. Future research could focus on refining the findings for subdomains in this context, as well as validating the applicability of the findings for the broader civil engineering field. In terms of refinement, future research could distinguish between studying VDC for utility coordination in inner cities and residential areas. Such stratification of project types would allow researchers to differentiate between the use and benefits of VDC elements in distinct project environments. Alternatively, findings may be applicable also to civil engineering projects other than utility works. Therefore, the next research steps could test my developed methods and validate VDC's contribution to mindfulness in other infrastructure projects.

A final suggestion for future research pertains to the findings of chapter 5 where statements and activities related to mindfulness principles were observed to a different degree. For example, activities related to *sensitivity to operations* were observed more often than activities related to *deference to expertise*. From this, one can draw a preliminary conclusion that some mindfulness principles apply more than others. I suggest others can look more closely and investigate whether some mindfulness principles are followed in construction more than others.

In summary, both the reflection on the research method and theoretical lens adopted highlight that:

- Compared to lab-experiments, practice-engaged empirical research on VDC systems is time consuming. It involves careful management of practitioners' expectations and acknowledgement of their possible optimism bias. The benefit is that it delivers a rich data set and highly relevant research outcomes.
- Surveys to study reliability in organisations as a whole (as done in existing HRO literature) are not suited for VDC studies in utility projects. Instead, mindfulness activities should be observed more locally, at operational level.
- Future studies could try evaluating whether VDC-based projects have higher performance than projects with paper-based coordination.
- To continue research in future, researchers could test the introduced VDC development and implementation methods in project types other than and different to utilities; study the cost impact of VDC implementation, and analyse whether construction uses each mindfulness principle to a different degree.

8.4. Recommendations and outlook

During socio-technical research stakeholders modify, transfer or ignore technologies and, thus, influence research claims. Similarly, technologies that are under development are altered to match stakeholder interests. As elaborated in the tradition of Latour's anthropology science (1987) and Van de Ven's engaged scholarship (2007), understanding technologies and facts also involves understanding the people that they connect with. Hence, *science*, *technology* and *society* should not be seen separately, but rather as a range of weaker and stronger associations (Latour 1987, pp. 140-141). This indicates implicitly that it is difficult to separate strictly the research on one particular technology from socio-technical trends that simultaneously shape the context of the study.

As a 'scientist in action,' I did not develop knowledge systematically only about VDC systems for utilities. In addition, my field-experience; dialogues with organisations; and, graduation student tutoring allowed me also to identify legal and technological developments that impact on utility construction. These trends are likely to support future challenges to build in more densely populated urban environments. These settings face an increased need to maintain existing infrastructures, while at the same time introducing new systems, such as fibre glass; subsurface energy conservation; smart grids; and, subsurface waste collection.

In this chapter, I address five identified developments that contribute to these challenges, these are: 1) tightening requirements for utility information storage and exchange; 2) a transition from 2D design to 3D modelling practices; 3) a gradual uptake of subsurface mapping technologies; 4) the introduction of databases and product lifecycle management systems; and 5) integration of geographical information systems (GIS) and building information modelling (BIM) software. Figure 15 allocates these trends to phases in the life cycle of a utility network.

Recently, various large utility strikes (such as in The Hague, Diemen, and Ludwigshafen in 2014) and network-incidents (such as the blackout in the Province of North Holland in March 2015; and the large electrical fire in London in April 2015) created urgency to plan and execute utility construction work much more carefully. To address this issue, service providers and platforms organisations, such as Reggefiber, Velin (pipe owners' association); KLO and GPKL (public and private utility associations); and Netbeheer Nederland (association for energy providers) already have developed guidelines, best practices, and legislative proposals to reduce the amount of strikes. In essence, the industry initiatives push for more mindful execution of construction activities and are expected to accelerate the five outlined trends. Each trend and related recommendations will be elaborated below.

The first trend I came across was while I collaborated with The Netherlands' Cadastre, Land Registry and Mapping Agency and the Dutch Association for Utilities (in Dutch: Kadaster, and Kabel en Leidingoverleg, respectively). The legal changes that these organisations work on could **ease access to and increase quality of exchanged utility information** during design, planning and execution stages. Dutch law currently mandates all utility owners (public *and* private) to store their assets' location information. This information, in turn, supports desk-survey of organisations that prepare excavation activities. To date, the national utility information exchange system (KLIC) executed this exchange by collecting information semi-automatically from each different utility company. In future, the EU directive INSPIRE changes this system, as it requires all public utility owners to provide 24/7 access to their asset information. Currently, private utility owners discuss whether they should follow this directive by storing their asset information centrally. If they comply with the directive, a comprehensive and accessible database can be created that provides fast and ubiquitous access to asset information. This, in turn, enables software developers to create new applications that can be used onsite to support excavation with frequently updated asset information.

Figure 15 - trends and developments influencing management of utility infrastructure life cycles

The recent inauguration of Professor Stoter at TU Delft strengthens this development. Prof. Stoter's objective is to use 3D data efficiently. She champions the development of a national approach around standards and structures for 3D geo-data. In my view, both the INSPIRE directive and 3D-initiative speed-up solution-finding for the utility sector's information issues. Our BSc. Student, Kevin Tankink, identified, for example, that such issues are, amongst others, standardisation of utility maps; the reporting of inconsistencies and errors on maps; and use of more detailed digital drawings. Therefore, to address these points I recommend private utility companies to comply with the public INSPIRE guidelines, as well as to support the 3D-initiative.

Another development in practice relates to the previous one and concerns the increased use of 3D modelling for urban infrastructures. Four years ago, the utility

companies involved in my research used 2D CAD drawings only to communicate designs to contractors, authorities and utility companies. This tradition gradually changes as organisations now develop a positive attitude toward **3D modelling**. On the one hand, this may be because clients and engineering firms are inspired by how 3D building information modelling enhanced facility and highway construction projects. The positive attitude was visible when our students (Berry Busker and Jesper Reuvers) were received with great interest by two local municipalities to conduct their BSc graduation assignment on the use of 3D/4D VDC. Another reason for the gradual uptake of 3D may be that austerity measures led to reorganisations within municipalities. For example, two municipalities in my network relocated urban planners to civil engineering departments. These planners were more advanced users of 3D software and obtained a small role to champion 3D infrastructure modelling. Finally, the 3D modelling trend is supported also by technology suppliers. Bentley systems, for example, introduced a dedicated package for subsurface utility modelling in 2014. Such tools make it less cumbersome for network owners to convert existing 2D utility maps and to develop 3D infrastructure models.

In essence, the crossover of 3D benefits from other construction domains; the championing of 3D in engineering departments, as well as the introduction of utility modelling tools, have created a positive attitude toward 3D modelling. To lever the adoption of this technology further I recommend clients and engineering firms to investigate where 3D modelling can support their work practices. By developing more mature 3D practices it also becomes easier for them subsequently to profit from 4D features and to achieve more mindful behaviour in construction coordination.

Another development identified in the past two years was when I found municipalities (e.g. Gemeente Hengelo), contractors (Siers, Twentse Weg- en Waterbouw) surveyors (Geofox Lexmond), and technology developers (GT Frontline) working with **subsurface mapping technologies**, such as ground penetrating radars and electromagnetic locators (GPR/EML). In addition, the University of Birmingham (member of the UK-Mapping the Underworld programme) had worked on developing a multi-sensor prototype tool that can be used to map different types of utilities that reside in different soil types. Discussions with our British colleagues and Dutch practitioners have shown that clients often are not well informed about what they can expect from the accuracy and completeness of the scans that such tools deliver. As this is indispensable for fruitful adoption of these surveying techniques, I provide three suggestions:

First, I recommend that surveying firms inform their clients about the outcomes that subsurface scans can deliver under different environmental conditions. Second, I advise clients to work out the information needs that they have during utility projects. This eventually will help surveying companies to align their services with their clients' needs. The work of our BSc. Student, Thom Brands, on contextualising the UK PAS-128 surveying guidelines was the first step to achieve this. Third, I recommend the Dutch utility sector to follow the British example by developing training and vocational education programmes about subsurface surveying. As the sector's knowledge and skills about subsurface surveying grows, I expect that utility construction projects can become enriched with significantly more detailed underground data.

There is another development that influences the later stages of the utility infrastructure lifecycle. Over recent years I have observed that asset owners, such as utility companies, municipalities, and facility service companies, tried to professionalise their **utility asset management**. One reason for this trend may be that since 2008 utility owners have the legal obligation to keep records of their assets and since 2010 to make these digitally available. To support asset management, I recommend utility companies to use product lifecycle management systems (e.g. from Siemens or Dassault Systèmes) as these can help them mapping and query databases of asset information. I suggest also that network owners explicate the specific attributes of information that these tools should contain. These requirements help organisations to design databases with relevant asset information. Furthermore, software developers should anticipate how information from, for example, 3D-models and subsurface scans can be integrated in their tools to support life cycle management of utilities meaningfully.

The last identified development deals with the integration of **geographical information systems** and **building information models**. To my belief, this development is driven by the increased affordability of laser scanning, photogrammetry techniques, 360°-street view and GPS. Developers of engineering software (e.g. Autodesk, Bentley Systems) and survey techniques (Trimble) currently offer software that integrates geophysical scans - such as point clouds models of buildings and terrain-level scans - with maps and design models. The integration of the geophysical data and building models enhances understanding of design-environment interaction. I expect that, in the future, features are developed that also enable integration of utility models, surface level scans and subsurface utility scans. I recommend municipalities, utility owners and con-

tractors to push for such features, as they could help to make design decisions about ground levels, utility tracks and cable depths in complex inner city projects.

All in all, the gradual development toward 24/7 accessible 3D GIS utility data, 3D modelling practices, subsurface surveying, utility asset management and GIS-BIM integration enriches the life cycle management of utility infrastructure systems. My recommendations related to these trends are summarised as follows:

1. I advise private utility companies to comply with the public INSPIRE guidelines, as well as to support the 3D-initiative. This allows creation of a national approach around standards and structures for a 3D geo-database, eventually providing access to a comprehensive set of asset information.
2. Clients and engineering firms should investigate where 3D modelling supports their work practices. If established, 3D practices enable 4D implementation, and, ultimately, support more mindful behaviour in construction coordination.
3. I suggest surveying firms teach their clients about the information that subsurface scans can deliver under different environmental conditions. To align survey services with client needs, I advise clients also to specify the survey information that they demand during utility works. Further, the Dutch utility sector should consider developing education programmes and training about subsurface mapping.
4. I recommend municipalities and service providers to invest in product lifecycle management systems to support asset management. I suggest that network owners systematically map their asset management information requirements to adequately tailor these systems to network owners' needs.
5. Finally, I suggest municipalities, utility owners and contractors to explore the potential of using GIS and terrain level scans in complex inner city projects to support design decisions related to ground levels, utility tracks and cable depths.

Some benefits of using rich information and more careful excavation technologies (e.g. vacuum excavators, soil brushers) are achieved already. The statistics from the Dutch Radio Communications Agency, for example, show a decrease in reported utility strikes. One main objective for the future is to maintain this trend and to implement techniques wisely that support maintenance of existing urban infrastructure and construction of new urban infrastructures. This objective will be central in the new BSc. course that, currently, I am developing about construction and mainte-

nance in cities of the future. In addition, the technologies and trends outlined will be explored, monitored and developed in the 'life setting' of our university's campus. Most of the platform organisations mentioned continue to be involved in this trajectory with the aim ultimately to connect the various industry initiatives and deliver exciting results that professionalise the (utility) construction in urban space.

Epilogue

Besides conducting research and presenting findings a PhD also involves making sense of science. This epilogue reflects on my experiences in ‘becoming’ a scientist to describe elements of this sense making process. This chapter addresses my questions ‘what is a PhD? And, what does science mean?’; but without attempting to be philosophically comprehensive. It also elaborates how I personally experienced the process of conducting science.²¹

Doctor of philosophy; science and philosophy of science

The translation of the Latin *philosophiae doctor* shows us a PhD is a doctor who is in pursuit of knowledge or – more literally – a teacher who is in love of wisdom. Philosophy can be considered a conceptual and formal discipline that centres on questions related to existence, knowledge and reality. Although science is an empirical discipline, philosophy is not necessarily so from a historical viewpoint. Currently, in academia, a doctorate refers to the activity of science. So, although *PhD* literally means doctor of philosophy, therewith implying that a PhD involves philosophy, the title actually qualifies a person as being a scientist. Despite the differences between science and philosophy as disciplines, the fields relate if it comes to fundamental topics, such as definitions and meaning of science, knowledge and reality. These themes are addressed in Philosophy of Science. I elaborate aspects below that I learnt science to be associated with, based on my modest experience in Philosophy of Science. Examples of aspects generally related to the science domain and the activity of science are listed briefly below:

Associations with the science domain:

- Pure science studies physical phenomena (Dutch: *natuurwetenschap*)
- Science can include also studies of social phenomena and liberal arts (as is common in German and Dutch translations of science: *wetenschap* and *wissenschaft*)

²¹ I thank Dr. Jacques Bos for reviewing the earlier version of this chapter

Science as an activity may involve:

- Deductive reasoning. In early science history, Aristotle started using syllogisms to do this.
- Predicting reality. Copernicus argued that theory is an instrument to predict reality.
- Describing reality. Galilei argued that theory describes reality.
- Using rigid methodologies to inductively examine empirical phenomena (e.g. Bacon).
- Deriving laws and axioms from observations (e.g. Newton and Hempel).
- Falsifying hypotheses. Popper argued that falsifiability is a criterion for ‘good science’.
- Interpreting phenomena. Gadamer argues that people do this continuously. It is central in present-day philosophy of humanities and some domains of social science.
- Extending knowledge, or, as cited by Newton: “standing on the shoulders of giants”.
- Being surprised, curious and willing to discover.

During my experience as a junior researcher in the field of construction management I developed the view that science, at least, involves studying reality *empirically*; and, contributing *specific* and *new* knowledge, or *ways to obtain* to new knowledge. In addition, its outcomes should be *relevant* for the construction domain. In construction management research, relevance is important since scientists can help improve professional practice, for example, by introducing new concepts, tools and methods. In case where institutional fragmentation hampers such innovations, scientists sometimes can have the leverage and legitimacy to push experiments with such new solutions.

A question that went together with my making sense of science is how knowledge and (social) reality should be approached when doing research. These epistemological and ontological questions lie at the heart of a dichotomy between methodological positivists and interpretivists. Positivist views assume there is an independent, self-standing social and physical reality that exists irrespective of the subjects that live in it. In their view, this reality can be objectively studied. A more interpretive methodological stance would be that social reality is constructed by people. In this case, access to social reality can be obtained only through perceptions of us as humans – although one can still believe that the physical reality exists independently of the ones who live in it. A more

relative statement would be to argue that one could draw subjective conclusions only from this. However, there are also viewpoints (e.g. Searle's) that social realities can be studied objectively. From a research methodology point of view, positivists mostly measure and quantify formal propositions and explore causality using, for example, lab experiments and surveys. Methodological interpretivists embrace reality as a whole and more often use sense-making methodologies, such as ethnography and grounded theory. Insights in these two perspectives about knowledge and (social) reality may help me in future to understand methodological choices better.

Conducting science

Deliberating about the definition of science is thought-provoking and, to my view, helpful to reflect on research practice. However, only being able to provide a definition about science does not make someone a good researcher; just as being knowledgeable about automotive techniques does not make one a good car driver. Besides asking 'what is science', my sense making also involved a more pragmatic question: 'how to do science?' The remainder of this section addresses practical lessons that I learnt during my PhD to address this question.

The PhD experience let me observe two types of study outcomes – often at conferences - that were not yet very scientific in my view. The first observed outcome is a *case description* which I define as a narrative about a construction project's life cycle. Such a narrative may have an interesting and highly informative storyline but, in contrast with a case study, does not necessarily answer a sound research question. Therefore, these studies are not likely to provide specific conclusions or new knowledge. The second observation relates to desk-based survey research. I was impressed often by the precise work and significant effort that peers conducted to do these studies but noticed, at the same time, that some surveys did not deliver new and relevant conclusions. For one, this was because surveys were not based on a thorough review of existing knowledge, or an exploration of the empirical contexts in which the survey's constructs get meaning. As can be derived from the examples above, specific and relevant outcomes can be obtained by: 1) guiding explorative empirical research with sound research questions that help extend the body of knowledge; while also 2) supporting desk-based research approaches and empirical exploration of main concepts and constructs. Both suggestions show that defining a specific research objective it is worth the investment upfront as it prevents studies from reaching either irrelevant or common sense conclusions.

Finally, I learnt that it was necessary to manage two practical risks while conducting research. These are: '*paralysis by analysis*'; and, being '*untempered curiosity*'. First, *paralysis by analysis* means spending a dysfunctional amount of time thinking and analysing and, thereby, hampering the decision-making that it should support. I recognised this while supervising students. I also experienced this myself when I wrote my MSc. graduation proposal. To outline strategies and possible research outcomes in this proposal, I spent significant time searching and analysing 'the best strategy'. While developing a comprehensive strategy to deal with a wide range of research outcomes, I lost time and got diverted from doing actual research. I learnt from this experience that it is more useful to choose one satisfactory research strategy and accept that the emerging research process deviates from it. After all, the essence of a research plan not only is, to predict the exact research process but also, to understand from which plan a study may deviate.

Another research management risk relates to '*untempered curiosity*'. Although curiosity is one of the main drivers in research, it can also lead one's attention away from achieving initial research goals. This happened particularly at the end of my PhD research. In one situation, for example, my curiosity led me to start additional research projects about utility project coordination. This endeavour took more time than anticipated and I realised that I had to focus on achieving my original research goals, rather than to continue exploring the utility domain. I learnt from this that there will always be many more questions than there would be time to answer them.

In conclusion, this section argues that the PhD title slightly deflects the present-day meaning degree as it refers literally to philosophy, but actually qualifies and qualifies a person as a scientist. After summarising aspects that influence the meaning of science, I stated that construction management science, at least, involves studying reality *empirically*; contributing *specific new* knowledge or *ways to obtain* to new knowledge (methods, tools or instruments); and, generating *relevant* conclusions. Further, I explained that my awareness about methodological positivism and interpretivism helped to better understand methodological decisions. While making sense of conducting science, I learnt also that achieving a strong theoretical contribution requires guiding empirical explorations with a clear theoretically substantive goal and also requires supporting desk-research approaches with empirical exploration of concepts, constructs and items. While paying attention to this, researchers also need project management skills to prevent over-analysis and '*untempered curiosity*' from drifting a study away from achieving its goals.

Glossary

<i>coordination</i>	the identification, explication and alignment of interfaces – and potential conflicts - between the utility project stakeholders’ mutually dependent processes (pp. 2. After definitions of Thompson 1967, van der Ven 1976, Galbraith 1977).
<i>mindfulness</i>	capacity of organisations to focus on the present and to know how to detect anomalies in plans and processes. In turn, this allows them to better anticipate and contain unwanted, unexpected situations (pp. 6. After Weick and Sutcliffe 2006).
<i>mindful behavior</i>	behavior that follows the five mindfulness principles: sensitivity to operations, pre-occupation with failure, reluctance to simplify, commitment to resilience, deference to expertise (pp. 6. After Weick and Sutcliffe 2007; and Weick, Sutcliffe et al. 2008).
<i>mindfulness constructs</i>	constructs derived from HRO-surveys in the literature. The constructs measure reliability in organizations (pp. 108. Based on the surveys of Weick and Sutcliffe 2007; and Vogus and Sutcliffe 2007)
<i>reliability</i>	follows from organizational mindfulness and is a temporal state in which unwanted and unexpected situations are absent. Reductionist views dispute what is absolutely reliable and what is not (pp. 19. After Weick and Sutcliffe 2007; and, Weick, Sutcliffe et al. 2008).
<i>utility construction/ utility works</i>	the activities involving the design, planning and construction of subsurface utility networks such as sewage, energy and water pipes and telecom lines. These works can consist of installation, repair and replacement (pp. 3. Own definition).
<i>VDC systems</i>	Virtual Design and Construction systems visualize or simulate models of construction projects. These models, in turn, enable identification and evaluation of design-construction alternatives, therewith supporting multi-disciplinary project management tasks (pp. 3. After Kam and Fisher 2004; Kunz and Fisher 2013; and, Khanzode, Fisher et al. 2008)
<i>VDC models</i>	the input and output of VDC systems. Input models are, for example, domain ontologies. Output models are e.g. 4D visualizations (pp. 3. Follows from VDC system definition).

References

This list contains the references to the cited work from chapters 1, 6, 7 and 8

- Adriaanse, A., H. Voordijk and G. Dewulf (2010). "Adoption and use of interorganizational ICT in a construction project." *Journal of Construction Engineering and Management* **136**(9): 1003-1014.
- Adriaanse, A., H. Voordijk and G. Dewulf (2010). "The use of interorganisational ICT in United States construction projects." *Automation in Construction* **19**(1): 73-83.
- Benevolenskiy, A., K. Roos, P. Katranuschkov and R. J. Scherer (2012). "Construction processes configuration using process patterns." *Advanced Engineering Informatics* **26**(4): 727-736.
- Cheng, E. W. L., H. Li, P. E. D. Love and Z. Irani (2001). "An e-business model to support supply chain activities in construction." *Logistics Information Management* **14**(1/2): 68-78.
- Cropper, S., C. Huxham, M. Ebers and P. S. Ring (2009). *The Oxford Handbook of Inter-Organizational Relations*.
- Davis, F. D. (1989). "Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology." *MIS Quarterly* **13**(3): 319-340.
- Davis, F. D., R. P. Bagozzi and P. R. Warshaw (1989). "User Acceptance of Computer Technology: A Comparison of Two Theoretical Models." *Management Science* **35**(8): 982-1003.
- De Bruijne, M. and M. Van Eeten (2007). "Systems that should have failed: critical infrastructure protection in an institutionally fragmented environment." *Journal of Contingencies and Crisis Management* **15**(1): 18-29.
- Dorée, A. G. and E. Holmen (2004). "Achieving the unlikely: innovating in the loosely coupled construction system." *Construction Management and Economics* **22**(8): 827-838.
- Dubois, A. and L. E. Gadde (2002). "The construction industry as a loosely coupled system: implications for productivity and innovation." *Construction Management & Economics* **20**(7): 621-631.
- Galbraith, J. R. (1977). *Organization design*. Reading, MA, Addison-Wesley.
- Gemeentelijk Platform Kabels en Leidingen. "Kengetallen." Retrieved 20 June, 2015, from <http://www.gpkl.nl/page/144/kengetallen.html>.
- Golparvar-Fard, M., F. Peña-Mora and S. Savarese (2011). "Integrated sequential as-built and as-planned representation with D 4 AR tools in support of decision-making tasks in the AEC/FM industry." *Journal of Construction Engineering and Management* **137**(12): 1099-1116.

- Gruninger, M. and M. S. Fox (1995) "Methodology for the Design and Evaluation of Ontologies."
- Hartmann, T. (2008). *A Grassroots model of decision support system implementations by construction project teams*. PhD thesis, Stanford University.
- Hartmann, T. (2011). "Goal and process alignment during the implementation of decision support systems by project teams." *Journal of Construction Engineering and Management* **137**(12): 1134-1141.
- Hartmann, T., M. Fischer and J. Haymaker (2009). "Implementing information systems with project teams using ethnographic-action research." *Advanced Engineering Informatics* **23**(1): 57-67.
- Hartmann, T., J. Gao and M. Fischer (2008). "Areas of application for 3D and 4D models on construction projects." *Journal of Construction Engineering and Management* **134**(10): 776-785.
- Hartmann, T., L. olde Scholtenhuis, V. Zerjav and C. Champlin (2014). "Mindfully implementing simulation tools for supporting pragmatic design inquiries." *Engineering Project Organization Journal* **5**(1): 4-13.
- Jeffcott, S., N. Pidgeon, A. Weyman and J. Walls (2006). "Risk, trust, and safety culture in UK train operating companies." *Risk analysis* **26**(5): 1105-1121.
- Jeong, H. S., D. M. Abraham and J. J. Lew (2004). "Evaluation of an emerging market in subsurface utility engineering." *Journal of construction engineering and management* **130**(2): 225-234.
- Jongeling, R. and T. Olofsson (2007). "A method for planning of work-flow by combined use of location-based scheduling and 4D CAD." *Automation in Construction* **16**(2): 189-198.
- Kam, C. and M. Fischer (2004). "Capitalizing on early project decision-making opportunities to improve facility design, construction, and life-cycle performance—POP, PM4D, and decision dashboard approaches." *Automation in Construction* **13**(1): 53-65.
- Kettl, D. F. (2005). *The global public management revolution*, Brookings Institution Press.
- Khalfan, M. M. A., P. McDermott and W. Swan (2007). "Building trust in construction projects." *Supply Chain Management: An International Journal* **12**(6): 385-391.
- Khanzode, A., M. Fischer and D. Reed (2008). "Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing." *ITcon* **13**: 324-407.

- Kim, C., B. Kim and H. Kim (2013). "4D CAD model updating using image processing-based construction progress monitoring." *Automation in Construction* **35**: 44-52.
- Kim, C., H. Son and C. Kim (2013). "Automated construction progress measurement using a 4D building information model and 3D data." *Automation in Construction* **31**: 75-82.
- Kunz, J. and M. Fischer (2012). Virtual Design and Construction Themes, Case Studies and Implementation Suggestions. *CIFE Working Paper #097*. Stanford, Stanford University
- Latour, B. (1987). *Science in action: How to follow scientists and engineers through society*, Harvard university press.
- Leedy, P. D. and J. E. Ormrod (2010). *Practical Research: Planning and Design*, Pearson
- López, M. F., A. Gómez-Pérez, J. P. Sierra and A. P. Sierra (1999). "Building a chemical ontology using methontology and the ontology design environment." *Intelligent Systems and Their Applications, IEEE* **14**(1): 37-46.
- Love, P. E. D., Z. Irani and D. J. Edwards (2004). "A seamless supply chain management model for construction." *Supply Chain Management: An International Journal* **9**(1): 43-56.
- Mahalingam, A., R. Kashyap and C. Mahajan (2010). "An evaluation of the applicability of 4D CAD on construction projects." *Automation in Construction* **19**(2): 148-159.
- Martinez, J. I. and J. C. Jarillo (1989). "The evolution of research on coordination mechanisms in multinational corporations." *Journal of international business studies*: 489-514.
- McMahon, W., M. Burtwell and M. Evans (2005). Minimising street works disruption: the real costs of street works to the utility industry and society. London, UK Water Industry Research. **05/WM/12/8**.
- Meijberg, E. and L. L. Olde Scholtenhuis (2014). Stop het graven! In 2024 liggen alle kabels en leidingen in goten. *CROW Infradagen 2014*. Ermelo, the Netherlands.
- Mikulakova, E., M. König, E. Tauscher and K. Beucke (2010). "Knowledge-based schedule generation and evaluation." *Advanced Engineering Informatics* **24**(4): 389-403.
- Mintzberg, H. (1973). *The nature of managerial work*. New York, Harper & Row
- Mintzberg, H. (1990). "The Manager's Job." *Harvard Business Review*(March April): 1-13.
- Neeraj Jha, K. and S. Misra (2007). "Ranking and classification of construction coordination activities in Indian projects." *Construction Management and Economics* **25**(4): 409-421.

- Nguyen, L. D., T. K. Nguyen, D. Q. Tran and C. Villiers (2014). "Productivity in Daytime and Nighttime Construction of Urban Sewer Systems." *Journal of Construction Engineering and Management* **140**(7).
- olde Scholtenhuis, L. L. and A. G. Dorée (2012). De gordiaanse knoop van kabels en leidingen: hakken we hem door? *CROW Infradagen 2012*. Papendal, the Netherlands.
- olde Scholtenhuis, L. L. and A. G. Dorée (2013). *Welcoming high reliability organising in construction management*. 29th Annual ARCOM Conference, Reading, UK.
- olde Scholtenhuis, L. L. and T. Hartmann (2012). *An object model to support visualizations and simulations of inner city subsurface utility construction activities*. 14th international conference on computing in civil and building engineering, Moscow, Russia, Moscow State University of Civil Engineering.
- olde Scholtenhuis, L. L. and T. Hartmann (2014). *Changing Scheduling Purposes and Evolving 4D-CAD Models: A Study of Planning and Realization in a Utility Project*. 2014 International Conference on Computing in Civil and Building Engineering, Orlando, Florida, United States.
- olde Scholtenhuis, L. L., T. Hartmann and A. Dorée (2012). *Systems architecture for a virtual construction site to support utility construction management tasks*. EG-ICE 2012 international workshop: Intelligent computing in engineering, Herrsching, Germany, Technische Universitaet Muenchen.
- olde Scholtenhuis, L. L., T. Hartmann and A. Dorée (Unpublished manuscript). "Coordinating in network project organizations: how utility coordinators bridge voids in project-of-projects constellations."
- olde Scholtenhuis, L. L., T. Hartmann and A. G. Dorée (2014). *Comparing Mindfulness in Manual and 4D Supported Coordination Practices*. Construction Research Congress, construction in a global network, Atlanta, Georgia, USA ASCE.
- olde Scholtenhuis, L. L., T. Hartmann and A. G. Dorée (2015). *Characterizing coordination in both loose and very tightly coupled utility reconstruction processes*. 5th International/11th Construction Specialty Conference, University of British Columbia, Vancouver, Canada.
- olde Scholtenhuis, L. L., S. Hoitema, T. Hartmann and A. G. Dorée (Submitted). "Using simulations to verify and empirically validate a categorization of sewer construction scheduling knowledge."
- olde Scholtenhuis, L. L., E. Meijberg and J. Boes (2014). EMVI en snellere binnenstedelijke rioleringsprojecten: wat te doen met nutscoördinatie? *CROW Infradagen 2014*. Ermelo, the Netherlands.

- Roberts, K. H., R. Bea and D. L. Bartles (2001). "Must Accidents Happen? Lessons from High-Reliability Organizations [and Executive Commentary]." *The Academy of Management Executive (1993-2005)*: 70-79.
- Roberts, K. H. and D. M. Rousseau (1989). "Research in nearly failure-free, high-reliability organizations: having the bubble." *Engineering Management, IEEE Transactions on* **36**(2): 132-139.
- Rogers, C. D. F., T. Hao, S. B. Costello, M. P. N. Burrow, N. Metje, D. N. Chapman, J. Parker, R. J. Armitage, J. H. Anspach, J. M. Muggleton, K. Y. Foo, P. Wang, S. R. Pennock, P. R. Atkins, S. G. Swinger, A. G. Cohn, K. Goddard, P. L. Lewin, G. Orlando, M. A. Redfern, A. C. D. Royal and A. J. Saul (2012). "Condition assessment of the buried utility service infrastructure - A proposal for integration." *Tunnelling and Underground Space Technology* **28**(0): 202-211.
- Royal, A. C., P. R. Atkins, M. J. Brennan, D. N. Chapman, H. Chen, A. G. Cohn, K. Y. Foo, K. F. Goddard, R. Hayes and T. Hao (2011). "Site assessment of multiple-sensor approaches for buried utility detection." *International Journal of Geophysics* **2011**.
- Russell, A., S. Staub-French, N. Tran and W. Wong (2009). "Visualizing high-rise building construction strategies using linear scheduling and 4D CAD." *Automation in Construction* **18**(2): 219-236.
- Rutten, M. E. J., A. G. D. Dorée and J. I. M. Halman (2009). "Innovation and interorganizational cooperation: a synthesis of literature." *Construction Innovation* **9**(3): 285-297.
- Scherer, R. and A. Ismail (2011). *Process-based simulation library for construction project planning*. Simulation Conference (WSC), Proceedings of the 2011 Winter, IEEE.
- Scherer, R. J. and S. E. Schapke (2011). "A distributed multi-model-based Management Information System for simulation and decision-making on construction projects." *Advanced Engineering Informatics* **25**(4): 582-599.
- Shawn Burke, C., K. A. Wilson and E. Salas (2005). "The use of a team-based strategy for organizational transformation: guidance for moving toward a high reliability organization." *Theoretical Issues in Ergonomics Science* **6**(6): 509-530.
- Steenhuisen, B., W. Dicke and H. de Bruijn (2009). "'Soft' Public Values in Jeopardy: Reflecting on the Institutionally Fragmented Situation in Utility Sectors." *International Journal of Public Administration* **32**(6): 491-507.
- Strauss, A. L. and J. M. Corbin (1990). *Basics of qualitative research: Grounded Theory Procedures and Techniques*, Sage Publications, Inc.
- Studer, R., V. R. Benjamins and D. Fensel (1998). "Knowledge engineering: principles and methods." *Data & knowledge engineering* **25**(1): 161-197.

- Swanson, E. B. and N. C. Ramiller (2004). "Innovating mindfully with information technology." *MIS quarterly*: 553-583.
- Thompson, J. D. (1967). *Organizations in action: Social science bases of administrative theory*. New York, McGraw-Hill Book Company.
- Tsai, W. (2002). "Social structure of "coopetition" within a multiunit organization: Coordination, competition, and intraorganizational knowledge sharing." *Organization science* **13**(2): 179-190.
- Uschold, M. (1996). "Building ontologies: Towards a unified methodology." *Technical report-university of edinburgh artificial intelligence applications institute aiai tr*.
- Uschold, M. and M. Gruninger (1996). "Ontologies: Principles, methods and applications." *Knowledge engineering review* **11**(2): 93-136.
- Van de Ven, A. H. (2007). *Engaged scholarship: A guide for organizational and social research*, OUP Oxford.
- Van de Ven, A. H., A. L. Delbecq and R. Koenig, Jr. (1976). "Determinants of Coordination Modes within Organizations." *American Sociological Review* **41**(2): 322-338.
- van Ravesteijn, R., E. Westdijk and E. Boonsma (2014). Kabels, leidingen en mensen een verkenning naar samenwerking, COB. **Eindrapport o43**.
- Vogus, T. J. and K. M. Sutcliffe (2007). "The safety organizing scale: development and validation of a behavioral measure of safety culture in hospital nursing units." *Medical care* **45**(1): 46-54.
- Vogus, T. J. and K. M. Sutcliffe (2012). "Organizational mindfulness and mindful organizing: a reconciliation and path forward." *Academy of Management Learning & Education* **11**(4): 722-735.
- Weick, K. E. and K. M. Sutcliffe (2007). *Managing the unexpected: Resilient performance in an age of uncertainty*, Jossey-Bass Inc Pub.
- Weick, K. E., K. M. Sutcliffe and D. Obstfeld (2008). Organizing for high reliability: Processes of collective mindfulness. *Crisis Management*. A. Boin. Los Angeles, Sage. **3**: 31-66 (Reprinted from Research in Organisational Behavior, pp. 81-123, by Sutton, K.M. and Staw, B.M., 1999, JAI Press, Greenwich CT).
- Winch, G. (1989). "The construction firm and the construction project: a transaction cost approach." *Construction Management and Economics* **7**(4): 331-345.
- Winch, G. (1998). "Zephyrs of creative destruction: understanding the management of innovation in construction." *Building Research & Information* **26**(5): 268-279.
- Wood, G., P. McDermott and W. Swan (2002). "The ethical benefits of trust-based partnering: the example of the construction industry." *Business Ethics: A European Review* **11**(1): 4-13.

Zanen, P., T. Hartmann, S. Al-Jibouri and H. Heijmans (2013). "Using 4D CAD to visualize the impacts of highway construction on the public." *Automation in Construction* **32**.

About the author

Léon olde Scholtenhuis (27) was born in Hengelo, the Netherlands and obtained his Civil Engineering BSc. diploma in 2009. Léon started a combined MSc. and PhD programme after having organised a study tour to Brazil in 2010. He received his MSc. degree in Construction Management and Engineering in 2012 (cum laude) and continued his PhD directly afterwards. During his MSc. and PhD Léon developed relationships with regional municipalities, contractors, utility companies and technology suppliers. He obtained knowledge about the utilities sector, road infrastructure projects and virtual design. In addition, he organised a 4D-training session for practitioners and successfully has presented his research results at national and international conferences. Léon tutored during BSc. (9) and MSc. (2) graduation projects and co-instructed the MSc. course “Markets, Organisations and Innovations in Construction”. Currently, he coordinates and co-develops the BSc. course “Smart Ways to get Smart Cities Smarter.” Furthermore, Léon is involved in the organisation of sports events and social events. He is an active tennis player and winter sportsman who also likes outdoor activities.