University of Antwerp

Faculty of Design Sciences

Research Group for Urban Development

Real options for real urban projects

Uncertainty and adaptive planning in complex spatial projects

PhD thesis submitted for the degree of doctor in de stedenbouw en ruimtelijke ordening at University of Antwerp to be defended by Thomas Machiels

Supervisors:
Prof. dr. ir. Tom Coppens
Prof. dr. Tine Compernolle

Antwerp, 2023

Jury

Chair
Prof. dr. ir. Maarten Van Acker, University of Antwerp

Supervisors
Prof. dr. ir. Tom Coppens, University of Antwerp
Asst. prof. dr. Tine Compernolle, University of Antwerp

Members
Assoc. prof. dr. ir. Marian Bosch-Rekveldt, Delft University of Technology
Prof. dr. Verena Hagspiel, Norwegian University of Science and Technology
Prof. dr. Wouter Van Dooren, University of Antwerp

This research was funded by the research fund (BOF) of the University of Antwerp (PeopleSoft ID: 36492); and the Fonds Wetenschappelijk Onderzoek (FWO) with a PhD Fellowshop strategic basic research (Grant 1S51820N)

Table of contents

Tables and figures

Tables

Figures

Acknowledgements

Elke keer in de afgelopen vier en een half jaar dat ik bij oma en opa langsging, vroeg oma: ‘hoe is ’t op school? Hoe is het met de studies?’. Dan legde ik haar telkens opnieuw uit dat ik doctoreerde. ‘Ah ja’, zei ze dan, regelmatig gevolgd door een anekdote over de publieke verdediging van haar neef die ze ooit bijwoonde. Die verdediging zou zeer humoristisch zijn geweest. Hij wist het publiek naar zijn hand te zetten. De lat ligt hoog, bedankt oma. Hun gezegende leeftijd van inmiddels bijna 90 zal hen niet toelaten om fysiek aanwezig te zijn bij mijn verdediging. Jammer, want oma zou genieten, opa zou blinken van trots. Maar gelijk had ze natuurlijk, want doctoreren is ook studeren, althans volgens mijn studentenkaart waarmee ik zonder gêne nog steeds kortingen weet te scoren in binnen- en buitenland. Zelfs het plaatje ‘op school’ klopt. Ik heb een boekentas met daarin een boterhammendoos, een drinkbus, een tienuurtje, een vieruurtje, een pennenzak en een notieschriftje.

Eerlijk gezegd weet ik ook niet goed of er meer verschillen of gelijkenissen zijn tussen studeren of doctoreren. Ik ben niet langer een arme student, de dagen zien er anders uit, ik heb een eigen bureau met bijhorend kantoornummer, ik heb collega’s om samen mee achter koffie (thee in mijn geval) te gaan, ik sta aan de andere kant van het onderwijs. Anderzijds, net als toen ik hier studeerde, voelde ik mij als doctoraatsstudent vrij om naast deadlines en afspraken zelf zin en invulling te geven aan mijn dagen. Ik koos zelf wanneer mijn werkdag begon en eindigde, ik bepaalde het tempo, ik maakte mijn eigen planning. De weken waren om te werken zodat ik in het weekend alles kan loslaten en doen waar ik goesting in had. Ik ben zelfs een tijd blijven pendelen tussen Antwerpen door de week en Hasselt in het weekend. Er leek geen einde te komen aan mijn studententijd, dat vond ik geweldig. Zouden de clichés waarover we onder de collega’s zelf lachen dan toch kloppen? Het leven na een doctoraat, op zoek naar een ‘echte job’, welkom in de ‘echte wereld’. Oef.

Als dit achteraf niet de ‘echte wereld’ blijkt te zijn, laat mij hier dan nog maar even rondjes draaien. Ik heb dit traject ervaren als één waarbij vrijheid geen grenzen kent als je verantwoordelijkheidszin en plantrekkerij goed in de vingers hebt. Dit bleek een job te zijn die me op het lijf geschreven was. Of het nu studeren of werken was, ik heb de kans gekregen iets te mogen doen dat niet aanvoelde als werken, een voorrecht, geen verplichting, omdat ik het ontzettend graag deed. Voor dat grote geluk ben ik bovenal veel mensen dankbaar die deel hebben uitgemaakt van deze mooie periode.

Mijn ouders en mijn zus. Mama, jij hebt vroeger tijdens oudercontacten op school tot in den treure moeten aanhoren dat ik beter kon. Na verloop van tijd was het voor ons beide geen verrassing meer en werden de gesprekken die erop volgden in de auto naar huis een verplicht nummertje waar we door moesten. Dat heeft jou niet tegengehouden om mij alle kansen te geven die me hebben gebracht tot waar ik nu ben. Jij hebt ons altijd aangemoedigd om te doen wat we graag doen. Fouten maken was oké, want daaruit kan je leren. Jouw mooiste eigenschap is dat jij eerst aan anderen denkt en dan pas aan jezelf. Dank je voor de voorsprong die jij mij in het leven hebt gegeven. Papa, ik heb heel mijn studententijd onder jou 'op kot' mogen zitten. Dat was het beste van twee werelden: op mezelf maar altijd iemand waarop ik kon terugvallen. Spaghetti en bijbabbelen op woensdagavond, een traditie die we nog steeds aanhouden. Lisa, zusje, hoewel we elkaar vroeger vaak in de haren vlogen, kan ik niet genoeg benadrukken hoe trots ik ben op de weg die jij aan het afleggen bent. Jij bent een voorbeeld, ook voor mij. Onze dochter zal dolgelukkig zijn met haar meter.

Er is een stereotype over Vlamingen dat ze honkvast zijn. Of dat in 2023 nog klopt, weet ik niet, maar mijn geweldige vrienden maken het zeer moeilijk niet te blijven plakken. Kuringen, Hasselt, dat is en blijft thuis, met als epicentrum van de wereld de jeugd-lokalen van Chiro Kuringen Centrum. Zondagen die nooit hoefden te eindigen en zomerkampen waar vrienden familie werden. Sander en Kevin, ik ben dankbaar en trots dat ik jullie mijn beste vrienden mag noemen. Van een leven zonder zorgen tot mekaar volwassen zien worden, een kind zien krijgen, een huis zien kopen, een zaak zien beginnen, een eerste job zien scoren, grenzen zien verleggen, relaties zien aangaan en relaties uit elkaar zien vallen. We hebben de mooie en moeilijke momenten samen kunnen beleven. Door Corona hebben we avonturen in de wachtkamer moeten plaatsen, maar laten we de naam van ons Whatsapp-groepje snel in ere herstellen. Er zijn veel fantastische mensen met wie ik nog in de leiding heb gestaan tijdens de eerste jaren van mijn doctoraat – met op kop Kalki, Gertjan en Wannes. Elke week opnieuw het beste van onszelf geven in de overtuiging dat wij het meeste plezier hadden, zelfs al waren er griepsymptomen voor nodig om een werkweek aan mij voorbij te laten gaan (sorry Tom en Tine). De kerngroep van de oud-leiding, de '96 mannen, de '97 dames, al het jong geweld dat daarop volgt, de ene Aspi groep na de andere, jullie zijn toppers.

Een doctoraat maken kan je niet alleen. Tom en Tine, bedankt voor jullie constructieve, respectvolle en ondersteunende manier van begeleiden. Jullie gaven me de vrijheid om mij dit doctoraat eigen te maken. Congressen bijwonen of ze zelf organiseren, een onderzoeksverblijf, meedraaien in het onderwijs, of een project in de marge, jullie hielden me nooit tegen om het allemaal te doen. Tom, bedankt om zo veel te betrekken in onderwijs en ander onderzoek, telkens een verrijking. Tine, altijd bereikbaar en altijd veel tijd nemen om mij te helpen. Onze ongeplande gesprekken op de trein bleken vaak waarde-
volle hersenspinsels te creëren waarop ik kon verder bouwen. Maarten en Wouter, als leden van mijn doctoraatscommissie gaven jullie steeds waardevolle inzichten mee. Bedankt om van elke samenkomst een constructief moment te maken. Rob, thank you for having me in Ann Arbor. Those six months were an amazing experience, and it turned out to become the final piece of my PhD puzzle. I enjoyed our frequent talks and I have good memories of Ann Arbor and UM. Kris, een reëel optiemodel uitwerken leek lange

tijd een verre droom. Bedankt voor jouw geduld, hulp en de vele overlegmomenten en simulatie-uren. Het is ons gelukt, ongelofelijk maar waar. Verder was dit onderzoek niet mogelijk geweest zonder de medewerking van heel wat mensen die ik mocht interviewen of waarvoor ik mijn onderzoek mocht pitchen. Bedankt voor de vele boeiende gesprekken.

Ik had ook nog eens geweldige collega's. Stijn, Nina, Chris, Tara en Axelle, of te wel K2.19. Ons samen wegstoppen in dat duivenkot waar weinigen het bestaan van afweten, het leek onlogisch maar was ongelofelijk leuk. In de zomer veel te warm en in de winter vaak koud. Kiezen tussen de koude buitenlucht of de CO2-meter in het rood zien gaan. Verschillende configuraties uitproberen met of zonder pingpong tafel. Om nog maar te zwijgen over de lounge waar we onze promotoren zouden ontvangen. Luxueus klinkt het allerminst, maar gezellig was het wel. Met jullie erbij was het veel leuker dan ronddwalen in een lege campus tijdens de Covid-19 lockdown(s). Samen lunchen, ventileren, lachen, filosoferen, hulp vragen of hulp bieden, afterwork drinks of samen naar de kerstmarkt. Collega's kunnen ook vrienden zijn, daarvan zijn jullie het bewijs. Dat we samen een congres mogen organiseren is de kers op een overheerlijke taart. Aan de andere collega's van de Research Group of Urban Development, bedankt voor de feedback die jullie gaven op mijn werk. We zijn niet de grootste onderzoeksgroep, maar het is kwaliteit boven kwantiteit. Het leeft, er is goesting om samen ondernemend te zijn, houden zo.

Miek. Mijn laatste woorden zijn voor jou. Onze kennismaking was al even onverwachts als het mooie leven dat we sindsdien samen hebben opgebouwd. Ik heb genoten van de momenten samen in die kleine studio in Antwerpen en van de vele avondwandelingen doorheen de stad. Jij werd mijn bubbel tijdens de lockdown. Voor veel koppels bleek die periode en lange lijdensweg te zijn, wij hebben die met glans doorstaan. Het bracht ons dichter bij elkaar, gewoon jij en ik, rust en zekerheid. Ik begrijp hoe moeilijk het voor jou was toen ik naar Amerika vertrok. Hoewel ik geen spijt had van die keuze, deed het pijn voor ons beide, vooral voor jou. Jij hebt mij daarin onvoorwaardelijk gesteund en dat doe jij nog steeds bij alles wat ik wil bereiken. Elke mijlpaal die ik bereikte tijdens mijn doctoraat deelde ik graag met jou, niet omdat ik jou over de inhoud warm kon maken, maar omdat jij telkens jouw oprechte trots uitte. Jij doet me groeien als persoon. Ik leer nog altijd bij van jou en de persoon die jij bent. Mijn bewondering en liefde voor jou zijn heel groot. Ik wil jou bedanken voor de kleine gelukjes en de grote stappen die we samen hebben gezet. Dit jaar is veel groter dan dit doctoraat. Wij worden mama en papa van een dochtertje en het zal fantastisch worden. Of ik er klaar voor ben, dat doet er niet toe, want jij bent erbij. Dan komt altijd alles goed. Ik hou van jou.

Tijdens het schrijven van dit stukje bekroop mij het gevoel dat ik niet helemaal leek door te hebben deze periode er bijna opzit. Antwerpen en Hasselt, doctoreren, teleurstellingen en succes, vriendschap en liefde, ik heb het zo intens beleefd dat ik niet mag vergeten af en toe achterom te kijken terwijl dit hoofdstuk op haar einde loopt. Een hoofdstuk dat doet kriebelen om de bladzijde om te draaien en verder te gaan. Onzekerheid maakt onvoorwaardelijk deel uit van ons leven, dat leerde ik uit mijn onderzoek. Wat ik ook

leerde is dat we er geen schrik van moeten hebben. Ik kan niet wachten om vooruit te gaan en te ontdekken wat de toekomst zal brengen.

Thomas

Mei 2023

Summary

Public and private investments in complex spatial projects (CSPs) such as transportation infrastructure and urban development have increased world-wide during the 21st century. Despite increasing investments, many CSPs still underperform or even fail completely. Time delays, cost overruns, and benefit shortfalls plague many CSPs, and few decision makers consider the long-term sustainability, relevance, externalities, and spatial-environmental or socioeconomic impacts of CSPs. One of the main reasons for CSP underperformance is that uncertainties and unpredictable changes in the project environment are ignored in the dominant predict-and-plan approach. Predict-and-plan relies on the belief that future project outcomes can be predicted with clarity and certainty, and decisions are often based on single future forecasts and the illusion that projects will work out as predicted. The predict-and-plan approach stands in stark contrast with the increasingly uncertain and unpredictable future for which we must plan. If uncertainties and their impacts are ignored, there is a larger chance for the actual CSP outcomes to deviate from the predicted outcomes, leading to project underperformance. Ignoring uncertainties also removes any incentive to develop flexible strategies that prepare projects to adapt to changing conditions.

While scholars in the field of planning and project management are increasingly advocating adaptive planning approaches that incorporate uncertainties and develop flexible strategies so CSPs can adapt to change, the predict-and-plan approach remains dominant in CSP practices. This dissertation departs from this gap between theory and practice and aims to offer novel contributions that advance our knowledge about how to manage uncertainties in CSPs through adaptive planning approaches. I do so in two ways: first, I question how uncertainties are managed in current Flemish CSP practices to better understand the tension between predict-and-plan and the inevitability of uncertainty in CSPs. Second, I introduce real options theory (ROT) to planning as a novel approach for adaptive planning, and question how uncertainty management and adaptive planning can be improved in CSP practice with ROT. ROT is an economic and financial theory that uses mathematical models to quantify the impacts of uncertainty and the value of flexibility. To answer these questions, I adopt an empirical approach based on multiple single case studies in which I engage with stakeholders as much as possible. Close engagement and communication with practitioners is an important condition to bridge the theory-practice gap.

Chapters 1 and 2 detailly sketch the background and main research gaps of the core concepts of this dissertation: CSPs, uncertainty, adaptive planning, and real options theory. Because most of the planning domain is unfamiliar with ROT, Chapter 2 takes a closer look at real option applications to transportation infrastructure projects in academic research in the 21st century. Through a literature review, a better understanding is gained

about the relevance of ROT for CSPs, and major obstacles that inhibit its application in current CSP practices. The main obstacles to exploiting ROT's potential are the mathematical complexity of real option models and a lack of empirical cases and good practices of applications in actual projects.

In Chapters 3 to 5, I look at current uncertainty management practices and stakeholder perceptions of uncertainty in Flemish CSPs. In Chapter 3, I research the New Lock infrastructure project in Zeebrugge through a document analysis to reveal the discrepancy between the practice of ignoring uncertainties in official CSP procedures and the inevitability of uncertainties arising during public inquiries. In Chapter 4, I extend this case study with semi-structured interviews and develop a theoretical framework with three models to explain uncertainty avoidance in CSPs: resource constraints, strategic behaviour, and planning institutions. The main findings show that planning institutions are most determining for ignoring uncertainties, meaning that official CSP procedures and regulatory frameworks in Flanders dictate the avoidance of uncertainty in favour of the legal certainty and credibility of decisions and project documents. In Chapter 5, I use Q methodology to research perceptions of uncertainty among stakeholders in the A102 infrastructure project. The revealed perceptions show the heterogeneity of stakeholder perceptions about uncertainty, and can help to anticipate conflict and prepare for stakeholder engagement about uncertainties. Chapters 3-5 offer a contradictory view between the varying perceptions stakeholders have about uncertainties on the one hand, and the persistent avoidance of uncertainty and the search for agreed certainties in official procedures on the other hand.

Chapters 6 and 7 shift the focus from uncertainties to adaptive planning, and the value of ROT for adaptive planning is showcased while addressing the obstacles identified in Chapter 2. In Chapter 6, I integrate ROT with scenario planning into an eight-step adaptive planning framework. I provide an illustration of how the framework could work in practice with an application to Plan Bay Area 2050 (PBA2050) and Link21 in the San Francisco Bay Area. Scenario planning are methods to understand the implications of uncertainties by exploring plausible future states. Link21 project team members were interviewed and asked to identify flexibility options for Link21 based on a real options typology and the scenarios that were already available for PBA2050. The findings from Chapters 6 show that stakeholders value the real options typology, and that qualitative real options reasoning is an accessible approach to identify adaptive strategies. In Chapter 7, I develop a quantitative real options approach that avoids complex mathematics, called the TIPROE model. The model integrates the scenarios from PBA2050 to calculate uncertainties, and a decision tree to value the flexibility options identified during the interviews from Chapter 6. The TIPROE model is applied to New Crossing, one of Link21's major rail infrastructure projects. The model results show that flexibility adds value to the project and significantly changes the decisions made when comparing the real options results with the results of a static predict-and-plan approach.

In conclusion, CSP practices in Flanders remain dominated by uncertainty avoidance as dictated by planning rules, procedures, and instruments. However, established rules do not match the reality of increasing uncertainty in the planning environment, and the predict-and-plan approach is difficult to maintain given the very heterogenous perceptions that stakeholders have about uncertainties and the future. In the search for new ways of planning in situations of uncertainty, ROT proves to be a valuable and accessible tool to either qualitatively or quantitatively identify and value flexibility. Chapters 6 and 7 offer one of the first in-depth applications of ROT to an actual empirical case study in collaboration with practitioners, and prove that flexibility adds value to CSPs. Building on these main conclusions, some remaining challenges are discussed in Chapter 8 that determine the agenda for future planning research and practice. Knowledge about uncertainty and flexibility remains limited among practitioners. Research is tasked with helping practitioners learn more about it. More importantly, research must figure out how planning institutions can be changed so that uncertainties and approaches like ROT can become incorporated in official practices. For planning practitioners and decision makers, the main challenge will be to change the overall mindset. Instead of believing that the robustness of plans and decisions relies on whether uncertainties can be removed, CSP stakeholders must embrace uncertainty and accept the impossibility of reducing every uncertainty. Only then can we start thinking how to adapt CSPs to their constantly changing planning context.

To summarize this dissertation in four words: be flexible, it's valuable!

Samenvatting

Publieke en private investeringen in complexe ruimtelijke projecten (CRP's) zoals transportinfrastructuur en stadsontwikkeling zijn wereldwijd sterk gestegen doorheen de 21ste eeuw. Ondanks deze toename presteren veel CRP's ondermaats of falen ze zelfs compleet. Veel CRP's worden gekenmerkt door vertragingen, kostenoverschrijdingen en opbrengst onderschrijdingen, en weinig besluitvormers houden rekening met de duurzaamheid, relevantie en impacts van CRPs op lange termijn. Een van de voornaamste redenen voor het onderpresteren van CRP's is dat, in de dominante voorspel-en-plan-aanpak onzekerheden en onverwachte veranderingen in de projectcontext worden genegeerd. Voorspel-en-plan is gebaseerd op het geloof dat de uitkomsten van een project met zekerheid voorspeld kunnen worden. Beslissingen volgens deze aanpak zijn vaak gebaseerd op de voorspelling van één toekomst en de illusie dat projecten zullen uitdraaien zoals voorspeld. De voorspel-en-plan-aanpak staat in schril contrast met de onzekere en onvoorspelbare toekomst waarvoor moeten plannen. Als de impact van onzekerheden wordt genegeerd, is er een grotere kans dat uiteindelijke CRP uitkomsten afwijken van de voorspelde uitkomsten, wat kan leiden tot project falen. Het negeren van onzekerheden neemt ook alle motovatie weg om flexibele strategieën te ontwikkelen die projecten voorbereiden om zich aan een veranderende omgeving aan te passen.

Hoewel academici in domeinen van planning en project management steeds meer pleiten voor adaptieve planningsaanpakken die onzekerheden incorporeren en flexibele strategieën voor CRPs uitwerken, blijft de voorspel-en-plan-aanpak dominant in de planningspraktijk. Deze thesis vertrekt vanuit deze kloof tussen theorie en praktijk en heeft als doel de kennis te verhogen over hoe omgaan met onzekerheden door middel van flexibele strategieën in CRPs. Dit wordt op twee manieren gedaan in deze thesis: ten eerste stel ik de vraag hoe momenteel met onzekerheden wordt omgegaan in CRPs in Vlaanderen, om dit vervolgens af te zetten tegenover de onvermijdbaarheid van onzekerheden in de planningscontext. Ten tweede introduceer ik de reële optietheorie (ROT) in het domein van planning als innovatieve methode voor adaptieve planning. Ik stel de vraag hoe ROT kan helpen om beter met onzekerheden om te gaan en om flexibiliteit te faciliteren in CRPs. ROT is een economische en financiële theorie die gebruikmaakt van wiskundige modellen om de impact van onzekerheden en de waarde van flexibiliteit te kwantificeren. Om tot een antwoord te komen op deze vragen, onderzoek ik meerdere casestudies waarin ik zoveel mogelijk in contact treed met stakeholders. Samenwerking met stakeholders is een belangrijke voorwaarde om de kloof tussen theorie en praktijk te overbruggen.

Hoofdstukken 1 en 2 schetsen op gedetailleerde wijze de kernconcepten van deze thesis en hun hiaten: CRPs, onzekerheden, adaptieve planning en ROT. Omdat ROT voor de meeste planners onbekend is, neem ik in Hoofdstuk 2 reële optietoepassingen op

transportinfrastructuur in de academische literatuur doorheen de 21ste eeuw onder de loep. Aan de hand van een literatuurreview komt ik tot een beter begrip over de relevantie van ROT voor CRPs en over de voornaamste obstakels die de toepassing van ROT in planning tegenhouden. De belangrijkste obstakels zijn de wiskundige complexiteit van reële optiemodellen en een gebrek aan empirisch bewijs en goede voorbeelden van reële optie toepassingen.

Hoofdstukken 3 tot 5 onderzoeken voor de Vlaamse planningspraktijk hoe er met onzekerheden wordt omgegaan in CRPs, en welke percepties stakeholders hebben over onzekerheden. In Hoofdstuk 3 leg ik aan de hand van een documentanalyse van de case Nieuwe Sluis Zeebrugge de discrepantie bloot tussen de dominante praktijk van onzekerheden negeren in officiële procedures en het onvermijdelijk naar boven komen van onzekerheden tijdens het openbaar onderzoek. In Hoofdstuk 4 diep ik deze case verder uit met semigestructureerde interviews om tot een verklaring te komen voor het negeren van onzekerheden. Hiervoor ontwikkel ik een theoretisch model met drie verklaringsmodellen voor het negeren van onzekerheden: beperkte middelen, strategisch gedrag, of planningsinstituten. De bevindingen tonen aan dat planningsinstituten het meest bepalend zijn voor het negeren van onzekerheden ten behoeve van de juridische zekerheid en geloofwaardigheid van beslissingen en projectdocumenten. In hoofdstuk 5 pas ik Q methodologie toe op het infrastructuurproject A102 om percepties over onzekerheden bij stakeholders te onderzoeken. De resultaten tonen de heterogeniteit van percepties over onzekerheden en kunnen helpen om te anticiperen op conflict en om stakeholderdialoog over onzekerheden voor te bereiden. Hoofdstukken 3 tot 5 geven een contradictorisch beeld weer over enerzijds de uiteenlopende visies over onzekerheden en dus de toekomst, en anderzijds het blijvend negeren van onzekerheden en zoeken naar zekerheden in officiële procedures van CRPs.

In Hoofdstukken 6 en 7 verschuift de focus van onzekerheden naar adaptieve planning. Hierin toon ik de meerwaarde van ROT voor adaptieve planning pak ik de obstakels voor reële optie toepassingen in planning aan. In Hoofdstuk 6 integreer ik reële opties met scenario planning in een acht stappen proces voor adaptieve planning. Ik bied een voorbeeld van hoe de acht stappen in de praktijk zouden werken met een toepassing op Plan Bay Area 2050 (PBA2050) en haar infrastructuurprogramma Link21 in de San Francisco Bay Area. Scenario planning zijn methoden om de gevolgen van onzekerheden te begrijpen door het ontwikkelen van mogelijke toekomstbeelden. Leden van het projectteam van Link21 werden tijdens een interview gevraagd om flexibiliteitsopties te identificeren voor Link21, gebaseerd op scenario's die al beschikbaar waren voor PBA2050 en een generieke reële optie typologie. De resultaten tonen dat stakeholders de reële optie typologie waardevol vinden en dat een kwalitatieve toepassing een toegankelijke manier is om reële opties toe te passen in CRP's. In hoofdstuk 7 ontwikkel ik een kwantitatief reëel optiemodel genaamd TIPROE, zonder complexe wiskunde. Het model is opgebouwd uit een beslisboom om flexibiliteitsopties die in Hoofdstuk 6 werden geïdentificeerd te waarderen. De scenario's van PBA2050 worden gebruikt om onzekerheden te kwantificeren. Ik pas het TIPROE-model toe op New Crossing, het grootste spoorweginfrastructuurprojecten binnen Link21. De resultaten van het model tonen dat flexibiliteit waarde toevoegt aan het project en beslissingen significant verandert dan wanneer beslissingen genomen zouden worden op basis van een voorspel-en-plan aanpak.

De conclusie van deze thesis is dat planningspraktijken in Vlaamse CRPs gedomineerd blijven door het negeren van onzekerheden omwille van regelgeving. De regelgeving komt echter niet overeen met de realiteit van toenemende onzekerheden in de planningscontext. De voorspel-en-plan-aanpak is moeilijk te verantwoorden gegeven de zeer heterogene percepties die stakeholders over onzekerheden en de toekomst hebben. In de zoektocht naar nieuwe methoden blijkt de ROT een waardevolle en toegankelijke tool te zijn om flexibiliteit te identificeren en waarderen, zowel op een kwalitatieve als kwantitatieve manier. De toepassing toont dat flexibiliteit de waarde van CRPs doet stijgen. Hoofdstukken 6 en 7 bieden overigens één van de eerste diepgaande reële optietoepassingen bij CRPs waarbij werd samengewerkt met stakeholders uit de praktijk. Verder bouwend op deze conclusies worden er in Hoofdstuk 8 een aantal overblijvende uitdagingen benoemd die het onderwerp moeten vormen van verder onderzoek. Kennis over onzekerheden en flexibiliteit is nog zeer beperkt bij planners en besluitvormers. Onderzoek heeft de taak om de praktijk hierover te laten bijleren. Belangijker nog, onderzoek moet antwoorden bieden op de vraag hoe we onzekerheden en methoden zoals ROT kunnen verankeren in de planningspraktijk en -wetgeving. Voor planners en besluitvormers is het de taak om hun beeldvorming te veranderen. In de plaats van te geloven dat de robuustheid van plannen en beslissingen afhangt van de mogelijkheid om onzekerheden weg te werken, moeten planners en besluitvormers onzekerheden omarmen en accepteren dat het onmogelijk is elke onzekerheid tot zekerheid te reduceren. Alleen dan kunnen we beginnen nadenken over hoe flexibel met overblijvende onzekerheden om te gaan.

De slagzin van deze thesis luidt dan ook: wees flexibel, het is waardevol!

1. Introduction

1.1. Complex spatial projects in times of uncertainty: For better or for worse

Complex spatial projects (CSPs), also called megaprojects, are a unique breed of projects in the field of planning. CSPs include transport infrastructure (roads, bridges, airports, railways), energy and water infrastructure (dams, wind farms), urban renewal and (re)development projects, or even entire new cities. CSPs have the ability to change a society's structure due to the scale of their potential socioeconomic and spatial-environmental impact (Christiaanse et al., 2019; Hanakata & Gasco, 2018). Public and private investments in CSPs have increased manifold over the course of the 21st century, and have become a global phenomenon. Despite the global increase in CSP investments and CSP experience, many CSPs still underperform or even fail completely. Time delays, cost overruns, and benefit shortfalls plague many CSPs (Flyvbjerg, 2014; Flyvbjerg et al., 2018), and few decision makers think beyond the traditional iron triangle criteria – cost, benefit, schedule – to consider the long-term sustainability, relevance, externalities, and spatial-environmental or socioeconomic impacts of CSPs (Lehtonen, 2014; Lehtonen et al., 2017b; Volden & Welde, 2022).

A CSP underperforms when its actual outcomes deviate negatively from initially set estimates, expectations or goals that serve as a benchmark against which a CSP is evaluated. Decision making in CSPs is often based on initial estimates and expectations about outcomes formulated during early project phases, when information is limited and uncertainty highest (Samset & Volden, 2016; Williams et al., 2019). CSPs are characterised by high complexity and uncertainty due to their large-scale, high investment cost, many affected public and private stakeholders, long time horizon, and large impact (Flyvbjerg, 2014). Many uncertainties can impact expected project outcomes between the early planning and decision-making phase, and the actual project implementation, delivery, and long-term operation. Also, the impact of CSPs themselves on their direct and indirect environment are difficult to predict and therefore uncertain (Bertolini, 2010).

There is a growing acknowledgement among planning and project management scholars that the future for which plans are made and projects are implemented, is becoming increasingly uncertain and unpredictable (Bergsma et al., 2019; de Roo et al., 2020; Taylor et al., 2020). CSP stakeholders must consider the possible impacts of uncertainties, changing situations and multiple possible futures on CSP outcomes (Salet et al., 2013; Skrimizea et al., 2019; Williams et al., 2019). Scholars are increasingly advocating the adoption of adaptive planning approaches that emphasize the need for flexibility to make CSPs adaptable to uncertainties and changing situations (Priemus et al., 2013; Rauws, 2017; Sohi et al., 2019). CSP practice however is still dominated by the rational planning model 'predict-and-plan', whereby decision making is based on single future forecasts in which uncertainties are generally ignored (Giezen, 2013; Lehtonen, 2014; Sanderson, 2012). Predict-and-plan relies on the false belief that the future can be predicted and that actual outcomes will match initially estimated expectations (de Roo, 2018; Nadin et al., 2021; Rauws, 2017). CSP investments are increasing in numbers, but, for better or for worse, dominant practices keep ignoring the potential impact of uncertainties on CSP outcomes, which can impact CSP performance.

This dissertation departs from this gap between theory and practice and aims to offer novel contributions that advance our knowledge about how to manage uncertainties in CSPs through adaptive planning approaches. To offer a fresh take on old but hot debates on uncertainty in planning and project management, I adopt real options theory (ROT) as a novel approach to facilitate adaptive planning in CSPs. ROT originated in the 1970s in the fields of finance and economics as a method and approach for decision making under uncertainty, and is slowly making its way into other disciplines such as planning, environmental studies, and project management. The objectives of this dissertation are to better understand current practices of uncertainty management in CSPs, and to provide methods and guidance on how to better manage uncertainties and how to facilitate adaptive planning with ROT in CSPs.

In the remainder of this chapter, I will further introduce the main concepts of this dissertation: CSPs, uncertainty, adaptive planning, and real options theory. I will highlight the research gaps, after which I introduce the research approach and the research questions. I will clarify the structure of this dissertation and describe how chapters 2 to 7 each address a specific knowledge gap and research question. The findings all come together in the conclusion, in which I reflect on the implications of my research for planning research and practice, research limitations and areas for further research.

1.1.1. The booming business of CSPs: trends and motives

CSP spendings have become a world-wide phenomenon and have never been as high as in the 21st century (Flyvbjerg, 2014). The motives for investing in CSPs are manifold: to replace or complement aging infrastructure and foster a more sustainable society; to facilitate economic growth; to increase societal welfare and well-being; to promote a city or region as centres of finance, business, tourism, art and culture to attract more investments, political power, and attention (Christiaanse et al., 2019; Hanakata & Gasco, 2018). Flyvbjerg (2014) has described the attractiveness of CSPs in terms of four sublimes: the aesthetic, economic, technological, and political appeal make CSPs an attractive investment for private investors, politicians, engineers and architects. World-wide, the importance of CSPs is growing as a means and strategy to address growing urbanization and the increasing pace of trends such as climate change, the energy transition, technological evolutions, and economic and sociodemographic changes.

Whatever the motives are for implementing a CSP, CSP investments are rapidly increasing and, overall, planning practice is becoming more project-based, with CSPs as strategic interventions that have a city-wide or region-wide impact. In 2008, The Economist (2008) called it “the biggest investment boom in history”. In Flanders, the interest for CSPs has increased through various initiatives. The Flemish government offers subsidies for strategic spatial projects and urban renewal projects as part of its urban policy. The COVID-19 pandemic led Flanders to launch its largest investment program ever, called Flemish Resilience, worth 4,3 billion euro of investments, including various types of CSPs (schools, hospitals, transportation infrastructure…). The Oosterweelverbinding in Antwerp is a multibillion infrastructure project and currently one of the largest construction sites in Europe. It is part of an even larger portfolio of transportation and urban CSPs in the Antwerp metropolitan region that will require tens of billions of euros of investments for decades to come.

In Europe, the EU programs Trans-European Transport Network (TEN-T) and Trans-European Networks for Energy (TEN-E) include the implementation of various multibillion transportation and energy CSPs. Both programs were launched in the 1990s and were expanded in 2013. In the USA, President Biden’s Infrastructure Investment and Jobs Act of 2021 entails a $550 billion five-year federal investment plan for transportation, energy, and water infrastructure. Already before this Act, expectations were that that CSP investments in the USA would increase with 600% between 2019 and 2029 (FMI, 2019). In the USA and probably in other places too, CSPs are not only increasing in number but also in cost, size and complexity (FMI, 2019). Asia and foremost China has taken the lead with CSP investments. Between 2011 and 2013, China spent more cement than the US did in the entire 20th century (Flyvbjerg, 2014). Notable examples that reflect the explosion of CSPs in developing countries are Azerbaijan’s artificial archipelago project, Turkey’s massive urban renewal project in Istanbul, and the creation of entire cities from scratch in Middle-Eastern countries such as Qatar and Saudi-Arabia. Although these contexts are completely different from each other, they show that CSPs are a booming business world-wide.

Despite the boom in CSP investments in Flanders and the rest of the world, the growing experience with CSPs in research and practice, and documented examples of successful CSPs (Rokicki, 2022; Siemiatycki, 2013; Volden & Welde, 2022), many CSPs remain plagued by underperformance issues in the form of cost overruns, time delays, (social) benefit shortfalls, stakeholder conflicts and societal protest, and unexpected externalities. Some CSPs are even overtaken by changing conditions, rendering them completely useless for society by the time they are completed. CSP underperformance can occur anywhere in the world (Flyvbjerg, 2014; Odeck, 2019). Europe and Flanders are no exceptions. As an illustration, Table 1.1 lists examples of CSPs in Flanders and Europe in which the actual outcomes deviated from initial estimates, causing underperformance and sometimes completely failed projects. To explain CSP underperformance, a closer look is needed at how CSPs are planned and managed.

Table 1.1. *Examples of underperformance in complex spatial projects (Compernolle et al., 2021; Defossé, 1990; European Court of Auditors 2020; Koppenjan et al., 2011; Rauws et al., 2014; Wiechmann, 2008)*

CSP	Description	Underperformance issues
Railport Lanaken	Freight railway connecting Flanders and the Netherlands	Project completed in 2011 with a cost of €33 million (2011 values). The railway was only used 15 times and did not attract the interest of companies as wrongly predicted in various study reports
Euroshopping Mechelen	Shopping centre in the city centre of Mechelen, Flanders	Build in the 1960s and renovated in 2000, but many stores have always remain vacated. Demolished in 2008 and replaced with a new residential project
Oosterweelverbinding	Road infrastructure project to close the Antwerp ring road, Flanders	Proposed in the 1990s with costs estimated in 2007 at €1,85 billion, current estimates surpass €4 billion (2021 values) and completion is scheduled for 2030. Due to unexpected soil pollution, the completion time may be delayed, and costs could further increase
Eurostadion	National football stadium in Brussels, Belgium.	Announced in 2014, but never built due to legal problems (not receiving a building permit) as a consequence of conflict and disagreement over expected impact on traffic on the already congested neighbouring highway network
Uplace	Shopping and entertainment centre in Machelen, north of Brussels, Belgium	Despite receiving building permits in 2011 and 2016, the project was never built due to legal action from neighbouring municipalities and the province Vlaams-Brabant. Opponents did not agree with estimated mobility effects and also feared it would harm local retail stores and economies.
Rail Baltica	900-kilometer railway through Lithuania, Latvia and Estonia	Cost increase from €4,6 to €7 billion (2019 values) and delayed with three years. There are concerns that the projected number of passengers will fall short of the EU benchmark and will render the project economically unsustainable
Lyon-Turin TGV link	High-speed railway connecting France (Lyon) and Italy (Turin)	Cost increase from €5,2 to €9,6 billion (2019 values) and a current delay of 15 years. The French Court of Audit released a report that questioned the realism of the cost estimates and traffic forecasts.
Canal Seine Nord Europe	1.100 km inland waterway network in France and Belgium	Cost increase from €1,7 to €5 billion (2019 values) and a current delay of 18 years. The premise of the project is that water traffic will increase fourfold by 2060 compared to 2030, but statistics from 2010-2020 do not suggest that this will be the case.
Fehmarn Belt	19km submarine road and rail link connecting Germany and Denmark	Cost increase from €5 to €7,7 billion (2019 values) and delayed with two years. The cost of protection measures against noise pollution was not taken into consideration.
Brenner Base Tunnel	65 km railway tunnel between Austria and Italy	Cost increase from €6 to €8,5 billion and delayed with four years. The project looks set for big delays and Austria and Italy have questioned each other's forecasting methods
Randstadrail	Light rail connecting The Hague and Rotterdam in the Netherlands	After the project became operational in 2007, it was plagued by technological problems, which led to a temporary closure and delay of one year. The safety of the new light rail system technology had not been sufficiently tested prior to the system's opening

Blauwestad	Development plan for a new area with 1.480 luxury home near Groningen, Netherlands	The investment costs for the public spaces were higher than expected, and demand for housing was lower than expected due to the economic crisis of 2008, leading to financial losses carried by the local government and a delay in the development
Dresden's urban strategy 1990-1995	Strategic planning in the German city Dresden	Dresden lost 60.000 of its 500.000 residents in the 1990s, but its urban strategy was based on demographic forecasts that predicted growth, leading to a construction peak and an oversupply of infrastructure, buildings, plots of lands, housing, and commercial spaces.

1.1.2. Predict-and-plan: An outdated approach for CSPs

In times of high unpredictability about the future and an increase in public budgets being spend on CSPs, considering uncertainties during the early phases of CSPs has become a difficult but urgent challenge that needs to be tackled. To avoid 'white elephants' – projects that fail to live up to their expectations (Davis, 2020) – decision making must be informed about the possible and difficult to predict impacts of uncertainties, and CSPs must be made more adaptive throughout their entire life cycle. Public budgets and (natural) resources are limited and threaten to be wasted if stakeholders stick to the 'EGAP-principle' – 'everything goes according to plan' (Flyvbjerg et al., 2003). The main premise of this dissertation is that CSP performance, outcomes and success is determined by the way uncertainties are managed and how the unpredictable future is prepared for (Dimitriou et al., 2014; Dimitriou et al., 2017; Patanakul et al., 2016). In other words, not the mere presence of complexity and uncertainty causes project underperformance, but rather how uncertainties are managed. I do not claim that ignoring uncertainties is the only cause of poor project performance, but it has been increasingly recognized as an important one (Davies et al., 2017; Denicol et al., 2020; Dimitriou et al., 2014; Sanderson, 2012).

Predict-and-plan as the dominant approach for CSPs has become incompatible with our contemporary planning context due to increased uncertainty. Single future forecasts have become unreliable. In planning literature, predict-and-plan is receiving increased criticism for being too linear, rigid, and unresponsive to changing situations (Balducci et al., 2011; Savini et al., 2015; Skrimizea et al., 2019). de Roo (2018) calls certainty, predictability of the future and the creation of the world according to plan, an illusion. Skrimizea et al. (2019, p. 131) attribute planning failures to "the fact that planning theories and methodologies have been based mainly on a simplified perception of reality (de Roo, 2010). This simplified perception regards either the denial of complexity and of uncertainty's existence, or the reflective action to restrict these 'barriers' by intensifying the processes of planning and control, deepening in more detailed methods and models, and ignoring the inherent uncertainty of complex spatial processes". In other words, while planning practice should consider multiple futures and uncertainties, it stubbornly keeps trying to predict the future by improving modelling methods and techniques.

There is an inevitable tension between the future, which is the essence of planning, and models used to inform decision making that are based on data from the past to forecast the future. Couclelis (2005, p. 1359) describes the "tension between (forecasting) models, which are essentially backward looking, and planning, which is by definition forward looking. (…) This is the `Janus partnership', (…) a partnership bound to prove problematic to the extent that the future does not unfold on quite the same principles as the past." Coping with uncertainty today is a pressing challenge in CSPs, and new approaches are needed that shift practice from predict-and-plan to prepare-and-adapt (Daniel & Daniel, 2018; Skrimizea et al., 2019).

Similar criticisms about predict-and-plan can be found in project management literature. According to Atkinson et al. (2006), the whole raison d'être of project management is to remove uncertainty. They describe project management that ignores uncertainty as "a castle built on shifting sands" (Atkinson et al., 2006, p. 691), waiting to collapse. However, explanations for poor CSP performance in project management studies are still dominated by theories from behavioural economics. Based on the research of megaproject scholar Bent Flyvbjerg, optimism bias and strategic misrepresentation have become two dominant explanations for poor CSP performance (Flyvbjerg, 2021; Flyvbjerg et al., 2018). Optimism bias means that actual project outcomes fall short of estimated expectations because humans are overly optimistic in their forecasts (Flyvbjerg, 2021; Flyv-bjerg et al., 2009; Welde & Odeck, 2017). Strategic misrepresentation means forecasts are deliberately tweaked to make the expected outcomes look better (Flyvbjerg, 2021; Flyvbjerg et al., 2009). This is done for economic or political reasons, i.e. to increase the chance of project approval and financial support. Optimism bias and strategic misrepresentation lead to 'survival of the unfittest' (Flyvbjerg, 2009, 2014), the best looking but, in the end, the worst CSPs get built.

Strategic misrepresentation can be prevented with increased accountability, external audits, and punishments for wrong forecasts or rewards for correct forecasts (Flyvbjerg, 2008, 2009). Optimism bias can be curbed with reference class forecasting, meaning estimates will be adjusted based on data from similar projects from the past (Flyvbjerg, 2008, 2013; Leleur et al., 2015). Generally, these solutions rely on financial or sche-dule reserves to prepare for cost increases or schedule delays. While evidence has been provided for optimism bias, and to a lesser extent strategic misrepresentation, the solutions offered to curb optimism bias and strategic misrepresentation have been criticized for keeping predict-and-plan in place. These solutions imply a continued belief in the ability to make accurate forecasts about the future, and do not incorporate uncertainty (Sanderson, 2012). Checks and balances to curb strategic misrepresentation or reference class forecasting to curb optimism bias have value to improve CSP performance, but in themselves do not offer guidance on what to do when the future is different from the set expectations and estimates (Denicol et al., 2020; Peter E. D. Love & Ahiaga-Dagbui, 2018).

Aside from ignoring uncertainties, predict-and-plan also poses a second tension with our contemporary society. Relying on single future forecasts implies a belief that there exists a single truth and consequently one shared vision about what the future will, or better, could look like. Not only do we need to plan for an unpredictable future, we also need to plan together with many different stakeholders with different and conflicting objectives, values, norms, and viewpoints (Aaltonen, 2011; Erkul et al., 2016; Mok et al., 2015). Stakeholders consequently have different views and impressions about the future. Incorporating uncertainty in planning processes also requires a consideration of different perceptions that stakeholders have about the future, about future outcomes and impacts of a CSP, and therefore about uncertainties (Atkinson et al., 2006; Lyons & Marsden, 2021; Zandvoort, van der Brugge, et al., 2018).

Two examples illustrate the tension between predict-and-plan and increased uncertainty and differences in stakeholder perceptions in our contemporary society. The Rail Baltica project, a 900-kilometer railway through Lithuania, Latvia and Estonia, is exemplary for the limited ability of models and modelers to forecast a single future. Three separate cost-benefit analyses were made because of concerns about the projected number of passengers, each including a different traffic forecast (European Court of Auditors 2020). In the Lyon-Turin cross-border railway project connecting France and Italy, proponents and opponents are in conflict because they hold different opinions about the forecasting methodology that was used to estimate traffic flows. They have different opinions about the model outcomes and thus about the project's expected future relevance and benefits (Esposito et al., 2022). In these two cases, which forecast is correct and which one is incorrect? Instead of trying to answer this question, which requires complete knowledge about the future, we must admit that there are multiple possible outcomes depending on how the future could unfold. We must also acknowledge that models can be constructed in different ways with different assumptions about the future, inevitably leading to different forecasts.

Both planning and project management literature are emphasizing the need and challenge to incorporate the impacts and effects of uncertainties in CSPs. More flexible approaches are needed to complement or even replace predict-and-plan. To tackle these challenges, I must first explain how the concepts of uncertainty and adaptive planning are understood in this dissertation.

1.2. Uncertainty: We know that we don't know

Uncertainty has received attention from the field of planning since the late 1960s, either as part of critique against the rational planning model that became dominant during that time, or either because researchers wanted to direct attention to the inevitability of uncertainty in planning. Notable examples are Christensen (1985), and the work of Friend and Jessop (1969) and Friend and Hickling (2005) about the strategic choice approach. In the past two decades, attention for uncertainty in planning literature has increased. More recent examples of influential studies are Abbott (2005), Skrimizea et al. (2019) and Zandvoort, van der Vlist, Klijn, et al. (2018).

Uncertainty in its most general definition is what Mack (1971, p. 1) describes as "the gap between what is known and what needs to be known to make correct decisions". Uncertainty is a lack of knowledge or data, lack of clarity, ambiguity, or a general lack of certainty that makes it impossible to accurately forecast the future for which we plan CSPs (Abbott, 2005; Ward & Chapman, 2003). In this introduction, I use the general definition of uncertainty in planning provided by Hillier (2017, p. 300): "Uncertainty refers to an incomplete knowledge of either how systems – such as urban systems, ecological systems, and so on – work, or/and of the impacts of planning decisions (or CSPs) on such systems". This definition defines uncertainty in two ways. There is uncertainty about how the environment or context in which we plan and make decisions will evolve and impact CSPs, and there is uncertainty about the impact of plans or CSPs on their environment. I deliberately adopt a general definition of uncertainty to introduce the concept in this first chapter, because uncertainty will be defined differently in chapters 2 to 7, for the specific purpose of each chapter. Aside from a general definition of uncertainty, scholars in planning studies and related disciplines have developed more detailed and different conceptualizations of uncertainty. As Hillier (2017) discusses herself, uncertainty is a fluid concept that can be used and conceptualised depending on the context it is used in, or purpose it is used for.

Uncertainty has been conceptualized from various perspectives. First, uncertainty types can be distinguished based on their degree of uncertainty or whether probabilities can be assigned to possible outcomes, ranging from complete certainty to complete uncertainty or ignorance. Examples are the distinction between known unknowns and unknown unknowns (Daniel & Daniel, 2018; Horne, 2007; Nachbagauer & Schirl-Boeck, 2019); Vander Heijden's (1996) distinction between risk, structural uncertainty and unknown uncertainty (Giezen, 2012, 2013; van der Heijden, 1996); Hillier's (2017) distinction between uncertainty and indeterminacy; Walker et al.'s (2003) uncertainty matrix including five different uncertainty types based on degree of uncertainty. Second, uncertainty can be described based on where the uncertainty occurs in the planning process, i.e. the nature of uncertainty. Abbott (2005) describes five different uncertainties that are either a form of environmental or process uncertainty, or a combination of both. Friend and Jessop (1969) and Friend and Hickling (2005) make a distinction between three uncertainty types: uncertainty about values, uncertainty about the decision-making environment, and uncertainty about decision making in other related domains. A third way to conceptualize uncertainty is by using thematic categorizations, whereby an uncertainty source reflects a specific sector of the internal or external planning environment. Examples of such uncertainty sources are market, legal, societal or social, socio-economic, political and policy, environmental, climate change, or impact uncertainty (Priemus, 2007; Priemus et al., 2013; Salet et al., 2013). Fourth, in project management studies, uncertainty is often conceptualised in relation to its related concept risk (PMI, 2021; Sanderson, 2012; Ward & Chapman, 2003).

Regardless of how uncertainties are described and defined, uncertainty creates a need for flexibility and a need to consider multiple alternative futures that must inform decision making (de Roo et al., 2020; Salet et al., 2013). If we are uncertain about how the future will impact CSPs, and how CSPs will impact its future environment, we need to be prepared to make changes. Vice versa, to be flexible, we need to understand the uncertainties that a plan or CSP needs to be flexible for. Adaptiveness and flexibility start from the premise of uncertainty (Zandvoort, van der Brugge, et al., 2018). Adaptive planning is therefore a logical approach to cope with uncertainty and to counterbalance or complement the rigidity of predict-and-plan approaches.

1.3. Adaptive planning: Preparing for change

Adaptive planning is considered in this dissertation as an umbrella term for planning approaches that intend to make plans or CSPs more responsive to uncertainties and adaptable to changing circumstances and alternative future conditions. As the attention for uncertainties has increased in both planning and project management studies, ideas about flexibility and adaptiveness have been integrated in various adaptive planning related concepts such as strategic spatial planning (Albrechts, 2010; Albrechts et al., 2017; Searle, 2020), the complexity turn and complexity sciences (de Roo & Zuidema, 2020; Skrimizea et al., 2019), adaptive and strategic capacity in CSPs (Giezen, 2013; Giezen, Bertolini, et al., 2015), monitor-and-adapt (Walker et al., 2013), prepare-and-commit (Koppenjan et al., 2011), and robustness and resilience (Davoudi, 2021; de Haan et al., 2011). These concepts share some common characteristics that help me to define adaptive planning: (i) awareness of uncertainty and change; (ii) responsiveness or the willingness to anticipate change; (iii) the institutional and organizational capacity to make changes; and (iv) understanding the limitations and constraints of adaptivity and flexibility.

Awareness of uncertainty and change. Since adaptiveness starts from the premise of understanding which uncertainties that plans need to be made flexible for, the first step is acknowledging and identifying uncertainties (de Roo et al., 2020; Zandvoort, van der Brugge, et al., 2018). Instead of using models to predict the future, they need to be employed as scenario generators (Zandvoort et al., 2019), and inform decision making about the likelihood of possible futures instead of claiming that the future can be predicted with certainty. Also, permanent monitoring of how uncertainties unfold is required.

Responsiveness and willingness to anticipate change. For plans and projects to stand the test of time, they need to be made flexible, adaptive, and responsive to changes in their environment (Bergsma et al., 2019; de Roo et al., 2020). Flexibility should be embedded in a plan from the start so that the plan is prepared for changes based on new input or knowledge (Ramjerdi & Fearnley, 2014), and not forced to make changes on an ad-hoc basis (de Haan et al., 2011; Walker et al., 2013). This requires finding a balance between closing down decisions and leaving options open (Bertolini, 2010; Lehtonen et al., 2017b). Only the most critical decisions should be made early in the planning process, while the timing of irreversible decisions should be moved until the latest possible moment, e.g. moving decision moments from the adoption of a plan to the formal granting or permit (Nadin et al., 2021).

Institutional and organizational capacity to make changes. Formal and informal planning institutions are required that support, enable, and formalize adaptive plans (de Roo et al., 2020). Adaptive planning must be institutionalized to become routinized in planning practice. Government rules, regulatory frameworks, and instruments either constrain or foster adaptive planning (Rauws, 2017). Adaptive planning must be assimilated with issues such as legal certainty, reliability, and sustainability within existing planning systems (de Roo et al., 2020). Implementing adaptive planning in existing planning systems requires a rethinking of planning traditions, planning institutions, and professional culture and capacity (Nadin et al., 2021; Neuendorf et al., 2018).

Understanding the limitations and constraints of flexibility. Flexibility can come at a cost that must be compared with its potential benefits. Adaptive planning is limited to the point where disadvantages might arise from a decrease in (legal) certainty for users of the planning system or a perceived lack of commitment as a consequence of keeping too many options open (Nadin et al., 2021). Financial, technical, spatial-environmental, and socio-political constraints can each determine in a different way the (un)feasibility of flexibility, depending on the specific planning context. Planning processes must always consider how flexible a plan can be (Rauws et al., 2014). One of the most difficult challenges to overcome for adaptive planning is exactly this tension between certainty and flexibility, or how much uncertainty we are willing to accept and plan for. Steele and Ruming (2012) even call the pursuit of both certainty and flexibility 'the holy grail of planning' (Hillier, 2017).

Many planning practitioners would likely agree that uncertainty is a challenge that cannot be managed through predict-and-plan (Hillier, 2017). Adaptive planning today, however, remains mainly theoretical. Planning practice and practitioners still rely on the predict-and-plan approach (Giezen, 2013; Giezen, Bertolini, et al., 2015; Giezen, Salet, et al., 2015), and even scholars seem to be caught in a struggle to figure out how to turn adaptive planning ideas into practical tools, approaches, and planning institutions that facilitate more adaptivity in CSPs. In the words of Hillier (2017, p. 302), "planning theorists and practitioners appear to have relegated coping with uncertainty to the proverbial too hard basket". The lack of practical examples and empirical research on how to cope with uncertainty and on how to facilitate and actually do adaptive planning in CSPs remains an important knowledge gap (Bertolini, 2012; Skrimizea et al., 2019; Zandvoort, van der Vlist, & van den Brink, 2018). Approaches for uncertainty management and adaptive planning need to be empirically tested in actual CSPs in collaboration with CSP stakeholders. Only then can we understand and illustrate the strengths and weaknesses of uncertainty-sensitive and adaptive planning approaches in contradiction to predict-and-plan. In the search for novel adaptive planning approaches for CSPs, I turn to real options theory as a potential valuable addition to the adaptive planning toolkit.

1.4. Real options theory: Be flexible, it's valuable!

Real options theory (ROT) is an approach to quantitatively calculate the value of flexibility through a variety of mathematical approaches that have been developed over the past 50 years. ROT originated in the 1970s in the fields of finance and economics as a critique against traditional discounted cash flow models, for example, net present value calculations still used today in cost-benefit analyses of CSPs. Traditional discounted cash flow models were criticised for not considering the impact of uncertainty on estimated cash flows of investment decisions and for not considering the value of managerial flexibility (Dixit & Pindyck, 1994; Trigeorgis, 1996). Since then, ROT has been increasingly proposed as a more suitable approach to value investment decisions in situations (i) where there is uncertainty about the future cash flows of an investment; (ii) where decisions are irreversible; and (iii) where there is flexibility in the timing of decision making (Dixit & Pindyck, 1994). ROT shows potential to be used in planning because these three situations also apply to CSPs.

First, as described earlier, CSPs are characterized by high uncertainty with regard to future costs, benefits, effects, long-term relevance and sustainability, due to uncertainty in the environment of the CSP as well as uncertainty about the impacts of a CSP itself. Second, CSPs imply physical (infra)structures and are therefore usually irreversible, which means that it is not possible to go back to the initial situation before project implementation and recover all the costs and resources spent (Ramjerdi & Fearnley, 2014; Verweij, 2017). There is no return policy if the outcomes are unsatisfactory. Yes, projects can be demolished to return to a pre-project situation, but this does not retrieve the initial investments made, and demolition also bears a cost. This irreversibility has led stakeholders in CSP processes, under the influence of predict-and-plan, to generally assume that a CSP is a go or no-go decision, all or nothing, now or never. This is also reflected in CBAs or other forecasting instruments used in predict-and-plan approaches, which only forecast costs, benefits, and impacts for a single future based on the assumption of an all or nothing implementation of a CSP.

Third, while CSPs are mainly considered as all or nothing investments, planners and decision makers actually have flexibility in the timing of decision making, and a variety of flexibility option types can be explored to make CSPs adaptive. Forecasting instruments and planning practice usually adopt a single timeline for project implementation and operation. This rigidity leads to a neglect of the possibilities of flexibility and the consequent value of flexibility. The main strength of ROT lies in its consideration of the added value of flexibility, which is currently not considered in planning (Coppens et al., 2021; Herder et al., 2011). Flexibility is the ability to adapt to uncertain and changing situations by making irreversible decisions more reversible or by postponing irreversible decisions where possible (de Roo, 2018; Sohi et al., 2019), in that way adding value to a project. Decision makers are not obligated to decide on every detail of a CSP in the early phases, which also does not make sense because uncertainty is highest during those early phases. ROT and adaptive planning in CSPs have the aim to keep options open, to find a balance between decisions that have to be made at a certain moment and decisions that can be delayed without delaying the overall planning and implementation process of a CSP (Lehtonen et al., 2017b; Priemus, 2010; Rauws et al., 2014). In ROT, flexibility options are called 'real options', referring to options available in real (physical) assets such as CSPs.

ROT was initially developed in finance to calculate the values of purchasing and selling stock options, but has been applied in other disciplines since the 1990s. The (theoretical) value of ROT has been discussed for urban design and masterplans (Coppens et al., 2021), transportation planning (Lyons & Davidson, 2016), various environmental topics (Fernandes et al., 2011; Kozlova, 2017), and project management and infrastructure projects or CSPs (Martins et al., 2015). With the introduction of ROT in various planning related fields, its general concepts and ideas have also expanded. Since the 1990s, two conceptual additions have that are relevant for CSPs and that will receive attention in this dissertation. A first important addition to ROT has been the distinction of different flexibility option types by Trigeorgis (1996) in his influential book 'Managerial Flexibility and Strategy in Resource Allocation'. Trigeorgis (1996) describes various option types with hypothetical applications to drilling infrastructure for an oil company. Due to the resemblance with and relevance for CSPs, the option types defined by Trigeorgis have been inspirational for other infrastructure and CSP studies on the use of ROT (Coppens et al., 2021; Herder et al., 2011). The options defined by Trigeorgis (1996) are:

- The option to delay a decision, or stage an investment or project in different phases
- The option to grow, meaning space is reserved in a plan or design that allows to add additional functions or infrastructures in the future, without predefining what those functions are.
- The option to scale (expand or contract), meaning the scale of a project or infrastructure can be expanded or contracted within the same function.
- The option to switch, allowing to change the functional use of a project or infrastructure
- The option to temporarily suspend (and restart) or completely abandon (parts of) a project or infrastructure.

The definition of specific option types helped to make ROT less abstract and more tangible for CSPs. A second conceptual extension of ROT is 'real options reasoning', a qualitative approach to real options in addition to the initial quantitative approaches (Gil, 2009; Krystallis et al., 2020; Trigeorgis & Reuer, 2017). The use of quantitative real option models requires a certain, sometimes high level of mathematical knowledge that is usually not present among stakeholders of, for example, CSPs. Real options reasoning entails a qualitative identification and evaluation of flexibility options and their value through brainstorming, workshops, or other deliberative approaches (Coppens et al., 2021; Trigeorgis & Reuer, 2017). Quantitative approaches can bring more rigour to discussions about flexibility, but qualitative real options reasoning in itself already adds value to CSPs (Alessandri et al., 2004; Coppens et al., 2021). It lowers the threshold of using ROT, and discussing the potential for flexibility options can increase awareness about the impact of uncertainties and the potential for flexible strategies, which is an important objective of adaptive planning (Coppens et al., 2021; Lyons & Davidson, 2016). Qualitative real options reasoning works well with the real options typology of Trigeorgis (1996) because the option types can be used to structurally identify flexibility options in CSPs.

Adaptive planning and ROT are in essence very straightforward ideas and concepts, and their theoretical similarities reveal an opportunity to link and integrate both concepts into one approach to better cope with uncertainties through flexibility in CSPs. So far, however, there remains a significant gap between the scholarly support for the use of ROT and adaptive planning in CSPs, and the dominance of predict-and-plan in CSP practice. ROT has received increased attention from the field of CSPs, predominantly energy and transportation infrastructure, but similar as with adaptive planning, ROT struggles to find its way into CSP practice (Garvin & Ford, 2012; Herder et al., 2011).

1.5. Research gaps, questions, and approaches: A reading guide

The main trend of the past ten years has been an increase of scholarly attention in uncertainty, adaptive planning and real options theory in response to underperforming CSPs and failing traditional planning and project management approaches for CSPs. A blind spot remains a lack of understanding about how uncertainties are currently managed and why they are ignored (specifically in Flanders), about how to do adaptive planning, and about how to better incorporate uncertainties in planning and decision-making processes of CSPs. This dissertation addresses these gaps in two ways. First, I will improve our understanding about current uncertainty management practices in CSPs by focusing on the tension between uncertainty avoidance in official CSP procedures and uncertainties that inevitably arise during early project phases. Second, I will research novel approaches, specifically real options theory, that help progress both theory and practice in the search for ways to better manage uncertainty and to do adaptive planning in CSP practices. The main research question of this dissertation is as follows:

What is the current state of uncertainty management in complex spatial projects (CSPs) in Flanders, and how can uncertainty management be improved and adaptive planning be facilitated, with real options theory, in CSPs?

By answering this twofold research question, this dissertation aims to contribute to closing the gap between theory and practice regarding adaptive planning and real options theory. Bringing theory and practice closer together requires more than a purely theoretical research approach. Therefore, the overall research approach of this dissertation is an empirical approach with case studies in which I engage as much as possible with stakeholders and practitioners. We need to equip planning practice with knowledge, approaches and good examples that actually facilitate a shift to adaptive approaches for CSPs. It is challenging for a researcher to directly impact planning practice, but close engagement and communication with practitioners can help to sensitise planning practice about challenges and innovative ways to do planning. Initially, the aim was to only research CSP cases in Flanders through participatory action research, meaning the researcher not only observes but also participates in the (CSP) process (Chevalier & Buckles, 2013). However, while CSP practitioners in Flanders understood the importance of my research, it was difficult to find a suitable Flemish case to research the potential of real options theory as an adaptive planning approach. Therefore, I expanded the research context with a case study from the United States that I researched during a stay at the University of Michigan. This allows me to highlight the influence of contextual factors on uncertainty management and adaptive planning when comparing the findings from the Flemish cases and the American case in the final chapter.

Chapters 2 to 7 each focus on a sub question and research gap, and have their own research approach. Each chapter is as a piece of the puzzle I try to solve to improve uncertainty management and facilitate adaptive planning in CSPs. Figure 1.1 provides an overview of the chapters in this dissertation.

Because planning practice is still unfamiliar with ROT, in Chapter 2, I further elaborate the state of the art of ROT set out in this chapter and research real options applications in CSPs, specifically transport infrastructure projects. There is an increase of ROT applications in transportation infrastructure studies, especially in the past ten years, but we have no idea how they impact CSP practice, and to what extent these studies are relevant for CSPs. Through an in-depth literature review, I explain the relevance of ROT for CSPs, and identify important obstacles that inhibit its application in current planning practice. The main obstacles are the mathematical complexity of real option models, a simplification of project contexts necessitated by the complexity of real option models, and a lack of empirical cases and good practices of applications in actual projects.

Chapters 3 to 5 focus on uncertainty management practices and stakeholders' views on uncertainties in Flemish CSPs. In Chapter 3, I address the lack of knowledge about to what extent uncertainties are incorporated in current CSP practices in Flanders, with the ongoing New Sea Lock port Infrastructure project in Zeebrugge as case study. I analysed project documents of the New Sea Lock port infrastructure project in Zeebrugge. This CSP is planned to expand port capacity to facilitate economic growth of the port. A document analysis allows me to understand the differences between the incorporation of uncertainties in official research reports and decision-making documents on the

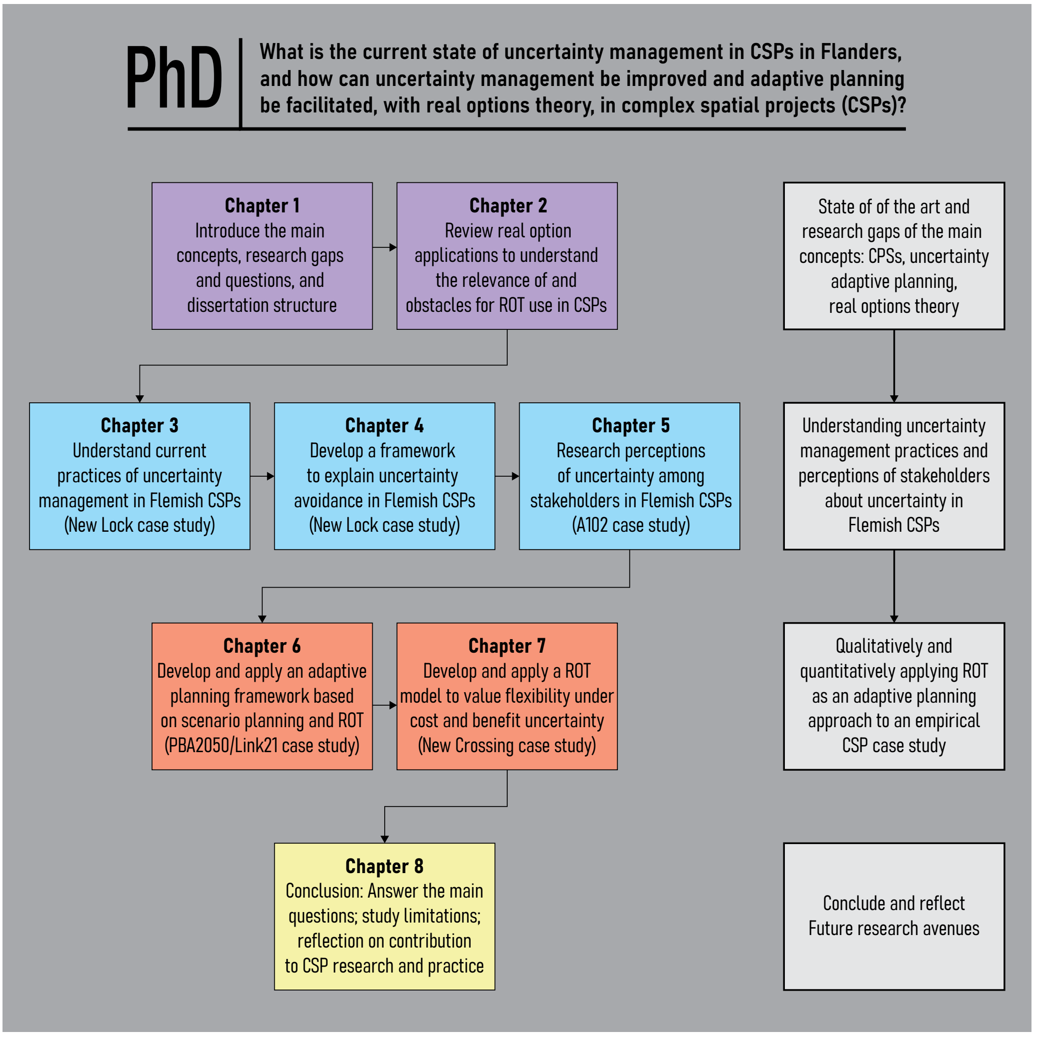


Figure 1.1. *Overview of the dissertation structure and the purpose of each chapter*

one hand, and the uncertainties that arise during public inquiries on the other hand. The findings prove that uncertainties inevitably arise during public inquires following concerns from various stakeholders after the publication of study reports or decision-making documents, but uncertainties were never explicitly incorporated nor analysed in study reports – societal cost benefit analysis and environmental impact assessment – and decision-making documents.

The findings from Chapter 3 generate a follow-up question that is addressed in Chapter 4: we know from various research, now also for Flanders, that uncertainties are often ignored in official CSP procedures and documents, but what are the motives that explain uncertainty avoidance in CSPs? Planning research increasingly stresses the importance of acknowledging uncertainties, but has not yet questioned or explained what motivates stakeholders to avoid uncertainties in CSPs. Answering this question is important, because explanations for uncertainty avoidance can help understand the conditions for acknowledging uncertainties. In Chapter 4, I develop a theoretical framework that consists of three explanatory models for uncertainty avoidance: uncertainties are either avoided because of (i) resource constraints, (ii) strategic behaviour, or (iii) becuase planning institutions prescribe uncertainty avoidance. To understand uncertainty avoidance and test the value of the framework, I dig deeper in the New Sea Lock case study through semi-structured interviews with project stakeholders. The findings show that each model has some explanatory power for uncertainty avoidance, proving the framework's value, but planning institutions are the most determining motive for not incorporating uncertainties in CSPs in Flanders.

Chapter 5, similarly as Chapter 4, focuses on uncertainty acknowledgement in CSPs, but in this chapter I research perceptions that stakeholders have about uncertainties in a CSP. We know from research and practice that CSPs involve many stakeholders that hold different opinions, values, positions, and interests. Departing from the premise that the future is difficult to predict because of uncertainty, I assume that this inability inevitably results in different perceptions of what then the future could look like, leading to different perceptions about uncertainties and their future outcomes. Managing uncertainties in CSPs requires a consideration of different perceptions of uncertainty among stakeholders, but this has, to my knowledge, not yet been researched. In Chapter 5, I therefore integrate uncertainty management and stakeholder management research and question how perceptions of uncertainties among stakeholders can be revealed, and of what use such perceptions are for project managers in CSP processes. I engaged with stakeholders from an early phase CSP in Flanders, the A102 road infrastructure project, part of De Nieuwe Rand, and used Q methodology to reveal perceptions of uncertainties among 32 different stakeholders. Q methodology is a mixed-method approach to study human subjectivity. The revealed perceptions help to understand how to broaden uncertainty management in CSPs, how to understand stakeholder heterogeneity, how to anticipate conflict, and how to prepare for stakeholder engagement about uncertainties.

In Chapter 6 and 7, I shift the focus from uncertainties to adaptive planning and ROT and address the obstacles to ROT's use in planning practice as found in Chapter 2. In Chapter 6, I integrate real options theory with scenario planning into an eight-step adaptive planning framework. Scenario planning is receiving increased attention in both planning research and practice as a method to understand uncertainties by exploring possible futures. A remaining gap is the poor translation from scenarios into adaptive plans, and scenario planning practices struggle to impact decision making in planning. The framework emphasizes how scenario planning and ROT are complementary and can compensate each other's weaknesses. I provide a hypothetical application of the framework to the case study Plan Bay Area 2050 (PBA2050) and its transportation program Link21. Plan Bay Area 2050 is a long-term planning vision for the San

Francisco Bay Area. Link21, one of Plan Bay Area 2050's transportation strategies, is a rail infrastructure program for the Bay Area and the Northern California Megaregion. An exploratory scenario planning exercise was performed in 2019 as part of PBA2050, which allows me to build on these results and use their scenarios to identify flexibility options. Flexibility options based on the real options typology from Trigeorgis (1996) were qualitatively identified and evaluated during interviews with Link21 experts, a form of real options reasoning. The results show that stakeholders see value in the real options typology, and that the scenario planning exercise from PBA2050 can serve as an inspirational source to increase attention for uncertainties in other planning initiatives and projects, such as Link21.

Chapter 7 builds on the findings from Chapter 6, in which I question how to develop a quantitative real options approach that avoids advanced mathematics while being able to simulate the complex reality of a CSP. I develop a quantitative real options approach, called the TIPROE model, that integrates scenarios, a decision tree, Monte Carlo simulations and limited foresight, to value options and uncertainties in Link21's largest infrastructure project, New Crossing. New Crossing is a multibillion under water rail tunnel to better connect East Bay and West Bay. Decision makers are faced with the questions of whether to invest in New Crossing or not, and which rail tunnel alternative to invest in, under conditions of social benefit and capital cost uncertainty. The scenarios from PBA2050 are used to incorporate uncertainty about the project's future social benefits, while data about project cost performance in US rail infrastructure projects is used to incorporate uncertainty about the capital costs. The flexibility options that were identified by Link21 members during the interviews presented in Chapter 6 are used to design a decision tree with options. The results show that flexibility adds value to the project and significantly changes the decisions made when comparing the real options results to the results of a static Net Present Value analysis. Taken together, Chapter 6 and 7 offer one of the first in-depth qualitative and quantitative applications of real options theory to an actual empirical case study in collaboration with practitioners.

In the conclusion (Chapter 8), I weave together the findings from Chapters 2 to 7 and reflect on their contributions for planning theory and practice. I also reflect on the added value of the results for the cases A102-Nieuwe Rand and PBA2050-Link21, and I discuss the research limitations and offer a guide for future planning research and practice about CSPs. The chapters were originally written as standalone papers that have been published or are currently in the process of review and publishing (Figure 1). When taken together, the insights from the chapters contribute to the bigger story of understanding current uncertainty management practices and finding ways to advance uncertainty management and adaptive planning through ROT in CSPs. Table 1.2 provides an overview of the chapters and their status. I hope the reader will become more attentive to uncertainties in planning practice, and can gain inspiration from this dissertation to cope with uncertainty through adaptive planning with real options theory in CSPs.

Table 1.2. *Status of the dissertation's chapters*

Chapter	**Output**	**Status**
1. Introduction	Dissertation only	NA
2. Real option applications in megaproject planning: trends, relevance and research gaps. A literature review	Paper	Published in European Planning Studies
3. Uncertainties in the decision-making process of megaprojects: the Zeebrugge new sea lock	Paper	Published in Proceedings of the Institution of Civil Engineers – Urban Design and Planning
4. Explaining Uncertainty Avoidance in Megaprojects: Resource Constraints, Strategic Behaviour, or Institutions?	Paper	Published in Planning Theory & Practice
5. Heterogenous stakeholder perceptions of uncertainty in megaprojects: The Flemish A102 infrastructure project	Paper	Published in International Journal of Project Management
6. Creating flexible plans for an uncertainty future: From exploratory scenarios to adaptive planning with real options	Paper	Conditional accept at Planning Theory & Practice
7. A real options approach to value flexibility in transportation infrastructure: The New Crossing case study	Paper	Submitted for review at Transportation Research Part A: Policy and Practice
8. Conclusion	Dissertation only	NA

2. Real option applications in megaproject planning: Trends, relevance and research gaps. A literature review

Thomas Machiels, Tine Compernolle & Tom Coppens

Published as:

Machiels, T., Compernolle, T., & Coppens, T. (2021). Real option applications in megaproject planning: Trends, relevance and research gaps. A literature review. *European Planning Studies*, 29(3), 446-467.

The journal publication and supplementary material are available at:

https://doi.org/10.1080/09654313.2020.1742665

Abstract

Megaprojects are complex and contain multiple risks and uncertainties. The dominant 'predict-and-plan' approach mainly ignores risks and uncertainties, making megaprojects inflexible and vulnerable to unforeseen changes. Insights and methods from real options theory (ROT) in economics and finance have the potential to improve planning of megaprojects in three ways: (a) better management and assessment of risks and uncertainties, (b) a more transparent and explicit identification and communication of risks and uncertainties, and (c) a monetary valuation of flexibility. An in-depth literature review of 42 papers of real options applications to megaprojects serves as a benchmark to analyze if current real options literature meets these three expectations. Through this review, we identify the main trends, relevance and research gaps. While its theoretical relevance is illustrated, three main gaps impede real options' practical relevance for megaprojects: the applications paint an incomplete picture of megaprojects; its mathematical complexity; and the lack of empirical evidence of real life cases. Based on a plea for more interactive research between scholars and planning practitioners, we provide an agenda for further research as to how ROT can better meet its expectations and fulfill its potential for the planning of megaprojects.

2.1. Introduction

The planning of megaprojects is complex and characterized by multiple sources of uncertainty. To integrate uncertainty analysis within the evaluation of megaprojects, scholars have put significant attention to the real options theory (ROT) during the past two decades. ROT rose in the fields of finance and economics in the 1970s following increased criticism against static and inflexible methods used in investment decision-making, mainly the cost-benefit analysis (CBA). In a CBA, discounted future cash flows are calculated for an investment decision over a certain period. ROT scholars criticize this method for not properly considering the impact of uncertainties that can alter these cash flows. These approaches often neglect the value of managerial flexibility to adapt to future changes (Trigeorgis, 1996).

ROT offers an alternative approach in which real options – relating to real assets – are valued throughout the decision-making process, so decision makers can adapt to future changes by exercising the options they hold. With roots in finance, the potential of ROT is now increasingly explored in planning and design of construction projects, and in particular in megaprojects. "Megaprojects are large-scale, complex ventures that typically cost US$1 billion or more, take many years to develop and build, involve multiple public and private stakeholders, are transformational, and impact millions of people" (Flyvbjerg, 2014, p. 6, p.6). Examples include hospitals, wind farms, large-scale signature architecture, or transport infrastructure (Flyvbjerg, 2014). Megaprojects' main challenges are its complexity and multiple uncertainties; planning for an uncertain future; and inaccurate forecasts and cost-benefit estimations.

In this paper, we focus specifically on real options applications in large transport infrastructure, generally the largest subcomponent of megaprojects. Transport infrastructure is a physical or tangible asset providing essential services and important for economic growth (Biatour et al., 2017). It encompasses roads, car parks, rails, ports (shipping), and airports. Transport infrastructure makes up the bulk of case studies and data sets in megaproject literature. Therefore, we use the term 'megaprojects' throughout this paper when discussing real options applications in large transport infrastructure projects.

We question '(I) how ROT is applied to megaprojects, and (II) to what extent these applications are solutions for the challenges megaprojects face? Answering these research questions allows us to illustrate and facilitate real option's potential for megaprojects. We conducted a qualitative and in-depth literature review (Petticrew & Roberts, 2008) of 42 articles of real options applications to transport infrastructure projects. While overviews on ROT applications in transport infrastructure exist (Martins et al., 2015), our analysis of the literature aims to provide insights on the trends, relevance and gaps of ROT applications; with the aim to explore the potential of ROT as a method for adaptive planning in megaprojects.

The introductory subsections that follow provide a theoretical background of megaprojects' challenges and ROT. In section 2, our method of an in-depth literature review is explatined, followed by an overview of the results in section 3, illustrating the main trends. In section 4, we discuss the relevance and gaps of real options applications in megaprojects, by connecting the main trends to the challenges identified in megaprojects literature. We introduce areas for further research for closing existing research gaps so the relevance and practical applicability of ROT for megaprojects could increase. The conclusion summarizes the main statements and contributions of this paper.

2.1.1. Megaprojects and their challenges

There is an abundance of literature covering megaprojects and their challenges (e.g., Flyvbjerg, 2017b; Priemus et al., 2008b; Priemus & Van Wee, 2013). Megaprojects are complex, contain many uncertainties and are "risk-rich". The possibility for an unexpected turn of events makes it difficult to make plans and predictions for decades into the future, and to make (all) decisions at an early stage. This often leads to inaccurate forecasts about expected costs and benefits (Flyvbjerg et al., 2005). Frequently returning inaccurate forecasts lead to cost overruns and time slippages. Nine out of ten projects have cost overruns (Flyvbjerg, 2014).

Explanations on cost overruns dominating megaproject literature are economic, psychological, or political in nature (Flyvbjerg et al., 2002). Optimism bias (psychological) means the initial costs are underestimated while the benefits are overestimated, because forecasters are overly optimistic, a form of self-deception or delusion (Flyvbjerg et al., 2009). Strategic misrepresentation (economic, political) implies that inaccurate forecasts are deliberately falsified through deception and lying to satisfy politicians and ease project approval (Flyvbjerg et al., 2009).

However, technical or methodological explanations for inaccurate forecasts are of equal importance. Many inaccurate forecasts, cost overruns and time slippages originate from the management method, rather than megaprojects' complexity itself. Despite the well-known history of inaccuracies, traditional but deficient methods are still widely used to manage the megaproject process, predict outcomes, and assess risks. Megaproject management is based on the dominant 'predict-and-plan' approach (Koppenjan et al., 2011), attempting to reduce complexity. Costs and benefits are predicted in a CBA, which deals with only one possible future at a time, making it a static and inflexible method. CBAs often lack an incorporation of uncertainties, ignoring unforeseen changes and creating an illusion of certainty about the future (Beukers et al., 2012b; van Wee & Rietveld, 2013). Traditional risk management aims to push out risks and uncertainties through risk avoidance, risk reduction, or shifting risks to other parties (Bruzelius et al., 2002). The predict-and-planning method therefore leaves little room for adaptation (Giezen, 2013), making megaprojects inflexible and vulnerable to uncertainties. Figure 2.1 summarizes Megaprojects' characteristics, the predict-and-plan approach, and megaprojects' challenges in a conceptual framework.

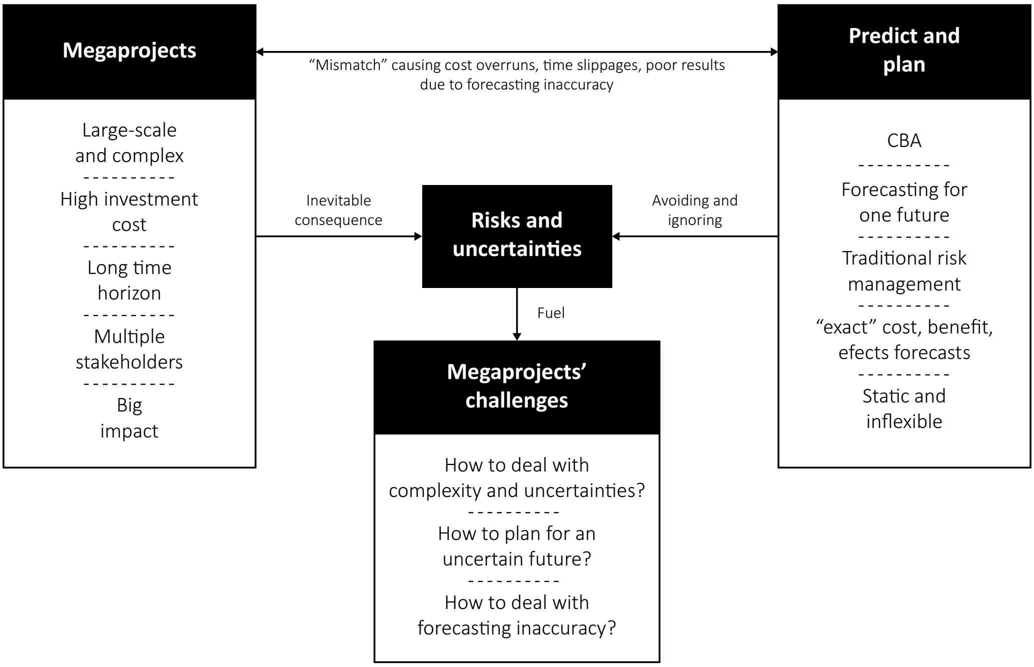


Figure 2.1. *Megaprojects: characteristics, dominant approach and their challenges*

2.1.2. Real options theory

ROT offers an alternative addition to the inflexible predict-and-plan approach. The theory was a response to the dissatisfaction of academics, strategists and corporate practitioners with the traditional techniques of capital budgeting, more specifically CBA (Trigeorgis, 1996), with the articles of Black and Scholes (1973) and Myers (1977) as two important milestones. CBA works well for passive investments in bonds and stocks, but less so in strategic planning (Trigeorgis, 1996). Trigeorgis (1996, p. 9) described this failure as "their inability to properly recognize the value of active management in adapting to changing market conditions or properly capture strategic value" (p.9).

ROT is applied to investment decisions that are irreversible, where there is uncertainty about the future benefits and/or costs of the decision, and where the decision maker has a choice in the timing of the investment (Dixit & Pindyck, 1994). Analogue to financial options, opportunities to acquire real assets can be called 'real options' or 'flexibility options'. The name 'real options theory' refers to an approach involving real assets, projects, or physical objects, contrary to purely financial agreements such as stock options (Trigeorgis, 1996). The holder of the option can either exercise or 'kill' it by choosing to invest, or delay the investment and wait for new information to arrive that dissolves some, but not all uncertainty about future benefits that might affect the timing of the investment (Dixit & Pindyck, 1994). The holder of the option will only exercise or 'kill the option' when the value of the underlying asset is higher than its strike price. This option to wait has a value in itself, which increases the overall benefit of the investment decision. It is important to understand that investing has an opportunity cost: If you invest, you lose the value of waiting. Because of this timing aspect, exercising an option is a right, not an obligation (Dixit & Pindyck, 1994). ROT not only calculates the value of holding options, it also determines the optimal timing to exercise or 'kill' it.

Real option types

The different types of 'real options' form a crucial part of the theory. Based on the overview from Trigeorgis (1996), seven option types are defined:

- The option to delay an investment.
- The option to stage, which means an investment or megaproject can be divided into different phases.
- The option to scale, which is a built-in flexibility in the design or operations that allows a project to either expand or contract. For example, the option to construct extra lanes on reserved land next to a highway (design) or increase/decrease the frequency of trains on a rail line (operations).
- The option to abandon, which means stopping a project altogether, with the possibility to receive salvage value.
- The option to switch use, which allows for a change in functional use, for example, by allowing a change from road lanes to rail road infrastructure in the design.
- The option to shut down and restart, which implies operations can better be shut down for some time when the operational costs surpass the benefits, and restarted again once the benefits surpass the operational costs.
- Growth options, often present in R&D projects, which set the path for future opportunities by creating multiple future options. For example, acquiring a plot of land creates new options on how to use the acquired land.

While we refer to these as the 'classical real options', other forms of risk management in megaprojects can be modeled by a real options approach. Examples include contractual agreements such as renegotiation claims or risk mitigation measures (e.g. government guarantees, subsidies, etc.).

Real option valuation methods

There are different quantitative techniques for valuing options. We briefly explain the most common and important ones. The standard works of Dixit and Pindyck (1994) and Trigeorgis (1996), as well as the overviews in Cheah and Garvin (2009) and Martins et al (2015) provide a more extensive overview.

- The binomial option pricing model (BLM) is a "tree-like model" and a simple representation of the evolution of an underlying asset, of which the value can only go up or down to two possible values. Multiple sequential periods result in a binomial tree with a large set of paths. Its main advantage is its simplicity, with values going two possible ways and the incorporation of only one uncertainty. However, this simplicity limits the use of the binomial tree in cases with multiple uncertainties (Martins et al., 2015).

- The decision tree analysis (DTA) is similar to the binomial tree model – a flowchart-like model representing a tree. It allows for infinite branches and thus more possible directions (options) a project could go, enabling it to better fit more complex problems and multiple uncertainties. Financial knowledge is required less as the probabilities of the different nodes of the branches could be approximate or relative valuations of flexibility and different options. Therefore, it lacks the provision of a project's true value. Another disadvantage is its possible complexity. When several branches are developed, the tree becomes more complex, difficult to read, and results too complicated to interpret (Martins et al., 2015).
- As opposed to the previous models, the Monte Carlo simulation (MCS) is a probability simulation model. Thousands or millions of simulations produce a probability distribution of different outcomes. It can incorporate multiple uncertainties and uses spreadsheet software, such as Microsoft Excel (Martins et al., 2015). It offers more precise and realistic results than the other two methods but is – despite available software – regarded as a more difficult and complex method.
- The three previous methods calculate the value of flexibility. Dynamic programming (DP) can be used to determine the optimal timing to exercise the option. It breaks the sequence of decisions in two: the immediate/initial decision, and a valuation function with consequences of all subsequent decisions (Dixit & Pindyck, 1994). By working backwards to the initial decision, values can be calculated for each scenario, identifying the best timing for exercising an option (Kozlova, 2017). This method can determine the optimal timing, but requires an understanding of advanced mathematical techniques (de Neufville et al., 2006).

Uncertainties and risks

Risks are defined as "an uncertain event or condition that, if it occurs, has a positive or negative effect on a project's objectives" (PMI, 2021, p. 373). Risks have a consequence and probability that can be determined with given data. With uncertainty, the probability of the outcome of an event is unknown or relative, not exact. In both ROT and mega-project literature, risk and uncertainty are used interchangeable.

We can identify three main uncertainty types in real options literature. The first is market uncertainty, related to the costs and benefits of a project. An example is the demand uncertainty in transport infrastructure, where revenues of, for example, toll roads depend on how many cars use the toll road. The second type is technological uncertainty over the physical difficulty of completing a project, or the effectiveness of a new technology used in a project (Dixit & Pindyck, 1994). The third type is policy uncertainty concerning future policy regulations – for example, when the timing and level of certain taxes or subsidies are being discussed (Dixit & Pindyck, 1994).

2.1.3. Real options' potential for megaprojects

ROT removes the urge to make every decision at the start of a project, but offers an approach for built-in flexibilities (real options), giving the decision maker the ability to better cope with uncertainties or risks and respond to circumstantial changes. Gathering information – albeit without ever reaching a state of complete certainty – creates the possibility to delay certain decisions and 'keep options alive'. How to cope with risk and uncertainty is an ever returning question in megaprojects (Priemus et al., 2008a), and flexibility or 'adaptive planning' in decision-making is strongly represented in megaproject literature:

"It is very important to keep open as many options as possible so that unexpected surprises, new insights and changed circumstances can be tackled in a flexible way. During the preparation and elaboration of the mega-projects it is crucial to maintain many options, which give the opportunity, at least at a number of strategic moments to make choices: adapt to changing environments, changing insights and improved knowledge, changing the scope or changing the time planning." (Priemus, 2010, p.1038).

We strongly believe ROT has the potential to aid and improve the quality of megaproject decision-making, as a tool for adaptive planning. Three arguments summarize this introduction and serve this premise, and allow us to extend the conceptual framework in Figure 2.2. (a) A real options approach allows for better risk and uncertainty management and assessment, instead of ignoring uncertainties, through more adaptive and flexible decision-making, addressing the limitations of the predict-and-plan model. (b) ROT is a tool for more transparent and explicit identification and communication of risks and uncertainties. (c) ROT is a predominantly quantitative approach that could be used as a tool to formally evaluate flexibility options and quantify their value. In current megaproject decision-making, the value of flexibility is absent from forecasting and cost and benefit estimations, and thus not considered. We consider these three points the main expectations of ROT for megaprojects, for which the in-depth literature review serves as a benchmark to analyze to what extent current trends in real option applications meet these expectations.

Note that real options theory's potential is not limited to megaprojects. However, the paper focuses on megaprojects only because of the strongly developed theories in planning literature regarding this subject. Furthermore, nearly all references found in the current literature on real options and transport infrastructure applied to large transport infrastructure projects.

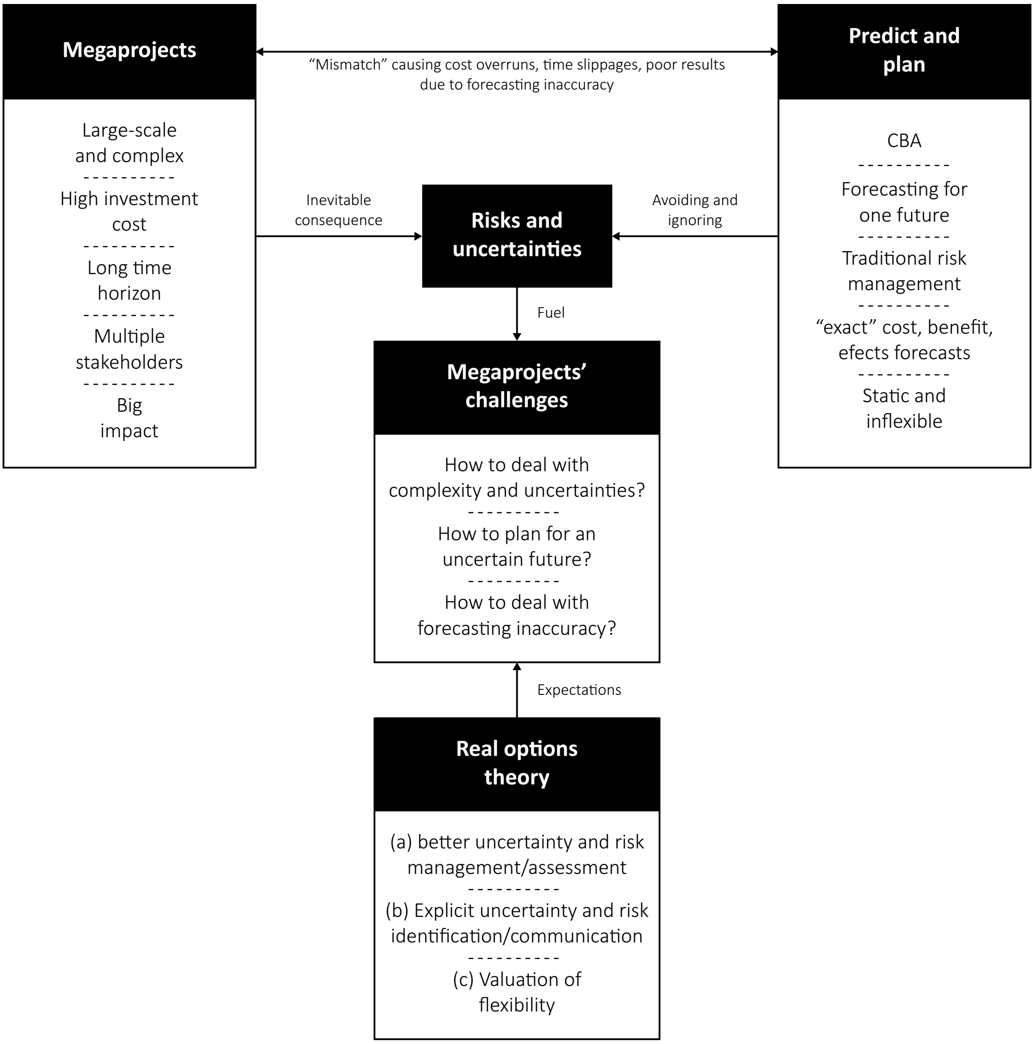


Figure 2.2. *ROT and megaprojects, conceptual framework*

2.2. Methodology

Articles were collected for the in-depth literature review in which ROT is applied to megaprojects, specifically transport infrastructure projects. 'Web of Science' was our main search engine. We used the term 'real option*' in combination with 'megaproject', 'infrastructure', 'transport infrastructure', 'project management', 'road/rail/port/airport infrastructure' as topics or parts of the title. The result was a total of about 425 articles, with duplicates in the results of multiple search combinations. The initial results were further refined by reading the abstracts of the articles, resulting in a selection of 31 articles. The selection was then extended with references from the initially obtained articles and searches in Google Scholar using the same search terms. The final selection contains 42 articles published between 2002 and 2019. Figure 2.3 shows that over half of the reviewed papers were published between 2014 and 2019. Therefore, they have not been a part of earlier overview/review articles (e.g., Martins et al., 2015). It illustrates the increased attention for infrastructure from real options scholars, or vice versa for real options from infrastructure scholars; and justifies the added value of this review paper.

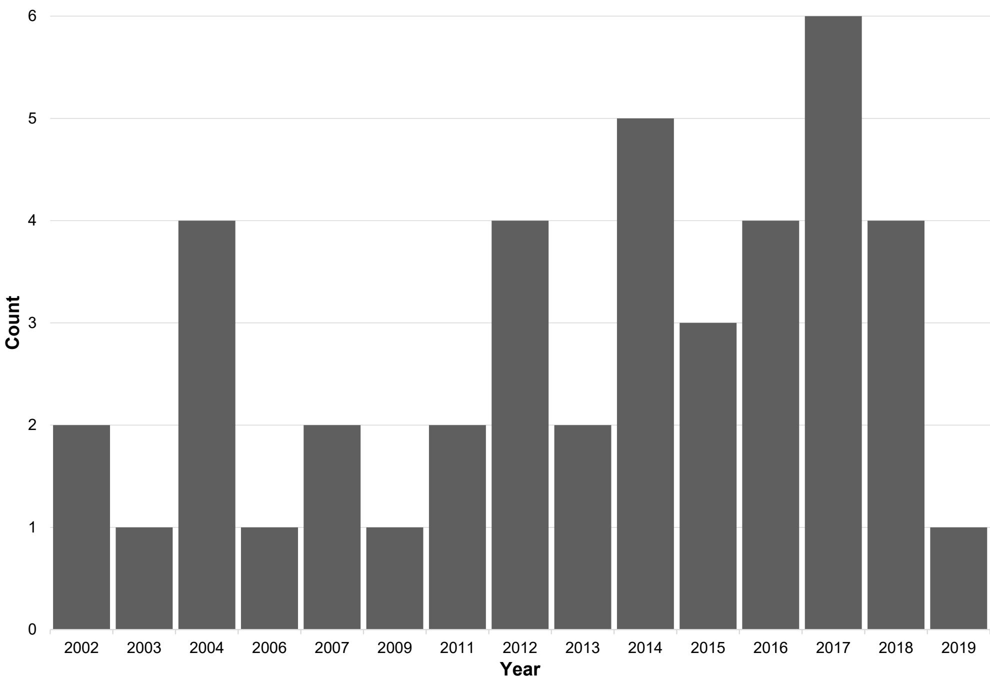


Figure 2.3. *Reviewed papers, publication date*

The review itself was conducted by answering the following six questions (Qs):

- Q1. What is the main research objective of the authors in the reviewed articles?
- Q2. To which type of transport infrastructure do the authors apply the ROT?
- Q3. Are these case studies hypothetical, ex post evaluations or part of an ongoing or future project?
- Q4. Which uncertainties and risks are considered and modeled in the real options application?
- Q5. Which real options are applied, and which built-in flexibilities are introduced in these applications?
- Q6. Which valuation models or methods are used in the applications?

The answers to the six questions were processed in an Excel spreadsheet, in which descriptive analyses were performed to identify the main trends. Appendix 1 provides an overview table summarizing the reviewed papers. Where possible, we refer in the tables of the results section to the numbered references in Appendix 1. It was impossible to discuss all 42 reviewed articles.

2.3. Results

2.3.1. Research objectives (Q1)

Four (I-IV) research objectives can be identified in the reviewed articles (Table 2.1). Real options are applied to case studies with the goal of displaying the benefits through (numerical) illustrations of ROT in three ways. (I) Quantitatively valuing flexibility (VF) allows to compare project values with or without flexibility options. (II) Some proceed further and determine the optimal timing (OT) of exercising the option, and how the threshold for optimal timing is affected by uncertainties. For instance, Couto et al (2012) determine the optimal demand level for investing in a high-speed rail project in Portugal. (III) Other authors developed new quantitative real option models to fit a specific case type, often focusing on instruments or contractual agreements for risk mitigation (RM) that fall outside the group of "classic" real options. Mirzadeh and Birgisson (2016) develop a real options model for the valuation of PACs – price adjustment clauses to protect contractors from increasing material or fuel prices during the construction of roads.

Table 2.1. *Research objectives in ROs applications (Q1)*

Research objective	Count	References
Valuing flexibility (VF)	38	1-5, 7-15, 17-23, 25, 27-42
Optimal timing (OT)	8	8, 9, 12, 15, 27, 33, 37, 42
Risk mitigation (RM)	19	1, 2, 4, 5, 7-10, 12, 18, 20, 21, 23, 24, 28, 29, 32, 34, 40
Practical relevance (PR)	39	1-22, 24-34, 36-41

Aside from displaying real options' potential, (IV) the articles propose ROT through a case study example as a valuable decision-making method for policy makers, project managers, or other actors involved in project management. They stress its practical relevance (PR). Buyukyoran and Gundes (2018) presented a model determining the lower and upper boundaries (values) of, respectively, a minimum revenue guarantee (MRG) and a maximum revenue cap (MRC) in concession contracts. They concluded that the public and private sector could use this model to test the effect of MRG and MRC on project value. Most articles take a private or public-private, profit maximizing perspective and do not take into account external costs like congestion or socio-environmental impacts.

While these articles succeed to illustrate the benefits of valuing real options through quantitative results, empirical evidence to support research results lacks in the reviewed papers.

2.3.2. Case types (Q2-3)

Table 2.2 shows that road infrastructure is the most popular case type (25 out of 42), especially toll roads (18 cases). Toll roads are a textbook example of public-private partnerships (PPPs) in transport infrastructure. In PPPs, proper risk allocation between public and private actors is crucial for a project's success, and therefore real options analysis is a valuable approach, as it integrates uncertainty and allows for the evaluation of different risk hedging mechanisms. Other transport infrastructure projects covered include (high-speed) rail cases (10) – including one subway and one metro line project – airports (4), car parking garages (2), and one container terminal case (port).

Twelve of these articles apply ROT to a hypothetical case study (Table 2.2). Hypothetical means there is no reference to an actual project, nor the use of data from an actual project. Zhao et al (2004) apply a real options model to a hypothetical 50-mile long highway section in the USA to argue how decision-making optimality can be achieved. Similar to this example, others use data from actual settings but not projects for their hypothetical cases. (e.g. discount rate in a specific country).

Table 2.2. *Transport infrastructure types and application type (Q2/Q3)*

	Hypothetical	Ex post	Current project	Total
Road	8	15	2	25
Rail	2	7	1	10
Airport	0	1	3	4
Parking	2	0	0	2
Port	0	1	0	1
Total	12	24	6	42

As for actual cases or projects, 24 articles are an ex post evaluation of existing projects, looking back at cases and using these to illustrate how these projects could have been developed or managed through a real options approach. In other words, these projects have not been developed, managed, or valuated from a real options viewpoint in reality, but serve as illustrations for real option models. Martins et al (2017) compare the values of the original terminal container expansion project in Ferol (Spain) without flexibility, with their adjusted case that includes the flexibility option to expand the port in different phases to avoid overcapacity. These articles have some overlap with hypothetical case studies, since ex post additions or adjustments to projects could be interpreted as hypothetical. In addition, sometimes hypothetical data is used if certain data for these projects is unavailable. However, we regard them as ex post evaluations because they still refer to existing projects.

Only six cases discuss or have direct links with ongoing or existing projects wherein important decisions still have to be made. Four articles discuss the value of a real options application for decision-making on future airport expansion through flexible strategies (e.g, Martins et al., 2014). Another example is the article by Fawcett et al (2015), which is part of a collaborative European research project (CILECCTA) on the application of ROT for software creation to evaluate the impact of flexible and responsive strategies for highways.

2.3.3. Uncertainty sources (Q4)

Based upon Dixit and Pindyck (1994), we distinguished three uncertainty types: market, technological, and policy uncertainty. Market uncertainty – mainly transport demand – dominates the results and is present in 39 of the 42 reviewed articles (Table 2.3). Private, profit maximizing firms need to understand how to protect themselves from demand volatility when they must decide on building a new bridge, (toll) road, rail line, or expanding an airport. Martins et al (2014) apply the option to stage to the New Lisbon Airport for Low Cost Carriers. They argue that by incorporating the flexibility option to stage the design in different phases, the project is better adapted to future changes of market uncertainty in the form of passenger traffic evolution.

Table 2.3. *Uncertainty types and sources in ROs applications (Q4)*

Uncertainty type	Uncertainty source	Count	References
Market uncertainty (MU)	Transport demand	35	1-12, 14, 15, 17, 18, 20-22, 24-26, 28-31, 33-36, 38-42
	Construction cost	2	3, 19
	Operations and maintenance cost	2	8, 15
	Land value/price	1	22
	Project value	1	23
	Population growth	1	22
	Revenue	1	36
	Investment cost	1	32
	Energy price	1	31
	Discount rate	1	17
MU in number of papers		**39**	
Technical uncertainty (TU)	Infrastructure conditions	3	
	Construction time	1	
TU in number of papers		**4**	

Technological uncertainty – the performance or possible difficulties for completing construction of a system or project, or uncertain effectiveness of new technology – is less frequent (4 articles), and if present, possibly in combination with market uncertainty (2 of 4 articles).

Most articles (33) implement one uncertainty source in their real option application model (Table 2.4). This leads to 'less complex' and 'more manageable' valuation methods or possible applications of ROT. Real option valuation models can become very complex real quick, and simplifying applications to one uncertainty source is a deliberate methodological choice. Market uncertainty is often the first choice, since this is a crucial element in the success or failure of not only transport infrastructure, but megaprojects in general. Another explanation could be that, beside some exceptions, one of the objectives of most articles is to prove the value of ROT for more accurate decision-making. Reducing the model's complexity then helps to increase the transparency or understanding of real options applications' results.

Table 2.4. *Number of uncertainty sources in ROs applications (Q4)*

Number of uncertainty sources	Number of papers	References
1	33	1, 2, 4-7, 9-14, 18-21, 23-32, 34, 35, 36, 38-41
2	6	3, 8, 15, 17, 33, 37
3	2	22, 42

Thijssen (2015) is one of the few who incorporates two different uncertainty types in his model. He illustrates that the project value and the optimal timing to invest is affected by both revenue uncertainties or demand (MU), and uncertainties or possible delays in the construction phase (TU).

Despite the clear distinction between three different uncertainty types in ROT literature (e.g. Dixit and Pindyck, 1994), none of the reviewed papers consider policy uncertainty.

2.3.4. Real options applied (Q5)

The three most applied 'classic' real options are the options to delay (12), scale (8) – expand or contract – and abandon (6) (Table 2.5). For example, Wooldridge et al (2002) examine the option to delay an investment decision to build a highway, based on an ex post evaluation of the Dull Toll Road in Virginia, which was constructed between 1993 and 1995. Less frequently used are the growth option (2), the option to switch use (1), and the option to stage (1). Martins et al (2014), for example, show that a flexible design leads to a more modular or phased airport expansion (option to stage). This facilitates an adaptive approach in response to changing demand or market conditions, thus avoiding overcapacity when expanding in one phase.

Beyond the 'classic' real options described by Trigeorgis (1996), in 17 papers, researchers also interpret other forms of case-specific built-in flexibilities as real options, which can be modeled and valued through a real options approach. Xiong and Zhang (2016) apply a real options model to capture the value of (contract) renegotiations. They interpret renegotiations as a real option for which a claim to renegotiate contract terms can be raised with flexibility in timing during the operational phase of a toll road by either the concessionaire or the government. Another example are different risk mitigation instruments. For example, Brandão et al (2012) apply a real options model to the São Paulo Metro Line 4 extension. To make PPPs more attractive for private actors, they incorporate government guarantees for minimal demand in the contract. The government will financially compensate the private actors operating the infrastructure when demand or profit drops below a predetermined level. Risk mitigation measures are an important part of megaprojects, especially when balancing risks between public and private actors in PPPs. The reviewed papers show that properly calculating their value can be done with ROT.

Only a small number of articles (5) looks at multiple embedded real options and their interactions (Table 2.6). Bowe and Lee (2004) combine the options to delay, expand and contract in their real option model for to the Taiwan high-speed rail project. They examine the interactions between these options rather than valuing them individually. Similar to the uncertainty sources, most articles (37) only use one real option. However, the few examples like Bowe and Lee (2004) illustrate the value of researching multiple embedded real options.

Table 2.5. *Real options used in applications (Q5)*

Real options	Count	References
Delay	12	1, 3, 12, 13, 15, 19, 22, 24, 27, 33, 36, 37, 39
Scale (expand/contract)	8	3, 6, 14, 17, 25, 31, 38, 42
Abandon	6	1, 6, 11, 18, 26, 29
Growth option	1	35
Stage	1	30
Switch use	1	26
Risk mitigation	17	1, 2, 4, 5, 7-10, 18, 20, 21, 23, 24, 28, 32, 34, 40

Table 2.6. *Number of real options in applications (Q5)*

Number of real options	Number of papers	References
1	37	2, 3-5, 7-17, 19-25, 27-42
2	3	3, 18, 26
3	2	1, 6

2.3.5. Application models and methods (Q6)

In a minority of cases, a descriptive or qualitative approach is adopted, without calculations and valuation models (Table 2.7). Cheah and Garvin (2009) used the Texas High-Speed Rail project in the early 1990s as an illustrative example demonstrating the possibilities of ROT. When, as in most cases, a quantitative method is used, the Monte

Carlo simulation (18) and the binomial lattice method (13) are most frequent. The use of a MCS is often combined with one of the 'tree-like' models. A sensitivity analysis to test the robustness of the results was performed in 7 articles. When determining the optimal timing of exercising an option is the research objectives – as illustrated in Table 2.1 – the mathematically advanced technique of dynamic programming is used. Other less frequent occurring methods are adaptions of the original Black-Scholes method, the inclusion of game theory, the system dynamics model and dynamic adaptive policies. Elaborating on these methods is beyond the scope of this paper. Different methods can be used in similar applications. Therefore, it remains hard to tell which valuation method is more suitable for which application type.

Table 2.7. *Valuation methods in ROs applications (Q6)*

Real options	Count	Count	References
Qualitative	Descriptive	3	6, 16, 26
Quantitative	Monte Carlo Simulation	19	1, 2, 4, 5, 8-11, 14, 15, 17, 20, 21, 30, 31, 34, 38, 40, 42
	Binomial Lattice Tree method	13	1-3, 15, 19, 24, 25, 30-32, 35, 39, 40
	Decision tree analysis	4	7, 19, 22, 25
	Dynamic programming	8	8, 9, 12, 15, 27, 33, 37, 42
	Black Scholes method	4	13, 23, 27, 36
	Sensitivity analysis	7	10, 17, 21, 23, 27, 31, 40
	Game theory	3	28, 35, 40
	Systems dynamic model	1	18
	Dynamic adaptive policies	1	41

Contrary to descriptive cases, a quantitative approach makes it possible to compare the net present values of projects with or without flexibility, and in some articles determine the optimal timing of a decision. Opting for the quantitative approach offers numerical results, but significantly increases complexity and the mathematical requirements for decision-makers and project managers (Garvin & Ford, 2012). The qualitative descriptive method is easier to understand but lacks numerical evidence or valuations to strengthen its case (Cheah & Garvin, 2009).

2.4. Relevance and research gaps for real options integration in megaproject practices

We analyze to what extent these trends are solutions for megaprojects' challenges, and meet the expectations from real option's theory for megaprojects: (a) better risk and uncertainty management and assessment; (b) transparent and explicit uncertainty identification and communication; and (c) valuing flexibility (quantitatively). In relation to megaproject literature, this allows us to stress its relevance, identify research gaps for the integration of ROT in megaproject practices, and define areas for further research.

2.4.1. Relevance of real options theory to megaprojects

a. Better uncertainty management and assessment. The reviewed papers first of all reflect the objective ROT shares with recent megaproject literature. Uncertainty and complexity are increasingly recognized by planning researchers, resulting in different streams – e.g. adaptive planning (Giezen, 2013) and scenario planning (Chakraborty & McMillan, 2015) – each advocating a proactive identification and management of uncertainties. It has been argued that simplification and ignoring uncertainties limit the possibility of adapting to changes in context, and thus dealing with unforeseen future changes (Giezen, Bertolini, et al., 2015). With ROT, megaprojects have a tool that forces you to assess and manage uncertainties; one that specifically focusses on the deficiencies of conventional decision support tools such as the CBA. The higher the uncertainty, the higher real option's relevance becomes (Couto et al., 2012).

b. Explicit uncertainty identification and communication. Identifying uncertainties is an important prerequisite for adaptive planning. You can only be adaptive once you know which uncertainty sources or future scenarios you want to be adaptive for. While the strength of ROT is the provision of quantitative results, the reviewed papers also illustrate the importance of the process towards these results itself. Identifying, describing and modelling the uncertainty in applications is an important part of the real options model. Understanding or applying ROT requires the identification of uncertainty sources. ROT can strengthen adaptive planning by increasing the attention for uncertainty identification. The regular use of real options could lead to an increased description and expanded perception of uncertainties (Ford et al., 2002).

c. Valuing flexibility. What ROT adds to existing concepts of adaptive planning in megaproject literature is its possibility for valuing flexibility. The quantitative results in the reviewed papers support the idea of adaptive planning by providing numerical results. This illustrates the advantage of valuing flexibility over valuing projects without taking into account uncertainties. Uncertainty and flexibility then become less vague terms once they are given a quantifiable face, increasing the relevance and added value of ROT for megaprojects.

The relevance of real options for megaprojects. ROT thinking and modeling in megaprojects could help facilitate a shift from the dominant but unrealistic premise that we can exactly predict and forecast the future, to the more realistic premise that we should accept an uncertain future. In the predict-and-plan model, there is an overall aim to improve and increase the exactness of estimations on costs, benefits, forecasts and effects. While it can only be encouraged to improve forecasting methods, an overemphasis on exact estimations has resulted in a lack of incorporating uncertainties in tools such as a CBA (Beukers et al., 2012b; Nicolaisen, 2012). ROT and adaptive planning do not simply try to improve forecasting accuracy, but want to offer an approach to manage uncertainties through flexibility – if such options exist. ROT does not try to tell what will happen, but rather what could happen.

Despite its relevance, gaps impede its applicability in planning practices and megaproject decision-making today, which are included in a further extension of the conceptual framework in Figure 2.4.

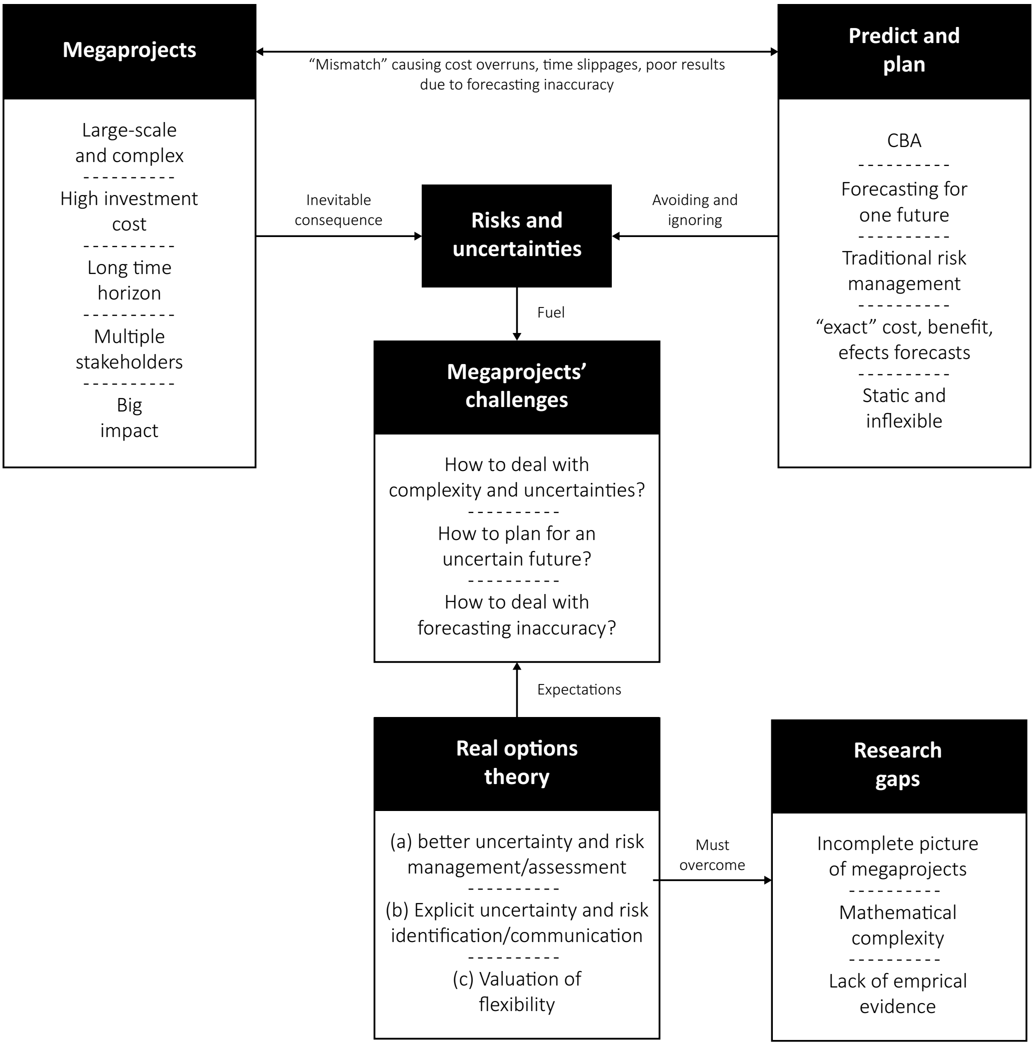


Figure 2.4. *ROT and megaprojects conceptual framework, research gaps*

2.4.2. Research gaps of real options theory for megaprojects

An incomplete picture of megaprojects. As illustrated in the main trends, mostly one uncertainty source – often market (demand) uncertainty – and one real option or risk mitigation instrument are considered. Technological uncertainty is underrepresented and policy uncertainty completely absent in the applications. Planning literature offers multiple and more extensive classifications of uncertainties and risks in megaprojects, emphasizing the presence of different and possibly interacting uncertainty sources. Table 2.8 provides a non-exhaustive overview of such classifications. The dominance of demand uncertainty in real option applications relates to an emphasis on (private) profit maximization. However, without comparable uncertainty assessments of different types of uncertainty within one megaproject, the dominance of market uncertainty does not mean market uncertainty is the most important uncertainty source in every case. Technological and policy uncertainty are underrepresented, but equally important, depending on the megaproject, and should thus receive equal academic attention.

Furthermore, real options applications to transport infrastructure ignore uncertainties and flexibility options that relate to the positive or negative socio-environmental effects of projects, presenting an incomplete picture of the complexity of megaprojects. Trigeorgis (1996, p. 18) noted more than 20 years ago that “Despite its enormous theoretical contribution, the earlier literature is of limited practical value because it focuses on valuing individual real options. Real-life projects are often more complex in that they involve a collection of multiple real options, whose values may interact” (p.19). The results show this statement is not outdated and still holds for recent real option literature on transport infrastructure and megaprojects.

Table 2.8. *Uncertainty and risk classifications*

References	Classification method	Uncertainties, risks, complexities
Bing et al (2005)	Three risk classes with subcategories	Macro- (exogenous), meso- (endogenous, project-related), micro-risks (endogenous, party-related)
Dixit and Pindyck (1994)	Three main uncertainty types	Market, technological, policy uncertainty
Hardcastle and Boothroyd (2003)	26 key risks encountered by PFI participants	Availability, commissioning, construction, credit, cost, demand, demographic changes, design, environment, finance, land, legislative changes, legal, market, operation, performance, planning permission, political, residual value, social issues, specification, sponsor, technical, technological obsolescence, time, volume
Irimia-Diéguez et al. (2014)	Nine main risk types	Force majeure, design, legal and/or political, contractual, construction, operation and maintenance, labor, clients/users/society, financial and/or economic risks
Krane et al (2010)	Project objective related risk levels	Operational, short-term strategic, long-term strategic risks
Little (2011)	Seven common risks	Force majeure, political, construction, operation and maintenance, legal and contractual, income, and financial risks
Priemus et al (2013)	Three main complexity types	Technical, organizational, and external complexity

Mathematical complexity. Narrowing down applications to one uncertainty and flexibility option is related to the mathematical complexity of real option valuation models. Grimes (2011) noted that while the intuition behind the ROT is straight-forward, the mathematics are complex. Critics are quick to say the real options field is mathematically elegant, but hardly useful in practice due to a lack of skills and understanding of the models (Cheah & Garvin, 2009). Education is necessary and the mathematical complexity limits the accessibility for average decision-makers (Garvin & Ford, 2012). Due to the variety of valuation approaches, it is unclear which one is the best in which case or situation (Cheah & Garvin, 2009). As long as a practical real options toolkit or hands on real options approach to assist project managers and decision makers is missing (Herder et al., 2011), decision-makers will prefer the 'easy road' and keep using the conventional approach (Garvin & Ford, 2012). Decision makers in megaproject management are bounded rational (Simon, 1997); existing procedures, norms, and legislation are difficult to change and often exclude more advanced approaches in CBA calculation. A toolkit could be a practical guide that helps decision makers or planners determine how their specific project might benefit from the adoption of ROT, or which valuation method is best suited for a specific case. A toolkit including best-practice examples and empirical evidence could encourage policy makers and planners to adopt a real options based adaptive management approach in megaproject decision-making.

Lack of empirical evidence and good practices. Unfortunately, while the main trends help to understand the relevance of ROT, they painfully expose lacking evidence on how this theory could be integrated in the planning, design and decision-making of actual megaprojects. The results do not allow us to conclude whether or not ROT actually has an impact on decision-making, to what extent or how it is used in planning practices today. As a consequence, real options applications currently raise more questions than answers about how to incorporate ROT in existing megaproject practice. The practical possibilities of real options theory are not clear without empirical evidence and best-practice examples. For example, does an optimal real options approach for public megaprojects differs from one for public-private partnerships; or how can flexibility through real options in megaprojects be harmonized with procurement rules that require steady contracts to guarantee legal certainty; or how should ROT be applied in different megaproject phases (e.g. exploration, planning, design, implementation, operation)? These are just a few examples of important future research questions for which empirical evidence is currently missing.

2.4.3. Areas for future research

Given the theoretically proven potential of ROT for megaprojects, research should focus on how its relevance can be practically illustrated. We need to look for ways to overcome existing gaps, so ROT can better meet its expectations and fulfill its potential for megaprojects. For this, we believe the main starting point for further research should be to interact more with planning practitioners and decision makers in megaprojects, and that the process of interaction should be documented in publications. The interactive process of applying ROT is equally important as the (quantitative) results. Real options thinking alone – valuations aside – can already extend uncertainty identification and communication, along with the generation of project flexibility (Cheah & Garvin, 2009). Valuing flexibility remains an important point of relevance, but in-between 'baby-steps', including qualitative case studies, are required to increase our knowledge on real options integration in megaproject practice.

Furthermore, interactive research and documenting the process of applying real options in actual megaprojects allows to identify opportunities and obstacles in existing planning legislation, procedures and instruments for the inclusion of real options or flexibility as an official assessment criterion. Planning legislation in most developed countries consists of rigid and sequential planning procedures that require decisions to be made early on, leaving little room for flexibility. Furthermore, the rational planning model is permeated by a culture of recurrent and more irrational elements such as: time pressure to make decisions (Gil, 2017); optimism bias, strategic misrepresentation or strategic behavior (Flyvbjerg et al., 2009); power relations; lock-inn leading to inflexibility and closure of alternatives (Chantal C Cantarelli, Flyvbjerg, van Wee, et al., 2010); consensus-building between multiple stakeholders (G. Winch, 2017). In this chaos of complexity, simplification is preferred. Our current planning frameworks are not designed to properly take into account uncertainty and integrate flexibility as an official evaluation and assessment criterion.

We believe this review paper has raised the following research questions that should be added to the research agenda of those interested in uncertainty, risk and flexibility, or applying real options in megaprojects:

1. How do we identify uncertainties collaboratively and reach a consensus on which uncertainties are important and how they should be further assessed, modelled, and managed, given the context of multiple uncertainties in megaprojects?
2. Following this, how to communicate the impact and possible consequences of the uncertainties modelled in a transparent, more explicit and understandable way to a broad range of megaproject stakeholders?
3. How to adapt, use or communicate existing valuation methods to address the issue of mathematical complexity? Are qualitative or intuitive flexibility values a first step towards quantifying flexibility in a more accessible way?
4. How can ROT fit within existing planning frameworks, and to what extent can a 'toolkit' facilitate a shift towards a more adaptive planning, making flexibility a decision-making criterion in megaprojects?

Questions one and two are directed at expectations (a) and (b), question three at expectation (c). Question four aims to encourage more awareness of the complex planning conditions and context in which real options are applied, acknowledging the diverse possibilities of applications regarding, for example, different megaproject types, phases and procurement methods.

To sum up, future research should focus on how ROT can actually improve and contribute to decision-making in megaprojects. For this, more empirical evidence is needed which should be achieved through interactive research with the field of planning. We understand its relevance, but we do not yet know how to capture its value in practice, and how ROT can meet its three expectations. This research agenda is added to the conceptual framework in Figure 2.5.

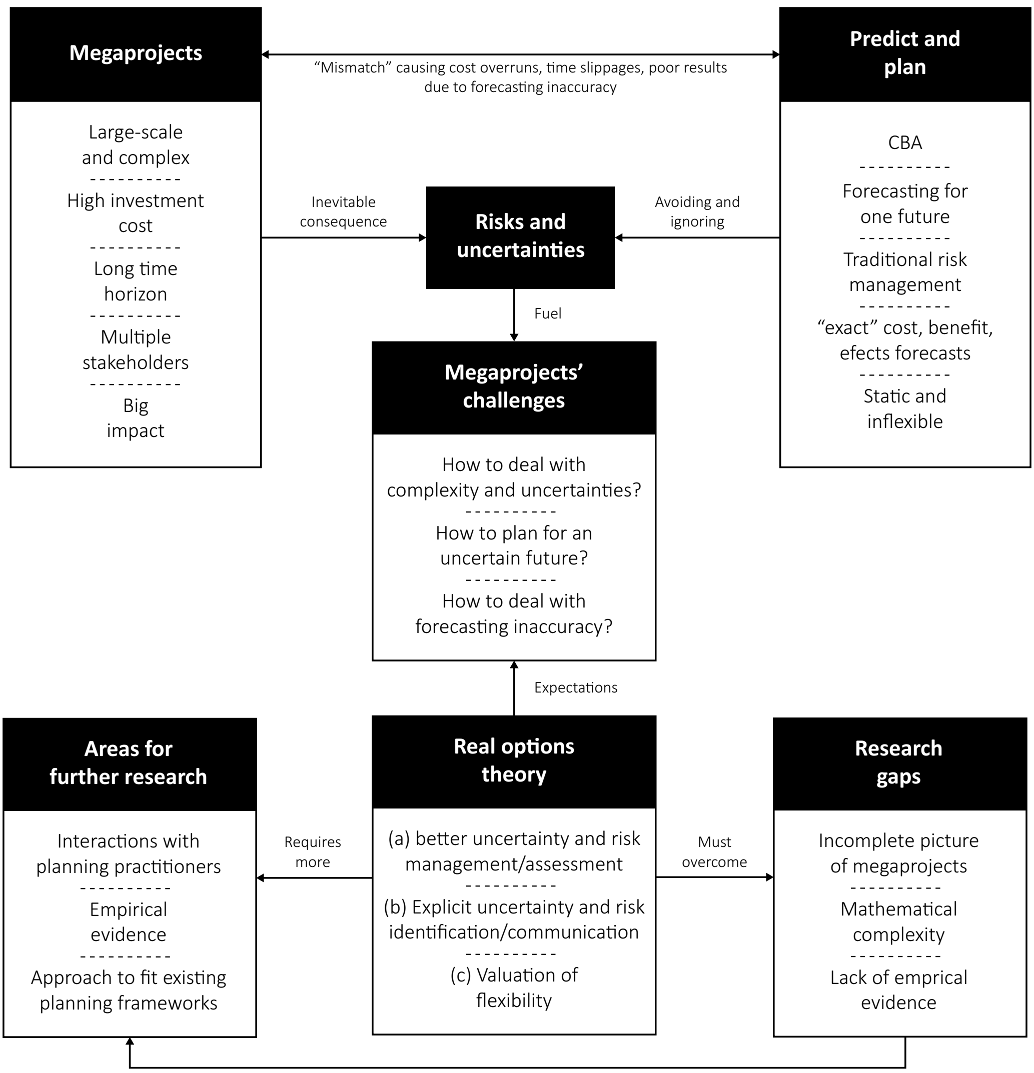


Figure 2.5. *ROT and megaprojects conceptual framework, areas for further research*

2.5. Conclusion

Megaprojects have received increased attention from ROT scholars. Our first objective was to identify and illustrate the main trends of the increasing number of real options applications to transport infrastructure, for which we conducted a literature review with 42 articles. ROT clearly has relevance and potential for implementation in megaproject planning practices, through its (a) improved assessment and management of uncertainties and risks, its (b) emphasis on identification and communication of uncertainties; and (c) its value of quantifying the value of flexibility. This could cause a shift towards a more realistic planning 'climate' in which we acknowledge an uncertain future to enable planning and designing flexible responses and strategies.

Significant gaps for further implementation in practice impede its relevance. Current applications of ROT consider real options as a methodological tool to integrate uncertainty and put a value on flexibility. These applications do not cover the full complexity of megaprojects due to methodological choices and mathematical complexity. More importantly, most papers lack to discuss how ROT can be practically implemented in current megaproject practice. We argue that to embed ROT into planning practice, ROT should not be merely used as a tool, but its features (irreversibility, uncertainty, and flexibility) should be stepwise discussed, analyzed, and communicated, during the different phases of megaprojects. Hence, future research should focus on how to apply ROT – not as a tool – but as a strategy for adaptive project management. Research in interaction with planning experts and practitioners could help to offer insights on how to develop a toolkit to aid and improve dealing with uncertainties through flexibility in the planning, design and decision-making of megaprojects.

Its relevance has been theoretically proven. The time has come to broaden our research scope and figure out how to translate theory into practice through interaction with the field of planning and megaprojects. The research gaps can only be addressed by working in close collaboration with decision makers and practitioners. For current planning practices, such participatory research will allow for the explicit acknowledgement of the importance of uncertainty identification, communication and assessment. Furthermore, embracing a flexible approach could have major policy implications. When taking into account uncertainty and flexibility values, decision makers and planning policy must open up for possible changes to existing planning frameworks, legislation, rules, procedures and practices.

3. Uncertainties in the decision-making process of megaprojects: the Zeebrugge New Sea Lock

Thomas Machiels, Tine Compernolle & Tom Coppens

Published as:

Machiels, T., Compernolle, T., & Coppens, T. (2020). Uncertainties in the decision-making process of megaprojects: the Zeebrugge new sea lock. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning*, 173(2), 41-53.

The journal publication is available at:

https://doi.org/10.1680/jurdp.19.00031

Abstract

Complexity and uncertainty are inherent to megaprojects. While the social cost-benefit analysis (SCBA) and environmental impact assessment (EIA) are increasingly used to support decision-making in megaprojects, these instruments often ignore and avoid uncertainty communication, documentation and analysis. By using a conceptual uncertainty matrix for decision-support analyses, this paper questions how uncertainties are taken into account in the SCBA and EIA when making decisions. A document analysis is applied to the SCBA, EIA and other project documents from the research (planning) phase of an ongoing sea port megaproject in Zeebrugge, Flanders. The results show that uncertainties are barely documented nor analyzed in the SCBA and EIA, but arise later during the decision-making process; mainly about which plan alternative is the best for achieving the project's objectives. Uncertainty or ambiguity about 'the best alternative' results from stakeholders' different interpretations of the SCBA and EIA. The paper reveals that research about megaproject uncertainty and decision-making should not be limited to the boundaries of either an SCBA or EIA. We need to further enlarge our research scope, and look at the dynamic interplay between uncertainties; multiple decision-support instruments; stakeholders' different interpretations of these instruments and perceptions about uncertainties; decision-making; and the general process.

3.1. Introduction

Complexity and uncertainty are related and inherent elements of the planning, design and decision-making process of megaprojects. They pose planners and decision makers with the difficult challenge of planning for an uncertain future, especially for megaprojects, which are more complex and involve many uncertainties due to their large-scale character, their high investment cost, the many affected and involved stakeholders, and their long time horizon (Flyvbjerg, 2014). The social cost-benefit analysis (SCBA) and the environmental impact assessment (EIA) are two important instruments that support decision-making in megaprojects. The SCBA is a socioeconomic assessment tool to compare alternatives based on direct, indirect and external effects. It takes into account the possible impacts from a broad welfare perspective (van Wee & Rietveld, 2013), including societal effects such as pollution, environment, safety, travel times, health, etc. The SCBA's aim is to monetize every effect, allowing for an easy to understand comparison of the costs and benefits of different alternatives (Brent, 2006). The EIA assesses the consequences of one or multiple alternatives or policy actions on the natural, spatial and social environment (Wathern, 2013). Both instruments fit the perspective of the dominant rational planning model of predict-and-plan, making informed decisions based on future forecasts and predictions (Beukers et al., 2012b; Giezen, Bertolini, et al., 2015; Nicolaisen, 2012; Terryn et al., 2016). Both SCBA and EIA have become widely used instruments in the appraisal and evaluation of large infrastructure projects in Flanders and many other countries (Bristow & Nellthorp, 2000; Haezendonck, 2008; Mackie, 2010).

However, the aim of SCBAs and EIAs to provide hard scientific evidence about forecasts and predictions – supporting the idea that decisions can be made in a rational way – is problematic for two reasons. First, it has long been known that decision-making and planning is irrational (Banfield, 1959). Decision makers are limited by time, budget and knowledge constraints, called bounded rationality (Simon, 1997). Decision-making is chaotic, coincidental (Cohen et al., 1972), and subject to windows of opportunity (Kingdon, 2003). It is a trade-off between the heterogeneous objectives, opinions, preferences and perceptions of involved and impacted stakeholders (Gil, 2017; Macharis & Nijkamp, 2013). Costs are often underestimated and benefits overestimated (Flyvbjerg et al., 2009). Second, there are limitations to the SCBA and EIA itself. In practice, uncertainties are barely communicated and receive few attention in SCBAs and EIAs (Leung et al., 2016; Nicolaisen, 2012). SCBAs and EIAs are static and create the illusion that we can exactly predict the future (Beukers et al., 2012b). The problem then becomes that, if we base our decision on SCBA/EIA results, the alternative chosen can be influenced by dynamic uncertainties or unforeseen changes that were not accounted for in the SCBA/EIA. This impedes the value and potential use of these instruments. Nevertheless, despite uncertainties, it is still better to base decisions on (S)CBA results than on a random selection (Asplund & Eliasson, 2016).

We question in this paper 'how are uncertainties taken into account in the SCBA and EIA of megaprojects when making decisions?'. Through a document analysis of a single case study in Flanders – an ongoing port project – we aim to illustrate (I) to what extent the uncertainties communicated – or not – in the SCBA and EIA align with the uncertainties that arise afterwards during the decision-making process, and (II) how the uncertainties in the SCBA and EIA impact decision-making, and how decision-making in turn impacts uncertainties.

Current research on megaproject decision-making and their supporting analyses are limited to research on either the SCBA or EIA, resulting in two different streams of literature, with a dominant focus on CBA research in megaproject literature. Annema (2013), Annema et al. (2017), and Eliasson and Lundberg (2012) illustrate to what extent the (S)CBA influences decision-making in megaprojects or transport infrastructure. Highly cited authors like Flyvbjerg (Flyvbjerg, 2017b; 2004), Cantarelli (2010) and Skamaris (1997) have extensively discussed megaproject problems like cost overruns and poor results, due to inaccuracies in cost and benefit estimates, often through large quantitative data sets on transport infrastructure projects. Nicolaisen (2012), Mouter et al. (2015), Welde and Odeck (2011) discuss that uncertainties need to be better managed, communicated and addressed more prominently in (S)CBAs. Similar, Bond (2015), Cardenas and Halman (2016) offer methods for better managing and coping with uncertainties in (E)IAs, while Leung et al. (2015) stress that practitioners need more guidance on how to communicate uncertainties in EIAs.

Despite their relevance, these papers narrow their focus to the boundaries of either an SCBA or EIA. Decisions however are based on the weightings of multiple criteria (Macharis & Nijkamp, 2013), not limited to only socioeconomic (SCBA) or environmental (EIA) concerns. Furthermore, narrowing down the research scope to one instrument, as well as using large quantitative data, ignores depth of decision-making processes and its specific steps in which both instruments are embedded and have influence. The decision-making process of megaprojects itself is characterized by complexity and uncertainty (Bertolini & Salet, 2008; Priemus et al., 2013; Salet et al., 2013). New to existing literature is that this paper (a) researches how uncertainties are documented in both the SCBA and EIA, and (b) analyzes the impact of both instruments on the decision-making process and how both instruments are used differently by stakeholders.

Section 2 explains the concept 'uncertainty', followed by the document analysis methodology in section 3. Then, the case is presented in section 4, followed by the results in section 5, and a discussion and conclusion in Sections 6 and 7.

3.2. The concept 'uncertainty'

We adopt the uncertainty framework by Walker et al. (2003), later enriched by Kwakkel et al. (2010). The framework – an uncertainty matrix – is intended to enhance the communication of uncertainties within model-based decision support analyses among policy analysts, policy makers and stakeholders (Kwakkel et al., 2010; Walker et al., 2003). Table 3.1 shows a simplified uncertainty matrix for the purposes of this paper. The framework defines uncertainties by three dimensions.

The level dimension focuses on the degree of uncertainty, from determinism – we know everything precisely – to total ignorance – we do not know what we do not know (Walker et al., 2003). In between are four uncertainty types: shallow uncertainty, where the likelihood of uncertain scenarios can be calculated; medium uncertainty, where scenarios can be ranked but without specifying the likelihood; deep uncertainty, where scenarios can be recognized but not ranked, thus considered equally likely scenarios; and recognized ignorance, where the possibility of being wrong is kept open (Kwakkel et al., 2010; Walker et al., 2003).

The nature dimension defines the nature of uncertainty through three different types: epistemic uncertainty due to imperfect knowledge; variability is the inherent uncertainty or randomness in input data, parameters… in the model; and ambiguity is uncertainty as a consequence of different interpretations of data, acknowledging different stakeholders' frame of value, opinions, knowledge, objectives and perceptions (Kwakkel et al., 2010). The location dimension specifies where in the SCBA and EIA models and analyses the uncertainty occurs: context, the conditions, circumstances and stakeholder values that underlie the choice of the system boundary; model, either a lack of sufficient understanding of the identified system (context), or the computer model itself (bugs, errors); input data uncertainty associated with determining parameter values; the accumulated model outcome uncertainty or prediction error caused by uncertainty in context, model, and input data. The 'decision-making process' is added to the original framework as location to categorize uncertainties that arise outside the boundaries of the SCBA or EIA, but during the process.

Table 3.1. *Uncertainty framework, adapted from Walker et al. (2003) and Kwakkel et al. (2010)*

Location	**Level (uncertainty degree)**				**Nature of uncertainty**		
	Shallow uncertainty	Medium uncertainty	Deep uncertainty	Recognized ignorance	Ambiguity	Epistemology	Variability
Context (system boundary)							
Model							
Input data							
Model outcome							
Decision-making process							

3.3. Research method: Document analysis of a single case

The document analysis is focused on a single case study. The megaproject under consideration involves the development of a new and second sea lock in the port of Zeebrugge. “A case study is an empirical method that investigates a phenomenon in depth and within its real-world context” (Yin, 2018, p. 15). In-depth case-study research is a necessity to understand a complex issue (Flyvbjerg, 2006), and to answer this paper’s research question on megaproject decision-making under uncertainty. The Zeebrugge case fits the definition of megaprojects well: an estimated cost of over one billion euro; many involved and affected stakeholders; and a long time horizon. It is a representative case for Flanders, because it follows a similar process and procedure for decision-making as other large Flemish infrastructure projects. The case chosen is an ongoing project, in which the research (planning) phase came to an end in June 2019, marking the start of the project (design) phase. A decision has already been made for a preferred plan (alternative), for which an SCBA and EIA were made to support decision-making and compare plan alternatives.

This paper uses a document analysis as the main research method. Analyzing documents requires the researcher to interpret its content, in order to gain an understanding and develop empirical knowledge (Bowen, 2009). The (a) SCBA and EIA are the main documents in this case study, extended with other project documents: (b) SCBA and EIA guidelines; (c) the ‘preferred decision’, which captures the decisions made and the arguments for (not) choosing a specific alternative; (d) the summaries of the consultation rounds among public/private institutions, and the public inquiry; (e) informational documents about the project, and (f) press articles. All these documents date from 2016 to June 2019. They are free to consult through the project’s website, and are listed and explained in Appendix 2.

The document analysis method was chosen as it provides a structured methodology to answer the research question in different steps through a combination of a content, discourse and narrative analysis (Hijmans, 1996). A content analysis looks at what is actually written in the documents, while a discourse analysis looks at the way a message is presented, the wording of argument patterns. Table 3.2 provides an overview of which document is used for which part of the document analysis, with reference to their number in Appendix 2. Step one looks at uncertainty documentation requirements in the SCBA and EIA guidelines (b), how they are translated in the project’s SCBA and EIA (a), and lists the specific documented uncertainties. Step two illustrates how the SCBA and EIA influenced decision-making, by looking at the arguments in the ‘preferred decision’ (c), and the summaries of the consultation rounds and public inquiry (d). We look specifically at how the questions or uncertainties raised in (d) has influenced the argument patterns and motivations in the follow-up versions of (c). In step three, we interpret and discuss the results from step one and two. The informational documents (e) and press articles (f) are subject of a narrative analysis to tell the case’s story.

Table 3.2. *Project documents used in the document analysis*

Research objective	Count
Step 1	a. SCBA Sea Lock Zeebrugge (1) a. EIA Sea Lock Zeebrugge (2) b. Guidelines for environmental impact assessment (13) b. Standard methodology for SCBA transport infrastructure projects (14)
Step 2	c. predesign preferred decision (4) c. design preferred decision (5) c. principal determination preferred decision (6) c. preferred decision (7) d. answers following the consultancy rounds for the predesign preferred decision (9) d. answers following the public inquiry from the design preferred decision (10)
Narrative analysis	Elements drawn from the documents used in step 1 and 2 extended with: e. alternatives research note (8) e. synthesis (11) f. process note (12) f. Press articles (15)

3.4. Megaproject case: New lock in the Port of Zeebrugge

The port of Zeebrugge is located in Flanders (Belgium), near the North sea, as seen on figure 3.2. The town Zeebrugge is located within the boundaries of the port, as seen on figure 3.3, inhabiting about 4300 people spread across three neighbourhoods: Zeebrugge-Dorp, Stationswijk and Strandwijk. It is Flanders' second most important port, ranked number one in the world for the shipment of cars, and provides about 10,000 direct and 10,000 indirect jobs, with around 400 companies. The port currently has two locks. The Visart-lock, built in 1907, is outdated and non-operational. The second lock, the Vandamme-lock, was built in 1984 to allow the port to extent its activities. Today this lock has to be operational full-time. Signs of decay and recurrent malfunctioning made the Zeebrugge port and the Flemish Government agree on the need for a new second lock. Between 2004 and 2016, a lot of research was conducted to find a solution, but this never led to any significant progress.

The project was given a kick-start halfway through 2016, when the Flemish Government signed the 'starting decision', meaning the project would follow the procedures and process of the new (2014) 'decree for complex projects'. This decree offers projects the possibility to follow a sequential procedure of four steps – the exploration phase, the research or planning phase, the design or project phase, and the implementation phase. The project was renamed Improving nautical accessibility to the (rear) port of Zeebrugge, which also became the project's main objective, next to several secondary criteria. The 'starting decision' marked the end of the exploration phase and the beginning of the research phase, in which all possible alternative plans within reason were identified. Alternatives were identified through (I) workshops with the project team, (port) companies and inhabitants; and (II) a public inquiry. Alternative plans could be suggested by anyone, of which the project team would decide whether or not these suggestions were reasonable. There was an agreement that each alternative plan should not only contain a new lock, but also a new mobility plan to separate local neighborhood traffic and port traffic, including new roads for cars, public transport and bikes or pedestrians. The new lock would be accompanied by a new regional road for port and ongoing traffic – called the NX. Six overall alternatives were identified, officially published in the alternatives research note (May 2017), and researched until December 2017. The location of the alternatives can be seen on Figure 3.5.

Figure 3.1. *Zeebrugge, aerial view*

The three alternatives in the west all required the removal of the old Visart lock. In Alternatives one to five, one new lock will be built, and the current 'Vandamme lock' will be renovated in 2049-2050, seizing its operations for two years. Alternative 6 – 'Verbindingsdok' – considers the construction of two new locks deeper into the rear port, requiring the removal of the current 'Vandamme lock'. Four of these alternatives hold two sub-alternatives, in which the NX regional road could be planned above ground, or as a tunnel.

The research resulted in three main reports, an SCBA, an EIA and a nautical screening (NS). In March 2018, A preliminary draft – officially called predesign for the preferred decision – was published, in which Alternative 2, Visart-lock current location with NX as tunnel (1) was chosen as ‘best alternative’. The motivation at that point was limited to providing arguments for eliminating the other alternatives and ending up with Alternative 2, rather than explaining why this is the ‘best alternative’. It was merely stated that Alternative 2 meets the project’s primary objective, based on the results from the SCBA, EIA and NS.

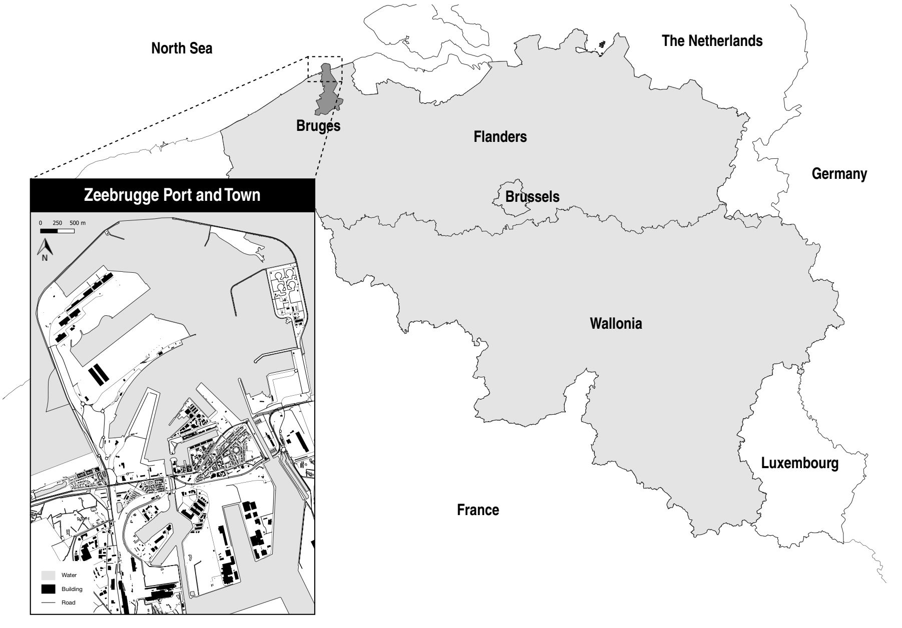


Figure 3.2. *Geographical location port*

During the two months that followed, consultation rounds were held among the involved organizations (e.g. Port of Zeebrugge, City of Bruges, Flemish Department of Environment…) to collect concerns, suggestions and advice on the predesign preferred decision and the motivation given. Despite critiques from several actors, Alternative 2 remained the preferred alternative, as expressed in the design preferred decision (December 2018) – an adjustment of the predesign preference decision. Again, critical and concerned voices – mainly by inhabitants supported by some political parties – pointed at the impact Alternative 2 would have on Zeebrugge town. One of the main concerns was that it would create a barrier between the neighborhoods stationswijk and Zeebrugge-Dorp, of which the latter would get squeezed in between two operational locks. According to the concerns, this could have a major impact on the future and livability of Zeebrugge. For this reason, Alternative 6 was favored by several stakeholders, of which the City of Bruges and inhabitants of Zeebrugge are frontrunners. This was strongly represented in the ‘notices of objection’ that were submitted during the 60-day period public inquiry (January-March 2019).

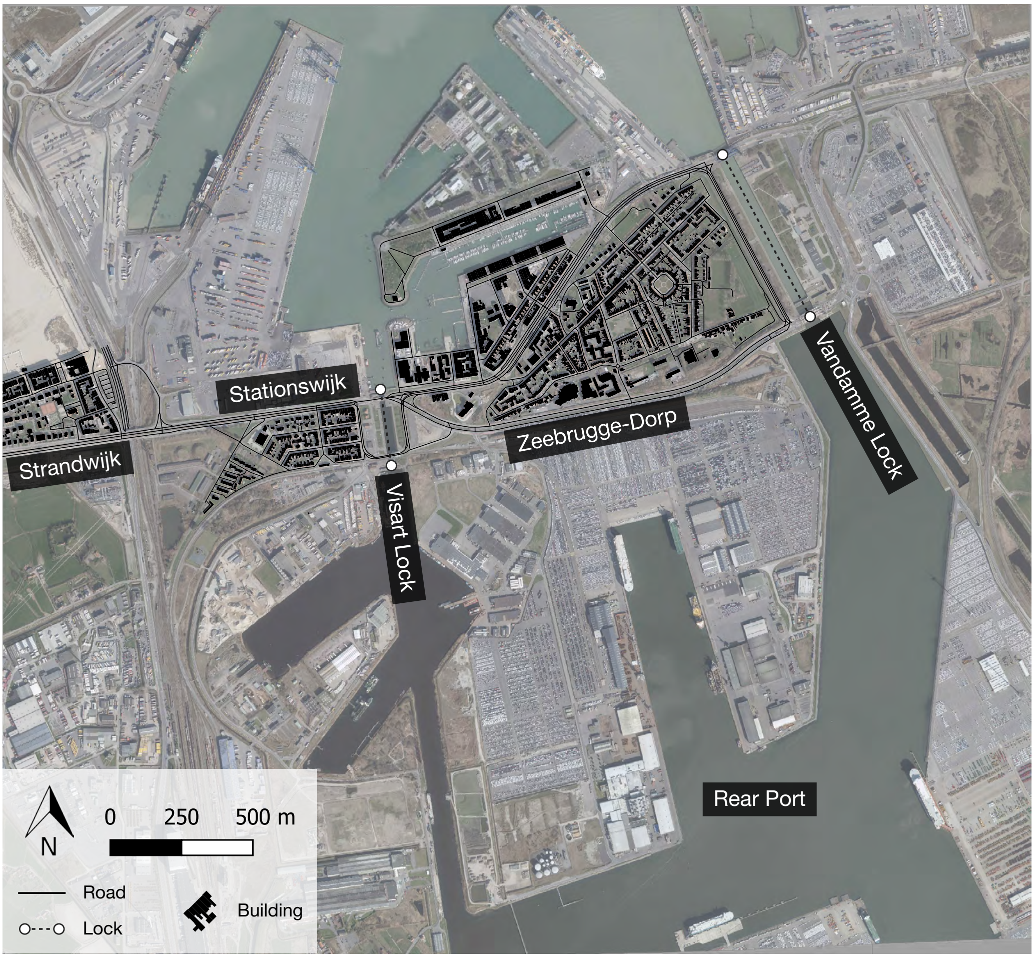


Figure 3.3. *Port and town of Zeebrugge*

After the consultation rounds and the public inquiry, the motivation for the chosen alternative and the rejected alternatives was adjusted and lengthened, as the list of actions to be undertaken during the design/project phase to deal with questions and concerns was extended. This resulted in the principal determination preferred decision on May 10th, 2019, with an official approval for the chosen alternative by the Flemish Government. After the advice of the Council of State, the final preferred decision was released on June 28th, 2019. The final preferred decision is an official and regulative decision, which contains the determination of the chosen alternative at the strategic level of the complex project. Possible legal consequences might be linked to the decision. It is a 'no point of return', and marks the start of the design/project phase, during which alternative designs and projects are identified and researched, traversing a similar procedure of decision-making as during the research phase. Table 3.3 summarizes the project's important moments.

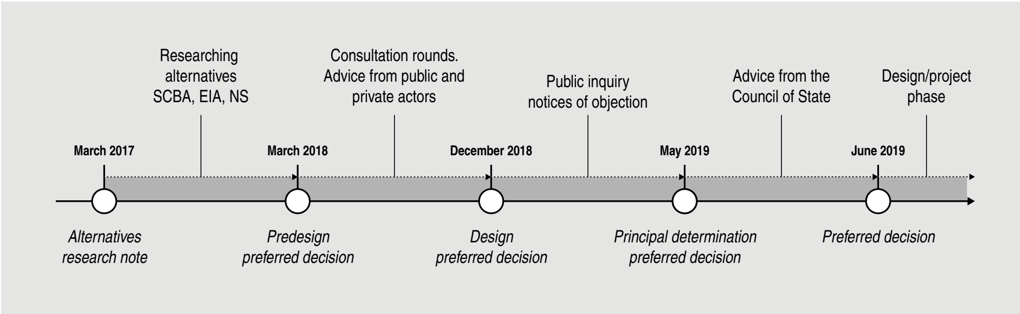


Figure 3.4. *Research phase, overview*

Table 3.3. *Important moments in the Zeebrugge New Sea Lock Megaproject*

Month	Year	Important moments
	2004	'SHIP-Project': Start of research into a new sea lock for Zeebrugge Port, initiated by the Flemish Government
	2009	'Carcoke site' appointed as the best location, cost estimations for the new sea lock are around 400 million euro
	2014	Confirmation of the choice for the 'Carcoke site'
July	2016	'Starting Decision' made by the Flemish Government ('Decree of Complex Projects'). The project is officially named Improving nautical accessibility to the (rear) port of Zeebrugge. – Start of the planning/research phase
March	2017	'Alternatives, research note' – overview of the six alternatives that will be compared on a strategic level
November	2017	Termination of the research and publication of the initial research reports: 'strategic environmental impact assessment (S-MER), 'strategic social cost benefit analysis' (S-MKBA), 'nautical screening'
March-April	2018	'pre-design preferred decision', choice for the alternative 'Visart-lock, current location with NX as tunnel'. Two month consultation round to collect and process advices and opinions on the 'pre-design preferred decision'.
March	2018	Information rounds for the affected residents (14 March) and other interested residents or parties (15 March)
December	2018	Determination and approval of the 'design preferred decision' by the Flemish Government. 'Visart-lock current location with NX as tunnel' remains the preferred alternative.
January-March	2019	Public inquiry (60 days) for consulting project documents/Research reports, and submitting 'notions of objection'; 750 notions of objections submitted at the end of the public inquiry
May	2019	Approval of the S-MER by the MER-administration, principal determination of the 'preferred decision', followed by a 30 day period during which the 'council of state' has to give its advice, which then leads to the final 'preferred decision', confirming the chosen alternative and marking the start of the project phase (no point of return).

June	2019	Final Preferred Decision, confirmed by the Flemish Government, with 'Visart-lock current location with NX as tunnel' as chosen alternative, marking the official start of the design (project) phase
October	2019	Publication of the Final Preferred Decision in the Belgian Official Journal, starting a period of 60 day in which it is possible to lodge an appeal against the decision with the Council of State.

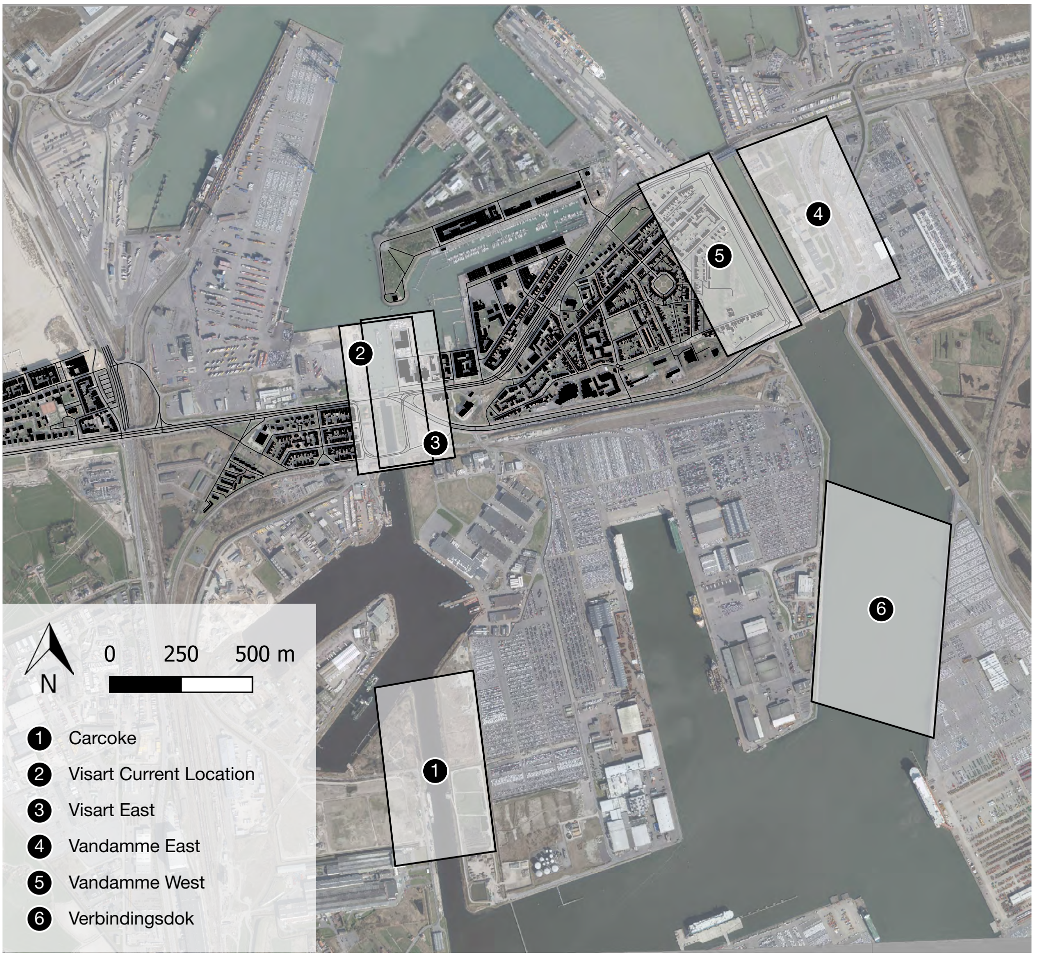


Figure 3.5. *Plan alternatives*

3.5. Document analysis. Uncertainties and decision-making in the Zeebrugge New Sea Lock Megaproject

3.5.1. Uncertainties in the SCBA and EIA: Not described in detail, nor analyzed

Three types of risks that can influence the deviation around the mean values of costs and benefits are identified in the SCBA guidelines: policy uncertainty, technical risks (uncertainties about the model variables), and market risks. The guidelines state that the SCBA should provide insights on the impact of uncertainties on the outcome of cost and benefit calculations. Sensitivity analysis for technical risks and scenario analysis for policy uncertainty and market risks are put forward as methods to provide insights on these uncertainties. In both methods changes are made to the values of the input data or parameters, to determine for which estimated variables the project is most sensitive. In the Zeebrugge project's SCBA, only one uncertainty is identified: the total costs. A sensitivity analysis is conducted, by increasing and decreasing the total costs of each alternative by 25%. Since this is an increase/decrease on the total estimated costs, the sensitivity analysis does not provide detailed information about the sources of uncertainty, the difference in uncertainty for different cost items, and does not show which variable affects the SCBA outcome the most. In both scenarios, the benefits of all alternatives still surpass the costs. Within the uncertainty framework, this can be described as a variability uncertainty (nature) in the model input data and model outcome (location) because it can be interpreted as a general prediction error. Since the SCBA did not determine the likelihood of each scenario, the scenarios are considered equally likely.

The EIA guidelines acknowledge that uncertainties are unavoidable, but indicate that they can lead to unreliability of the results, which in turn harms the value for using an EIA in decision-making. Tips are provided on how to deal with uncertainties: work with different future scenarios; make uncertainties explicit as much as possible; use adaptive strategies with mitigating measures and monitoring; and eliminate known uncertainties as much as possible. Uncertainties in the EIA report must be documented under a specific chapter entitled 'knowledge gaps'.

In the Zeebrugge project's EIA, this chapter is limited to one knowledge gap about the eco-hydrological effects of Alternative 6 Verbindingsdok on a neighboring natural environment categorized as 'Special Protection Zone'. Eco-hydrological effects are expected, but because of this knowledge gap, it cannot be concluded that there is no chance of a significant negative impact. These effects were merely based on expert judgement, and no groundwater modelling was conducted. This knowledge gap was not further researched, and must therefore be interpreted as an epistemic uncertainty (nature), due to a lack of knowledge. As for the level of uncertainty, this is a recognized uncertainty, since no future scenarios about the effects were identified. The uncertainty's location is the context, since it was excluded from further modeling, thus left out of the boundaries of the researched system or context.

3.5.2. Uncertainties arising during the decision-making process

While uncertainties are barely mentioned nor researched in the SCBA and EIA, the knowledge gap mentioned in the EIA was still an important part of the first draft of the report 'preferred decision – predesign preferred decision'. As mentioned earlier, no real arguments were given for choosing Alternative 2. It was said to be a relatively fast solution, which suits the objective of realizing a second new lock as soon as possible. When reading through the arguments of eliminating other alternatives, Alternative 6 was not chosen for two reasons. Its cost price was regarded too high, since it required the construction of two new locks. In absolute numbers, this is true. If also the benefits are considered however, it was ranked second best above Alternative 2 in the SCBA. The most extensive argument was related to the knowledge gap. If it would turn out that Alternative 6 has a negative impact on the surrounding protected natural environment, this alternative cannot be permitted due to environmental legislation. Since this remained an unsolved knowledge gap or epistemic uncertainty, no risks were taken and Alternative 6 was eliminated. The argumentation for eliminating alternative 6 fits the discourse of risk-averse behavior. Instead of dealing with risks and uncertainties, decision makers prefer to ignore and avoid risks (Bruzelius et al., 2002). Risk avoidance in this case is facilitated by environmental legislation, which states that if there is any uncertainty about possible negative effects on nature categorized as 'special protection zone', this alternative cannot be permitted or licensed, and thus risk is pushed out.

After it was known from the predesign preferred decision that Alternative 2 would be pursued, many concerns and questions were raised. These concerns are well-documented and answered to by the project team in the summaries of the consultancy rounds and the public inquiry. First, most concerns were raised about the potential impact of the project on the direct environment, mainly the neighborhoods Stationswijk and Zeebrugge-Dorp. Since the project definition of 2016, one of the conditions was that the project would facilitate the local relations between the different neighborhoods as much as possible. Dissatisfied inhabitants as well as several public actors such as the City of Bruges pointed at the environmental impact (noise, emissions, pollution, traffic, etc) during the construction and operational phase; the impact on livability; and the uncertain perimeter of expropriations which will be determined during the project phase. It was known from the EIA that Alternative 2 would have a significant negative impact on the environment, livability and spatial cohesion of Zeebrugge. However, the exact spatial impact remains an uncertainty. Despite not being identified as an uncertainty in the EIA, these concerns can thus be interpreted as spatial impact uncertainty, since the impact on livability cannot be simply expressed in a single number. This is a recognized and epistemic uncertainty, located within the decision-making process since it was not identified as an uncertainty within the EIA boundaries.

Second, critique was given both during the consultation rounds as during the public inquiry towards the fact that the 'knowledge gap' in Alternative 6 was not further researched, despite being used as an argument for elimination of this alternative. It was no secret that the Verbindingsdok Alternative was favored by several actors, such as most inhabitants of Zeebrugge, and the City of Bruges. They pointed at the benefits of the Verbindingsdok Alternative coming forth from the research reports. The biggest argument was that this alternative would spare the town because of its location deeper in the rear port. The project team responded to these comments in the following drafts of the preferred decision by lengthening the arguments for (not) choosing a specific alternative, as well as increasing the list of actions to be undertaken during the project and implementation phase in order to deal with the questions and concerns. Alternative 2 remained the chosen plan in the following drafts and the final preferred decision.

From the document analysis, it becomes clear that there is a discourse of uncertainty-avoidance with the decision maker and project team. There is no identification process of uncertainties prior to the SCBA and EIA, and both instruments document uncertainties to a bare minimum. The only uncertainty documented in the EIA nevertheless impacted decision-making, since it provided the main argument for eliminating Alternative 6. Vice versa, decision-making impacted uncertainties, in the sense that the choice for Alternative 2 initiated discussions and concerns about the spatial impact of a New Lock in between two town neighborhoods, which remains an uncertainty. This illustrates a non-alignment between uncertainties in the SCBA/EIA and decision-making process in this case, and shows that not properly identifying uncertainties in decision-support instruments does not eliminate uncertainties. In the following section, using the uncertainty framework from Kwakkel et al. (2010), we further discuss how stakeholders use the SCBA and EIA differently during the process, and the implications of this paper's results in light of other research.

3.6. The ambiguity and complexity of uncertainties in megaprojects

The decision-making process following the case's SCBA, EIA and predesign preferred decision can be interpreted as what Kwakkel et al. (2010) call ambiguity as the nature of uncertainty. Ambiguity is uncertainty that comes forth from different perceptions or frames of value about what the 'best alternative' is. The results and data from research reports can be interpreted in different ways, depending on different perceptions, objectives and preferences of different stakeholders. In this case study, the City of Bruges and the inhabitants are most concerned about the livability of the town Zeebrugge, so they don't care much for numbers on, for example, the cost of the project. They prefer Alternative 6 for its more remote location, which in their opinion contributes more to strengthening the locations between the neighborhoods and revitalizing the town. Therefore, they rely more on results from the EIA, in which spatial impact in terms of noise, air quality, spatial cohesion and relations, is negative for Alternative 2, but positive for Alternative 6. For this reason, a lot of questions were raised about the lack of research on the knowledge gap in Alternative 6.

Vice versa, the Flemish Government, who eventually decides on the alternative plan, prefers Alternative 2, mostly because its cost price and construction time are more reasonable than with Alternative 6, for which it draws its argumentation in the final preferred decision from the SCBA results. It is obvious that the Flemish Government is more concerned with the cost, because they pay for the investment. Based on the nautical screening, each alternative meets the project's main objective, improving access to the rear port. Choosing a 'best alternative' then becomes the result of an interpretation of the results of the SCBA and the EIA for secondary criteria, depending on individual perceptions, objectives and preferences of different stakeholders. Therefore, the 'best alternative' is an ambiguous uncertainty. Table 3.4 places all uncertainties from the document analysis in the empty framework from Table 3.1.

Table 3.4. *Uncertainties in the Zeebrugge Port Megaproject*

Location	Level (uncertainty degree)				Nature of uncertainty		
	Shallow uncertainty	Medium uncertainty	Deep uncertainty	Recognized ignorance	Ambiguity	Epistemology	Variability
Context (system boundary)				Knowledge gap (EIA)		Knowledge gap (EIA)	
Model							
Input data			Total project costs (SCBA)				Total project costs (SCBA)
Model outcome			Total project costs (SCBA)				Total project costs (SCBA)
Decision-making process				Spatial impact alternative 2	The 'best' alternative	Spatial impact Alternative 2	

In the Zeebrugge case, 'the best alternative' as an ambiguity and uncertainty dominates discussions between stakeholders. Opposite of this reality, dominant megaproject literature focusses more on the inaccuracy of traffic forecasts and assumptions about the monetary costs and benefits (e.g. Flyvbjerg et al., 2005; Nicolaisen, 2012). Cost overruns (cost), time slippages (timing) and poor project results (quality) following inaccuracies in CBA modelling are the key indicators of a project's success or failure in dominant megaproject literature. Forecasts should be regarded as uncertain. On the one hand, the Zeebrugge case fits the criteria for being at risk of forecasting inaccuracy. The port traffic forecasts for when a second sea lock would be built present themselves as an exact calculation of what the far future will look like, only considering one growth scenario. Even more striking, the assumptions are not based on forecasts of international sea freight traffic and port competition, but on the assumption that the promise of additional infrastructure will secure future growth. These forecasts are of crucial importance in the weighing of alternatives. They not only determine the effects (costs and benefits), but also the crucial point in time at which a second sea lock needs to be operational. Inaccuracies in this forecast also mean inaccuracies in the cost and benefit estimates.

At this point in time it is too early to evaluate the Zeebrugge case on forecasting inaccuracy. However, given the poor track record of transport infrastructure megaprojects on forecasting accuracy, the project team should be aware of this, while there is still the possibility in the design (project) phase to think about flexible strategies for dealing with unforeseen scenarios. On the other hand, there is a clear difference between what dominant megaproject literature regards as important to the project's success, and what is perceived as most important by the stakeholders in the case of Zeebrugge. In this case study, there is more discussion – ambiguity – about the 'best alternative', related mostly to the uncertainty about the town's future – the spatial and environmental impact – given the choice for Alternative 2. No model can predict what the future of the town will look like during the construction and operation of a new Visart Lock right between two neighborhoods, nor how this large infrastructure investment will impact the livability, social cohesion, or spatial and environmental quality of Zeebrugge. These are complex uncertainties, and very difficult to grasp within the boundaries of an SCBA and mostly an EIA.

Following this reasoning, the document analysis has shown that uncertainties in megaprojects cannot simply be understood within the boundaries of either an SCBA or EIA. This becomes clear from the fact that specific concerns only boiled up after the first decision was made for Alternative 2, and thus after a decision based on the SCBA and EIA results. In other words, a decision can be based on research reports, but as in this case, once a plan is chosen, the project is steered in a specific direction that triggers additional questions, uncertainties or concerns due to the project's complexity and large number of involved and affected stakeholders. In other words, the SCBA and EIA are mere starting points in which uncertainties could reside, and it is difficult to capture all uncertainties following decisions made later on in the process. Of equal importance after the initial decision are the different interpretations of data and results, for which this paper has illustrated how both instruments are used differently by different stakeholders, which can lead to ambiguity.

Nevertheless, the SCBA and EIA are an important first step in acknowledging and assessing uncertainties perceived by different stakeholders. However, the SCBA and EIA in this case poorly document and acknowledge uncertainties, which can harm credibility and the potential use of these reports (Annema et al., 2017; Leung et al., 2015; Leung et al., 2016). An SCBA and EIA will always be potentially interpreted differently by different stakeholders, but the more uncertainties are absent in these assessments, the further these reports drift from the reality of the complex and uncertain-prone process in which they are embedded. In addition to existing research, this paper has illustrated in detail at the level of a single case study megaproject that the SCBA and EIA cannot be detached from each other, nor from the complexity of the decision-making process, and that uncertainties reside in both these instruments as well as in the process in which they are embedded.

3.7. Conclusion

Uncertainty and complexity are inherent to the planning, design and decision-making process of megaprojects. We researched how uncertainties in the SCBA and EIA are taken into account when making decisions; and illustrated how they are nearly absent in the Zeebrugge project's SCBA and EIA. Therefore uncertainties did not have a direct impact on the first decision made. This however does not align with the uncertainty based questions and concerns raised afterwards, highlighting the ambiguity of what the 'best alternative' is in this case study. These uncertainty based concerns will have a big impact on the decisions still to be made in the design (project) phase, and are harmful for the credibility and value of the research results from the SCBA and EIA.

The paper shows that: (I) uncertainties are not limited to the boundaries of an SCBA or EIA, and they should not only be researched individually on uncertainties, but both within the broader context of the decision-making process as a whole; (II) these instruments are used differently by stakeholders, which can result in uncertainty or ambiguity about the best alternative; (III) there is a possible difference between what stakeholders perceive as uncertainties, and what mainstream megaproject literature pinpoints as uncertainties. If we want to understand the complexity of megaproject decision-making under uncertainty, we need to try to enlarge our research scope as much as possible, and look at the dynamic interplay between uncertainties, multiple decision-support instruments, decision-making, and the general process.

Furthermore, practitioners need to understand that limiting communication on uncertainties during the research phase in the SCBA and EIA for whatever reason does not result in an uncertainty-free process. If we want to increase the value as well as the quality of an SCBA or EIA, communication on uncertainties or possible future scenarios needs to be included as early as possible, opening up the debate among stakeholders as early as possible, thus including different perceptions. In this way, ad hoc responses to uncertainties can be turned in a more proactive way of identifying, understanding, and managing the possible impact of uncertainties collaboratively. However, more research is needed on stakeholders' perceptions on uncertainties in megaprojects, not limited to a single instrument but to the decision-making process as a whole.

The document analysis proved to be a good method to answer our research question, for the paper's main focus on a single project's SCBA and EIA. This was done through a combined content, discourse and narrative analysis. The conclusions however open up other research questions requiring possibly other research approaches. A next step would be to research deeper what happens behind the scenes in the build up towards the SCBA and the EIA, the decision-making and the discussions following decisions made. This requires thinking about the so-called rationality of these instruments in light of the irrationality of a decision-making process. This could help gain a better understanding on perceived uncertainties, rather than those marked as important in conventional literature. More comparative and in depth case studies on this subject are needed. This paper attempted to provide a first step to better understand and illustrate the complexity of decision-making under uncertainty in megaprojects, enlarging the research scope to the interaction between both the SCBA and EIA, as well as the project's decision-making process.

4. Explaining uncertainty avoidance in megaprojects: resource constraints, strategic behaviour, or institutions?

Thomas Machiels, Tine Compernolle & Tom Coppens

Published as:

Machiels, T., Compernolle, T., & Coppens, T. (2021). Explaining uncertainty avoidance in megaprojects: Resource constraints, strategic behaviour, or institutions? *Planning Theory & Practice*, 22(4), 537-555.

The journal publication is available at:

https://doi.org/10.1080/14649357.2021.1944659

Abstract

This paper asks why uncertainties are avoided in dominant megaproject practice while planning scholars are increasingly advocating adaptive planning and uncertainty acknowledgement. We propose a novel analytical framework to explain uncertainty avoidance, consisting of two current explanations – resource constraint and strategic behaviour models – and a complementary institutional model. We apply the framework to a seaport megaproject in Flanders to test its validity. Results show that the institutional model increases our understanding of uncertainty avoidance. More attention to planning institutions and far-reaching institutional changes are required to facilitate a move towards uncertainty acknowledgement and adaptive planning.

4.1. Introduction

Large urban and infrastructure projects, or 'megaprojects', involve complex planning processes. They are large-scale, require high investments, have a long-term horizon, involve and affect many stakeholders, and have a major impact on society (Flyvbjerg, 2014). Complexity and uncertainty about the future are inherent and irreducible features of megaprojects (Bertolini, 2010; Salet et al., 2013). Successful megaproject realization is therefore difficult, and poor performance is commonplace. Megaproject literature has increasingly shown that cost overruns, time delays, poor results, or adverse impacts occur frequently (e.g. C. C. Cantarelli, Molin, et al., 2012; Flyvbjerg et al., 2002; Welde & Odeck, 2017). Various causes for poor megaproject performance have been identified (De Jong et al., 2013; Denicol et al., 2020; Flyvbjerg et al., 2018). Two interrelated causes are inherent complexity and the need to make decisions and act under conditions of uncertainty (Sanderson, 2012).

Uncertainty does not cause project failure, but poor assessment and avoidance of uncertainties do. Through the rational 'planning and control' approach (Skrimizea et al., 2019), also called predict-and-plan (Koppenjan et al., 2011), practitioners try to simplify reality by denying the existence of complexity and uncertainty. Decision making is supported by supposedly accurate analyses of costs, benefits, and effects, but these have limitations in dealing with unforeseen developments (Rauws, 2017). While remaining dominant in planning and megaproject practice, predict-and-plan has lost its relevance in the contemporary planning context, which is characterized by uncertainty and complexity (Bergsma et al., 2019). As a response, planning and megaproject scholars are increasingly advocating a move towards uncertainty acknowledgement and adaptive planning that is more responsive to unexpected changes (Giezen, 2013; Salet et al., 2013; Skrimizea et al., 2019). Despite this growing consensus for integrating adaptivity in planning to better cope with uncertainties, in practice, predict-and-plan persists as the dominant approach (Bosch-Rekveldt et al., 2011; Giezen, Bertolini, et al., 2015; Lehtonen et al., 2017a).

To encourage the adoption of adaptive planning, we need to understand why uncertainty avoidance remains commonplace. Project failure has been researched extensively, but less research has tried to explain why megaproject practice still aims for certainty about the future, which De Roo (2018) has rightly called an illusion. To address the research gap, this paper considers what factors explain uncertainty avoidance in planning and decision making for complex planning issues, such as megaprojects, and what these explanations add to the concept of adaptive planning. To answer these questions, we consider bounded rationality (resource constraints) and strategic behaviour (manipulation and optimism bias) as models that explain uncertainty avoidance. Both concepts are well-researched explanations for poor megaproject performance. We show that although the resource constraint and strategic behaviour models do provide some clarification, these models are insufficient to explain uncertainty avoidance. Based on new institutionalism (NI), we propose the institutional model to explain uncertainty avoidance. Together, these three models form a novel analytical framework to understand uncertainty avoidance. To test and illustrate its merits, we apply the framework – using document analysis and interviews – to a case study of an ongoing seaport megaproject in Flanders.

The remainder of this paper is organized as follows. We first explore the growing trend of uncertainty research in megaproject and planning literature. Next, we present our analytical framework and the three theoretical models. We then apply this framework to our case study. Finally, we discuss the merits of the different theoretical approaches for explaining uncertainty avoidance and what they add to the concept of adaptive planning.

4.2. Megaprojects and uncertainties

Uncertainty and adaptive planning are well-researched topics in planning literature and megaproject literature. From the late 1960s onwards, planning scholars have recognized the challenge of coping with uncertainty in planning. Friend and Hickling (2005) distinguish three uncertainty types in public planning: uncertainty in the environment, in related decision areas, and in value systems. Their strategic choice approach is an early advocate of uncertainty acknowledgement and flexibility, allowing decision makers to better respond to unexpected circumstances (Friend & Hickling, 2005; Friend & Jessop, 1969). Another influential example is Christensen's (1985) distinction between four planning problem conditions, based on (un)certainty over means and ends. Christensen argues that planners should address uncertainty, not ignore it: "if uncertainty is the source of planners' problems, it can also be the path to those problems' solutions" (Christensen, 1985, p. 71). More recent planning contributions that conceptualize uncertainty and propose adaptive planning are inspired by climate studies (Zandvoort, van der Vlist, Klijn, et al., 2018) and complexity theory (Rauws, 2017; Skrimizea et al., 2019).

In project management literature, different uncertainty types have been distinguished by various scholars. Bertolini and Salet (2008) identify four sources of complexity and uncertainty in megaprojects: the dynamic and multiple possible interpretations of megaprojects, political and social conditions, legal and financial conditions, and technical conditions. A similar distinction between sources of uncertainty is presented by Priemus (2010), Priemus et al. (2013), and Machiels et al. (2021b). Other scholars approach uncertainty as a concept different from risk, arguing that these terms are often used interchangeably but should not be equated (Atkinson et al., 2006; Sanderson, 2012; Williams et al., 2019).

In harmony with planning literature, megaproject scholars argue that adaptive planning is the key to coping with uncertainty. Different options need to be kept open as long as possible to guarantee flexibility and allow adaptations (Bertolini, 2010; Priemus, 2010). Approaches that represent adaptive planning are the 'prepare and commit' perspective (Koppenjan et al., 2011), adaptive and strategic capacity (Giezen, 2013), and real options theory (Machiels et al., 2021b).

While planning literature and megaproject literature increasingly stress the importance of adaptive planning, both assume that uncertainty acknowledgement is self-evident. We agree that uncertainty acknowledgement is a prerequisite for adaptive planning, but argue that uncertainty acknowledgement must be achieved by first overcoming uncertainty avoidance. Therefore, an analytical theoretical framework to understand uncertainty avoidance is a valuable addition to this growing academic field.

4.3. A theoretical framework to explain uncertainty avoidance: Three explanatory models

4.3.1. The resource constraint model

The first model that explains uncertainty avoidance in current planning practice is the resource constraint model. The origins of this model date to the 1950s, when Herbert Simon coined the term bounded rationality as a critique of the rational model (Simon, 1997). Rationality is limited because decisions are made under knowledge, time, and budget constraints (Simon, 1997). Decision makers show satisficing behaviour; they make decisions that are "satisfactory or good enough" in a context of imperfect knowledge (Simon, 1997, p. 119). We cannot know everything; thus rationalizing reality is impossible (Simon, 1997). Applying this principle to megaprojects, decision makers lack complete information and are uncertain about the future (van Marrewijk et al., 2008; Williams & Samset, 2010). The search for alternatives is limited by time, money, and cognitive capacity (Sanderson, 2012). Time pressure on politicians, who are required to make rapid decisions, and a lack of funding are examples of barriers to a detailed assessment of uncertainties. Friend and Hickling (2005, p. 13) already noted this in the 1980s: "In general, however, uncertainty can only be reduced at a cost – whether this be merely the cost of delay when there may be urgent issues to be settled, or whether it also includes more direct costs in terms of money, skills or other scarce resources."

The essence of the resource constraint model is that practitioners lack the means to manage uncertainties adequately and therefore avoid them.

4.3.2. The strategic behaviour model

The second model is the strategic behaviour model, based on recent megaproject literature by Flyvbjerg and others, in which increasing quantitative evidence has shown the high frequency of forecast inaccuracy (e.g. C. C. Cantarelli, Molin, et al., 2012; Flyvbjerg et al., 2002; Welde & Odeck, 2017). According to behavioural science, the root cause of project failure due to cost underestimation and benefit overestimation is human bias, either psychological or economic-political (Flyvbjerg et al., 2018). On the one hand, optimism bias – a psychological explanation – suggests that decision makers and forecasters fall victim to overconfidence by underestimating costs and overestimating benefits (Flyvbjerg et al., 2009). An overly optimistic scenario is created, in which known risks and uncertainties are circumvented (Denicol et al., 2020). On the other hand, strategic misrepresentation – an economic-political explanation – means forecasts are deliberately falsified to satisfy decision makers or politicians and obtain approval for a project proposal (Flyvbjerg et al., 2009). Beukers et al. (2012a) suggest that cost–benefit analyses (CBA) occur too late in the process and are used only to justify decisions. Cardenas et al. (2016) indicate that uncertainties in environmental impact assessments (EIA) are often obscured to avoid controversy among stakeholders or to enable rapid approval. Deliberate falsification is not penalized because forecasters and decision makers are not accountable for inaccuracies (Flyvbjerg et al., 2002). Manipulation of forecasts usually happens by underestimating costs and ignoring risks (Denicol et al., 2020). The essence of the strategic behaviour model is that practitioners deliberately underestimate and ignore uncertainties and megaproject complexities for strategic reasons or because of overoptimism.

4.3.3. The institutional model

Recently, both planning and megaproject literature have argued that increased attention to the institutional contexts in which planning practices are embedded is required, from the viewpoint of an institutional analysis (Biesenthal et al., 2018; Salet, 2018). New institutionalism has not yet been used to its full potential in planning theory and practice (Sorensen, 2017). It is the basis for the institutional model that we propose.

New institutionalism consists of three main branches: rational choice institutionalism, sociological institutionalism, and historical institutionalism. Excellent overviews are provided by Hall and Taylor (1996) and Sorenson (2017). At the core of NI is the analytic distinction between formal and informal institutions (Sorensen, 2017; Taylor, 2013), described by North (1990) as “the rules of the game” (p. 5). Every branch of NI defines institutions as sets of rules (formal) and shared understandings (informal) that shape actions (Sorensen, 2017). Megaproject planning and decision making are deeply embedded in formal and informal institutions. Formal institutions, for instance, include juridical procedures and legal instruments, such as EIAs, zoning plans, planning procedures, and expropriation procedures. Informal institutions include shared norms, conventions, ideas, routines, and customary practices. Project managers of megaprojects use scripts of project management approaches (such as phase models) and rule-of-thumb approaches that have evolved in their field.

The three branches of NI explain institutional change and how institutions shape action, create order, and provide structure in everyday life (North, 1990; Sorensen, 2017). Planning institutions create institutional stability so that decision makers, planners, and project managers know the rules of the game, which determine the criteria for legitimate decision making. The integration of uncertainties in decision-making processes in megaproject planning itself creates an uncertainty, or a meta-uncertainty: for example, decision makers must decide what kinds of uncertainties are relevant and how to manage uncertainties so that their decisions are accepted as legitimate. In such a context of meta-uncertainties, NI argues that decision makers and project managers rely on prescriptions from vested norms and procedures. These constitute accepted, legitimate approaches to making decisions and either avoiding or managing uncertainties. The essence of the institutional model is that the institutional context of planning prescribes uncertainty avoidance. Hence, uncertainty is avoided, and the predict-and-plan approach is maintained. Table 4.1 summarizes the three theoretical approaches in one analytical framework.

Table 4.1. *Analytical framework: theoretical models to explain uncertainty avoidance*

Theoretical model	Explanation for uncertainty avoidance in megaproject planning	References
Resource constraint model	Constraints on time, money and cognitive capacity to address uncertainties Not enough or the right resources to address uncertainties Imperfect knowledge or information makes uncertainty inevitable, ignoring what we do not know	(Sanderson, 2012; Simon, 1997; van Marrewijk et al., 2008; Williams & Samset, 2010)
Strategic behaviour model	Optimism bias: creating an (overly) optimistic scenario, thereby ignoring risks and uncertainties. Strategic misrepresentation: manipulation of estimates by underestimating costs and ignoring uncertainties to make projects look better and increase chances of project approval	(Flyvbjerg et al., 2009; Flyvbjerg et al., 2002)
Institutional model	The institutional context of planning prescribes and routinizes uncertainty avoidance. Decision makers and planners rely on prescriptions and routines when confronted with uncertainties.	(Biesenthal et al., 2018; Hall & Taylor, 1996; North, 1990; Sorensen, 2017; Taylor, 2013)

4.4. Research methods

The New Lock Zeebrugge seaport megaproject involves the construction of a large sea lock in Flanders' second most important port. The ongoing project has passed the initiation and planning phases. At the planning level, the Flemish government has officially decided the location of the new lock. The current phase, at the project level, consists of designing the lock for the selected location. Because uncertainty is at its highest during the early stages of a project (Samset & Volden, 2016; Williams et al., 2019), we researched uncertainty avoidance during the planning phase of the case.

4.4.1. Single case study: The New Lock Zeebrugge

The port of Zeebrugge is in the province of West Flanders, near the North Sea. The town of Zeebrugge (part of the city of Bruges) is located within the boundaries of the port and consists of three neighbourhoods – Zeebrugge Dorp, Stationswijk, and Strandwijk – inhabited by about 4300 people. Figure 4.1 provides an overview of the port and town structure. The smaller Visart lock, constructed in 1907, is outdated and too small for modern shipping. All major traffic to the rear port moves through the Vandamme lock, which opened in 1985 and is increasingly showing signs of decay and malfunction. If the Vandamme lock malfunctions for a long period, the rear port becomes inaccessible to incoming traffic, and outgoing traffic cannot leave. To avoid the risk of an economic shutdown, there has been agreement since the early 2000s that a second modern lock is needed. Despite a great deal of research and planning, no significant progress was made until 2016 due to opposition and legal action by local citizens and some fishing and port companies.

The project was restarted in 2016 with the Flemish decree of complex projects, a new procedure for complex planning projects with an emphasis on transparency, openness, broad stakeholder involvement, and accelerated realization. This procedure guides projects through four phases: an initiation or exploration phase, a research or planning phase, a project or design phase, and an implementation phase. We limited our analysis to the planning phase (Figure 4.2), during which six location alternatives for a new lock and a regional road, NX, to separate heavy port traffic and local town traffic were compared (Figure 4.1). Research was completed at the end of 2017 and consisted of a social CBA (SCBA) to compare the monetary costs and benefits of each alternative, an EIA to compare the environmental impacts, and maritime research to compare safety and nautical accessibility. These are institutionalized instruments in Flanders and mandatory steps in the planning phase, each with guidelines and procedures. Based on the reports, the Flemish Minister of Mobility and Public Works decided in March 2018 on alternative 2, Visart, which has an estimated cost of 1.09 billion euros and an expected construction time of six years. Visart involves the construction of a new lock at the location of the old Visart lock, with the NX as a tunnel under the new lock.

This decision came as a surprise because Visart scored lowest in the maritime research. It provoked opposition from dissatisfied citizens, the impacted marina, local politicians, and some port companies. Opponents fear this new lock, which is between two neighbourhoods, will have a large negative spatial and environmental impact on the town's liveability. The Verbindingsdok Alternative was preferred by the City of Bruges, local citizens, and others for its remote location. Verbindingsdok was more expensive (1.46 billion euros) and had a 12-year construction period. Despite many questions and concerns raised during the subsequent consultations with government institutions and a public inquiry, the decision for Visart was made official in May 2019. The Flemish Minister for Mobility and Public Works argued that Visart was chosen for its reasonable price and implementation time compared with other alternatives. An action plan was promised in the final decision-making document, including nautical optimizations and measures to safeguard the liveability and spatial quality of the town's neighbourhoods. While the project phase has been initiated, legal complaints are requesting annulment of the official decision. The verdict is expected in early 2021. A verdict in favour of the opponents could mean the planning phase has to be (partly) repeated, causing a delay of at least two years.

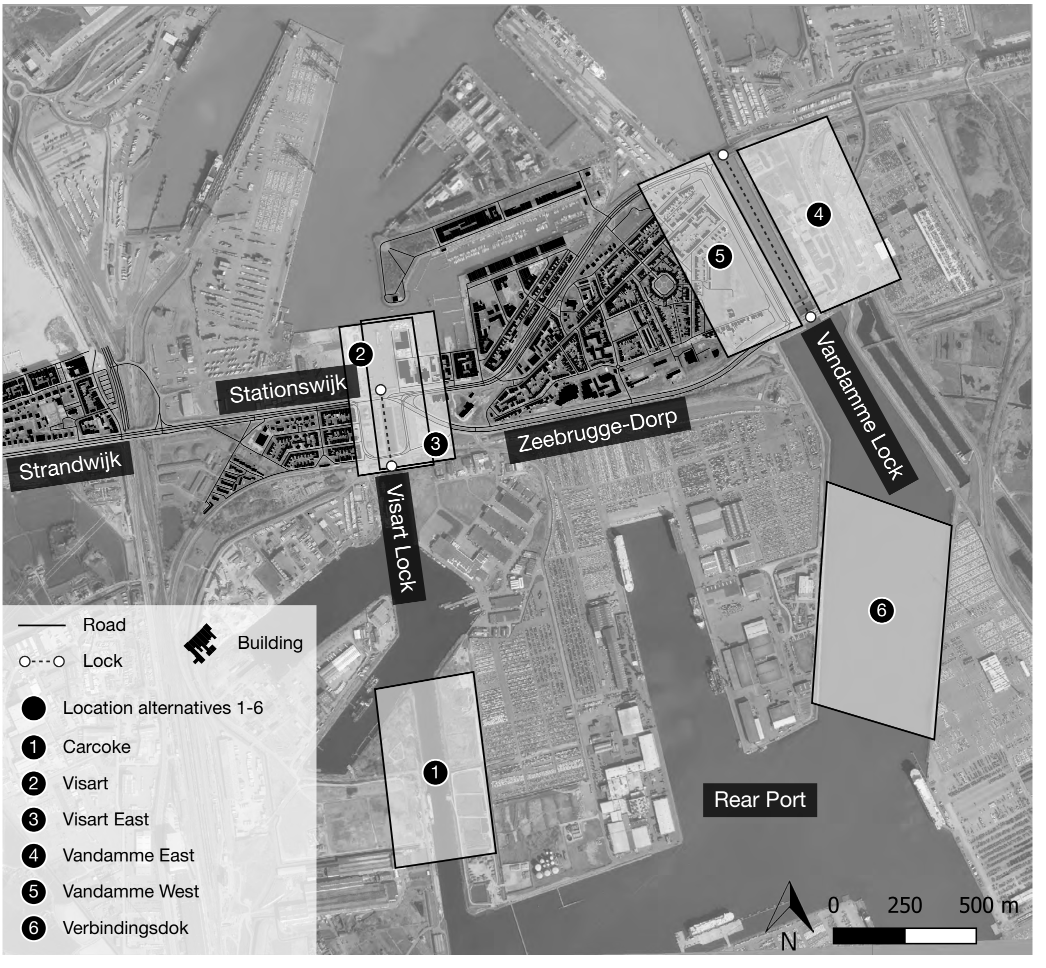


Figure 4.1. *Zeebrugge town and port and location alternatives for the new lock*

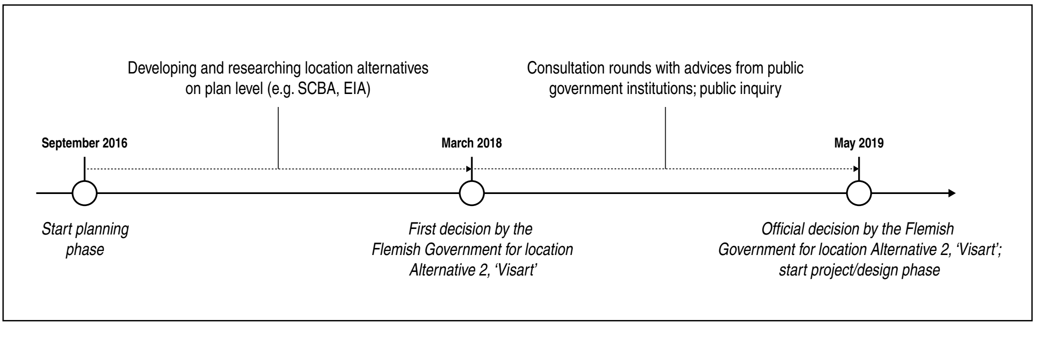


Figure 4.2. *New Lock Zeebrugge, overview of the planning phase*

4.4.2. Document analysis and interviews

To analyse how uncertainties are reported and whether our theoretical models explain uncertainty avoidance in a real-life case study, we combined a document analysis with semi-structured interviews. These information sources are complementary. Documents provide an understanding of the project's content, while interviews help to reconstruct the 'behind-the-scenes' processes of planning and decision making. Such an approach, along with developing a theoretical framework and applying it to an in-depth single case study, has delivered valuable insights in comparable studies (Giezen, 2013; Koppenjan et al., 2011).

The document analysis consisted of regulatory documents, project documents, and press articles. Regulatory documents are legislation and procedures that apply to all projects in Flanders, such as EIA legislation and guidelines, and the Decree of Complex Projects. Project documents are the case's mandatory documents arising from regulation and procedures. These include the planning phase's research reports (e.g. EIA, SCBA), governmental decision-making documents, summaries of advice from consultations and the public inquiry, and documents with general project information. Fourteen project documents were subjected to a content and discourse analysis. The content analysis considered what is written about uncertainties in the documents, while the discourse analysis considered argument patterns (Hijmans, 1996). Additional press articles were used to better understand the case. This approach permitted us to illustrate to what extent project elements were officially identified, researched, and communicated as uncertainties and whether uncertainties influenced decision making. A comparison could then be made with concerns and questions raised during the public inquiry and consultations. This made it possible to assess whether questions and concerns that can be regarded as uncertainties were recognized or avoided in the policy evaluation and decision making. We interpreted project elements as uncertainties if their future states were unknown; they thus had an uncertain effect on the expected timing, costs, impacts, and benefits of the project. All project documents used in the analysis are available on the project's website.

Additionally, 16 interviews were conducted between September 2019 and March 2020 with 25 people, who represent 15 internal and external project stakeholders or organizations. Internal stakeholders are either part of the project team or involved in the decision making: for example, the project leader, the Port of Zeebrugge, and the Ministry of Mobility and Public Works. External stakeholders are either directly or indirectly impacted by the project: for example, the fishing companies, the marina, and the town's citizen action committee. During the interviews, respondents were asked to describe the planning phase and decision-making process from their perspective, with emphasis on which uncertainties had (not) been identified and addressed, how uncertainties were treated, which uncertainties were important to them, and why they believed specific uncertainties were (not) addressed.

Interviews were recorded, transcribed, and analysed in NVivo, a software program for coding and analysing qualitative data. We created an initial list of codes based on the document analysis results and our theoretical framework, which was extended inductively by creating new codes while coding and reading the transcripts. The final codes revolved around three main topics: the three theoretical approaches to explaining uncertainty avoidance; the process of identifying, assessing, and communicating about uncertainties within the case; and specific uncertainties perceived by the interview respondents. By analysing the respondents' stories this way, we determined how stakeholders framed their understandings of uncertainty avoidance, which allowed us to assess the relative merits of the three explanatory models. The interview respondents were not aware of the theoretical framework while being interviewed, which strengthens the empirical evidence (Bosch-Rekveldt et al., 2011; Yin, 2018).

4.5. Results: Uncertainties and uncertainty avoidance in the New Lock Zeebrugge megaproject

4.5.1. Which uncertainties did stakeholders identify?

We identified uncertainties as perceived by project stakeholders in two steps. First, the reports of the consultations and public inquiry were analysed to identify questions and concerns that can be interpreted as uncertainties. These reports document each piece of advice (from consultation rounds) and complaint or comment (from the public inquiry) that was officially submitted. Second, we asked stakeholders during the interviews which uncertainties they perceived as important for the project. Concerns or questions that arose during the interviews were also considered uncertainties.

Overall, similar uncertainties were identified from both sources. Table 4.2 provides an overview and brief explanation of the most important uncertainties. We interpreted these project elements as uncertainties because, at the end of the planning phase, their future states and effects on the timing, costs, benefits, and impacts of the project were unknown. Many of these uncertainties are specifically related to Visart, the alternative chosen by the Flemish Government. For example, local citizens, the marina, and the fishing companies expressed concerns about the direct spatial and environmental impact of the new lock, due to its location. A different decision would have generated other perceived uncertainties.

The overview of uncertainties in Table 4.2 is not an exhaustive inventory of uncertainties but only the known unknowns as perceived by stakeholders. None of the interview respondents were concerned with, for instance, traffic forecasting inaccuracies. This is surprising since seaport traffic evolutions are dependent on various uncertain factors outside the control of a single port, such as the evolution of the global demand for shipping, technological change in shipping and related sectors, and the future position of seaports in European and global shipping networks. Internal stakeholders and project proponents acknowledged the possibility of forecasting inaccuracies but did not consider the uncertainty important. In their opinion, the second lock is an infrastructural requirement to ensure the accessibility of the rear port, regardless of evolutions in demand. Local stakeholders were only concerned about uncertainties related to the chosen alternative that directly impacted them. If uncertainties are not proactively identified, many uncertainties and their impact are neglected and remain unknown unknowns. Identifying all uncertainties is difficult, but not trying at all increases the chance of 'black swans', unforeseen events with adverse consequences or missed opportunities for the project and its environment (Taleb, 2007; G. M. Winch & Maytorena, 2012).

Table 4.2. *Project elements interpreted as uncertainties deducted from project documents and interviews*

Uncertainty	Description
Phasing and timing	No timing or phasing yet for the construction of the lock and NX road
Construction, technical feasibility	The impact during construction on the direct environment, size of construction area, construction method, exact location of the lock
Nautical accessibility to the rear port	Optimizations are required in the design of VIsart to increase its maritime score, nautical safety and accessibility to the rear port. These optimizations, their effectiveness, costs and impacts are unknown
NX road tunnel	The NX road tunnel will follow a separate procedure as an individual project. The exact length, location and spatial impact are unknown
Additional measures to mitigate negative impacts	Which additional measures to mitigate negative post-realization impacts on the direct environment, what will their effectiveness be? Guarantees from decision makers on their realization and financing (e.g. 'liveability plan')
Financial means and responsibility	who will pay for what and availability of financial means (e.g. for additional measures to compensate impacted stakeholders and citizens)?
Number of Expropriations	A spatial buffer between the lock and residential areas requiring additional expropriations is not yet part of the plan
Impact on port companies	Where will displaced companies go, and which assistance will they get?
Impact on the marina	Accessibility during and after implementation; how will large ships passing the marina impact their operations and (economic) liveability?
Impact on the fishing companies	Accessibility during and after implementation; the impact of large ships passing smaller fishing vessels near the fishing companies' dock
Impact on the town Zeebrugge	The overall post-realization impact of the project on the liveability (e.g. health, air quality) and spatial quality of the various neighbourhoods in Zeebrugge
Total project costs	Exact project costs are unknown as required design optimizations and additions for the lock and NX road, additional measures, timing and phasing have not been estimated
Council of State	The verdict of the Council of State. If the official decision is judged as legally correct, the project can proceed. If not, the planning phase might have to be (partly) redone, causing delay.

4.5.2. Which uncertainties were part of the research reports and decision making?

Despite the variety of perceived uncertainties, only a limited number received attention in the decision-making process. Policy evaluation in this case strongly relied on predict and plan. Forecasts were either exact values or estimates of a single future and few uncertainties were documented, implying that there were barely any uncertainties.

Social cost-benefit analysis guidelines for infrastructure projects in Flanders seem to play a decisive role in the way uncertainties are managed. These guidelines were written in 2013 by a consultancy company commissioned by the Flemish government. The guidelines contain standardized methods and quantitative assumptions that apply to all infrastructure projects in Flanders, distinguishing only between general types of projects (e.g. airport or seaport). Regarding uncertainties, the guidelines prescribe a sensitivity analysis alone, which was applied in the Zeebrugge case with a 25% increase and decrease in the total estimated costs for all six location alternatives. This sensitivity analysis is simple and brief. It does not identify or analyse in depth which project elements are uncertain and could contribute to a project cost increase or decrease. The choice of a 25% variation is not explained and appears arbitrary. Furthermore, sensitivity analyses following SCBA guidelines are applied in the same way to every infrastructure project and do not distinguish between projects or specific uncertainties.

Environmental impact assessment guidelines in Flanders derive from EU legislation that since 1985 has required member states to conduct an EIA for projects that could have negative environmental impacts. Regulations in Flanders were established with the 1995 decree on environmental policy. The EU and Flemish EIA legislation have both since been revised multiple times. The general guidelines for Flemish EIA practice were last revised in 2015 and prescribe a mandatory chapter entitled 'knowledge gaps', in which all uncertainties must be described. The chapter in the project's EIA details one knowledge gap, described on one page of the 350-page report. This knowledge gap is an uncertainty regarding the potential impact of the Verbindingsdok alternative on a neighbouring nature reserve, caused by possible changes in groundwater level and composition. The nature reserve is a special protection area under the EU's Natura 2000 environmental legislation. To reduce the knowledge gap, additional groundwater modelling was required but not conducted. Consequently, a possible negative impact could not be excluded. Following EU Natura 2000 legislation, a worst-case scenario had to be applied. Internal project stakeholders argued that this alternative could not be permitted if a negative impact was possible. This uncertainty was one of the three arguments that caused the rejection of Verbindingsdok, alongside its higher price and longer implementation time.

Internal stakeholders stated during the interviews that uncertainties were identified ad hoc or not at all. Uncertainties arose during meetings, consultations, or public participation but were not identified proactively. If uncertainties arose, stakeholders stated, they were 'cleared out' through consultations and discussions or, if deemed necessary, through additional research. Open communication and discussions between internal stakeholders needed to result in a consensus about which assumption, parameter, or result would be used in the research reports. Removing uncertainties thus meant achieving an agreed certainty between the stakeholders rather than considering multiple scenarios or future states. Second, uncertainties deemed irrelevant for the planning level were transferred to the project phase. Most questions and concerns from stakeholders were acknowledged in the final decision-making document of May 2019 through an action plan. These project elements were not acknowledged as uncertainties but as solvable problems to be fixed during the project phase.

4.5.3. Why are uncertainties avoided in policy evaluation and decision making?

The results show a gap between the uncertainties perceived and those that were officially acknowledged in policy evaluation instruments and decision making. Applying our theoretical framework makes it possible to explain why uncertainties were largely avoided in this megaproject.

The resource constraint model partly explains why additional research was not conducted to reduce the Verbindingsdok knowledge gap. Lack of time was one important reason, according to various respondents. To choose this alternative, additional time and money needed to be invested in 'clearing out' the knowledge gap. A fast decision was preferable because the project had already lasted for more than 15 years, and there was urgency created by the aging Vandamme lock. Additionally, local citizens were tired of research, and the city of Bruges wanted to move forwards, as they had been requesting a second lock for years. There simply was no time for further research.

However, the institutional model explains better why this alternative was not chosen. Even after additional research, the results would have remained uncertain because a groundwater model is an estimate based on uncertain parameters. The actual impact can only be known upon project realization. In cases of uncertainty, environmental legislation and the precautionary principle prescribe that if a negative impact is possible, the worst must be assumed and the alternative cannot be permitted. One interviewee stated, "If Verbindingsdok is chosen, with this knowledge gap, the decision is vulnerable to legal action". According to the deputy head of the Minister's Cabinet, this knowledge gap was the main reason why Verbindingsdok was rejected: "the environmental impacts were uncertain, and therefore the risk that it would not legally hold was too big". Even if there was time to conduct additional research, it would not have had an impact: the remaining uncertainty forced the decision maker to reject this alternative based on the institutional context of environmental legislation.

The strategic behaviour model partly explains why many perceived uncertainties were not acknowledged as such in policy evaluation and decision making. Several stakeholders, mainly external ones, described the decision-making process as a political one, in which a political decision was made for the alternative favoured by the Flemish Minister of Mobility and Public Works. The SCBA and EIA were believed to be politically manipulated, aimed at achieving the results needed to justify the decision for Visart. The Flemish Fish Auction believed that "several things were underestimated and overestimated to get the results they wanted, and the dangers of the impact on the (direct) environment were underestimated". One interviewee implied that the decision makers deluded themselves about the project costs but made the decision based on that factor. The local action committee felt that the "studies were made to make Visart look good" and various elements were deliberately excluded from the cost estimations, such as the required nautical optimizations, the possible increased length of the NX tunnel, the actual number of displacements, and the liveability plan. In contrast, they believed that unnecessary assumptions were made to make Verbindingsdok more expensive than Visart. On a similar note, the Marina believed research had been conducted in such a way as to make "other alternatives as infeasible as possible". The City of Bruges questioned if the price comparison had been conducted correctly. Finally, even the Port's CEO doubted the neutrality of the research reports and indicated that several benefits were not considered within the Port's preferred Carcoke alternative because it would make the Carcoke alternative look too good.

The institutional model provides an additional explanation for why project elements with clearly uncertain outcomes were not acknowledged as uncertainties. Planning institutions prescribe an uncertainty-aversive approach, and hence uncertainties are avoided. Seven of the eight internal stakeholders highlighted that uncertainties or knowledge gaps are avoided at all costs in decision making and official documents to ensure decisions are legally incontestable, to withstand legal action, and to facilitate project approval. This requires settling everything, reaching an agreed certainty, so there is no room left for discussion. The project leader said that "most parts need to be cleared out, so that after the decision making they are incontestable if other parties take legal action'. The EIA coordinator felt that while the chapter on knowledge gaps is mandatory and important, not much time is spent on it. Knowledge gaps need to be resolved before a decision can be made. If there are knowledge gaps left at the end of the next phase, this presents the opportunity for legal action. This explains why little is written about uncertainties. To have an incontestable decision, project documents and research reports need to have as few discussion points as possible, and therefore as few uncertainties as possible. If this is not the case, legal action is almost certain to follow.

Therefore, whether or not uncertainties are ignored as a consequence of manipulation or overoptimism, they cannot be acknowledged as uncertainties in official documents to ensure the legal stability of an official decision. Furthermore, while the possible role of strategic behaviour cannot be ignored, strategic manipulation cannot be proven in this case without evidence. For the most part, it was external stakeholders who presented critical viewpoints and opponents of Visart who suggested manipulation. Additionally, it seems unreasonable to believe that the decision maker in this case had the power to manipulate the large network of stakeholders involved.

The empirical results illustrate the value of each explanatory model and thus the analytical framework for explaining uncertainty avoidance. Alongside resource constraints and strategic behaviour, the institutional model offers an important additional explanation that complements the explanatory power of the first two models. Overall, the interviewees realized that certainty about the future does not exist, but they still applied the predict-and-plan approach by internally reaching an agreed certainty and hence avoiding uncertainty. The legal instability of a decision was understood to be positively correlated with uncertainty acknowledgement. Interpreting concerns as solvable problems allowed the project to proceed linearly along the projected path while avoiding uncertainties and thus legal instability. In general, Flemish planning legislation and procedures do not enforce uncertainty acknowledgement or assessments and still rely on linear predict-and-plan processes. The institutional context penalizes uncertainty acknowledgement and makes it undesirable; it prescribes, routinizes, and legitimizes uncertainty avoidance in day-to-day planning practices.

4.6. Uncertainty acceptance and adaptive planning: The need for an institutional approach

The resource constraint model and strategic behaviour model have value in explaining uncertainty avoidance, but their theoretical approaches are limited in facilitating uncertainty acknowledgement and adaptive planning. Resource constraints have been important drivers in the development of Lindblom's (1959) incremental planning model, which nevertheless aims to avoid uncertainty by sticking to alternatives that only differ marginally from the base scenario rather than searching for radical alternatives with unknown impacts. In today's megaprojects, minor changes are made intuitively or ad hoc when problems occur, as illustrated by the 'solvable problems' in the Zeebrugge seaport case. Incremental changes alone do not encourage proactively identifying uncertainties and considering multiple possible future outcomes.

Strategic misrepresentation and optimism bias can be curbed by a system of governance mechanisms, such as external quality control, increased transparency, increased accountability, proper risk allocation in contractual agreements, and so on (Flyvbjerg et al., 2003; Flyvbjerg et al., 2009). While important for curbing strategic behaviour, these solutions to project failure have been criticized as they provide "little or no explanation of how performance may be improved by making decisions to address unforeseen events and circumstances when a megaproject is underway" (Denicol et al., 2020, p. 336). Mechanisms to curb strategic behaviour still rely on the assumptions that the future is controllable and it is possible to calculate the probabilities of a future path (Sanderson, 2012). However, linear ex ante planning cannot control inherent complexity and irreducible uncertainties (Lehtonen et al., 2017a; Sanderson, 2012). It does not deviate strongly enough from predict-and-plan to encourage a move towards adaptive planning.

The institutional analysis of megaprojects adds more to adaptive planning concepts than the previous models. A change in institutional prescriptions is required to deal with complexity and uncertainty in complex projects (Salet et al., 2013). If the framing of projects is kept narrow to reduce complexity and uncertainty, the institutional capacity for adaptive planning is also kept narrow (Giezen, 2013). Flexibility in megaprojects is constrained by regulatory frameworks (Denicol et al., 2020), as current institutions have limits in their ability to cope with uncertainty and complexity (Bertolini & Salet, 2008). Adaptive planning is not yet common because legal and institutional structures do not support it (Kato & Ahern, 2008). The adaptive capacity of planning is either fostered or constrained by a variety of conditions, including governmental rules, regulatory frameworks, and instruments (Rauws, 2017). Therefore, planning processes and institutions that enhance adaptivity should be favoured (Bertolini & Salet, 2008).

The Flemish institutional context restricts adaptive planning opportunities. Flemish Environmental impact assessment guidelines dictate that uncertainties need to be excluded as much as possible, because uncertainties undermine the validation of EIA results and the motivation for selecting alternatives. Uncertainties limit the use of EIAs as a tool to support 'good' decision making. These guidelines inform legal practice in litigation procedures, on which EIA technicians anticipate. Planning legislation forces the selection of one alternative at the end of the planning phase to ensure legal certainty, while other promising alternatives that could be more cost-efficient but have an uncertain impact are eliminated. This early elimination of options significantly reduces the project's adaptive capacity and flexibility. The institutionalized suppression of uncertainty acknowledgement and adaptive planning accompanies day-to-day practices during which uncertainties are not proactively identified but addressed only when they arise, as mentioned during multiple interviews.

These examples illustrate the mismatch between the current institutional planning context and the increasingly complex societal context for which we plan. The former prescribes single future estimates and uncertainty avoidance, while the latter implies that the truth lies closer to such expressions as 'we are uncertain and should consider plausible future scenarios'. This mismatch cannot be overcome if more truthful expressions that acknowledge uncertainty are legally penalized and considered institutionally unstable, while illusions of certainty are approved and considered to provide institutionally stable decisions. The 'planning game' needs new 'rules'. A regulatory framework and instruments are required that institutionalize not only adaptive planning but also uncertainty acknowledgement. Additionally, we need to change not only our approach through formal institutions but also how we informally think about planning and uncertainty in routines, shared norms, and daily practices. Acknowledging and accepting uncertainties challenges the nature of planning itself (Skrimizea et al., 2019).

Far-reaching institutional change is required to enforce and routinize uncertainty acknowledgement and to facilitate adaptive planning. Questions such as 'which planning institutions can facilitate uncertainty acknowledgement and adaptive planning?' and 'how can institutional change be achieved?' should be the subject of further research. On the one hand, research must start with a critical, in-depth analysis of current institutional contexts to understand how both formal and informal institutions discourage uncertainty acknowledgement and adaptive planning. On the other hand, such analyses can reveal the underused adaptive capacity of current institutions.

In addition, we need more empirical results describing good examples of adaptive planning practices in megaprojects from an intuitionalist viewpoint. Rauws et al. (2014), for example, develop an instrumental framework of design principles for flexible development plans, including incremental development strategies and loose rules. Future studies must research how such frameworks can be formally institutionalized. In contrast to changes in formal institutions, changes in day-to-day practices need to be initiated through a participatory approach. A wide variety of actors needs to be accustomed to uncertainty acknowledgement and adaptive planning through learning and experimentation. Bergsma et al. (2019), for example, illustrate how Dutch infrastructure planning organizations reconsidered their informal institutional practices concerning stakeholder involvement as a consequence of increasing complexity and uncertainty.

Planning scholars have only recently been adopting NI in planning, hoping to boost institutionalist analyses (Salet, 2018; Sorensen, 2017). For example, Sorensen's historical institutionalism (2015, 2018) and Healey's sociological institutionalism (2006, 2018) can help explain how uncertainty-averse behaviour and actions are institutionalized, why the predict-and-plan approach is so hard to change despite increasing criticism, and how institutional change can occur. For example, Sorenson (2018) states that "planners should (…) consider the implications of institutional and physical designs that constrain the adaptability of urban areas to changing conditions" (p. 35). Institutional innovation and design involve changing both habitual practices and formal structures and rules (Healey, 2018). The objective of institutional design, in this case, is to make the institutional environment more hospitable to adaptive planning and to create more effective planning contexts (Beauregard, 2005; Taylor, 2013).

Overall, an institutionalist viewpoint is a valuable addition to existing theories for understanding megaproject decision making. This viewpoint is necessary to foster a move from uncertainty-aversion and predict-and-plan to uncertainty-acknowledgement and adaptive planning. Because we opted for an in-depth single-case study, it is not possible to generalize our results. The explanatory power of the institutional model strongly relates, in this paper, to the institutional planning context of Flanders. On the one hand, additional research on uncertainty avoidance in different contexts can allow comparative institutionalist analyses and further test the analytical framework presented in this paper. On the other hand, research into good practice in institutional contexts that facilitate adaptive planning can offer insights into the possible trajectories of institutional change. Nevertheless, the institutionalized instruments described here, such as the SCBA and EIA, and informed decision-making processes apply to similar projects in Flanders, making this a representative case for the region.

4.7. Conclusion

As Christensen (1985) notes, "Planners hate uncertainty as much as most other people do, and they spend their working lives trying to reduce it" (p. 63). Over three decades later, Christensen's impression still applies to megaproject planning, and her message to not ignore uncertainties has not been heeded in planning practice.

We have contributed, in this paper, to the growing field of adaptive planning and megaproject literature by developing an analytical framework to explain uncertainty avoidance in megaproject planning and decision making. Current planning and megaproject research stress the importance of uncertainty acceptance as a prerequisite for adaptive planning but assumes uncertainty acknowledgement. Understanding uncertainty avoidance is a condition for uncertainty acknowledgement and adaptive planning. The empirical results from a seaport megaproject in Flanders show that uncertainty avoidance should be understood as an institutionalized practice, routinized in formal and informal planning institutions. Key concepts of NI can help better understand how planning institutions fix uncertainty-aversive behaviour. Future theory-oriented research should address how these institutions are maintained, and how institutional change, innovation, and design can contribute to improved uncertainty acknowledgement and adaptive planning.

We have contributed to planning practice by highlighting the possible limitations of institutional contexts through a Flemish case. Flanders' planning context is not suited to cope with uncertainties or to adopt an adaptive planning rationale. We do not believe that Flanders is an isolated case, given the geographically wide data on planning and megaproject failures and the international focus of scholars on uncertainty and adaptive planning. Practitioners should become more aware of the formal and informal institutions that determine how they behave in planning and decision-making processes. Such self-awareness is an important first step. It promotes change and innovation to form an institutional environment that creates more effective and adaptive planning contexts. Future practice-oriented research should focus on which institutions facilitate or discourage uncertainty acknowledgement and adaptive planning.

5. Stakeholder perceptions of uncertainty matter in megaprojects: The Flemish A102 infrastructure project

Thomas Machiels, Tine Compernolle & Tom Coppens

Published as:

Machiels, T., Compernolle, T., & Coppens, T. (2023). Stakeholder perceptions of uncertainty matter in megaprojects: The Flemish A102 infrastructure project. *International Journal of Project Management*, 41(1), 102437.

The journal publication and supplementary material are available at:

https://doi.org/10.1016/j.ijproman.2023.102437

Abstract

Complexity in megaprojects leads to uncertainty about the future, which means forecasting is difficult, and perceptions of uncertainty can differ among stakeholders based on differing interests and values. We contribute to uncertainty and stakeholder management research and practice in megaprojects by conceptualising perception of uncertainty and by adopting Q methodology as a mixed method for stakeholder analysis to empirically study stakeholders' perceptions of uncertainty in the Flemish A102 road project. Four perception groups are revealed that show why understanding perceptions of uncertainties in megaprojects matters: (i) uncertainty management must be broadened by considering relations between uncertainties; (ii) assessing whether uncertainties are irreducible or reducible and how they should be managed can be perceived differently; (iii) stakeholder analysis must aim to understand stakeholder heterogeneity and avoid classifying stakeholders based on a priori assumptions; (iv) revealing perceptions of uncertainty can help project managers anticipate conflict and prepare for stakeholder dialogue and engagement.

5.1. Introduction

Megaprojects, such as transport or energy infrastructure projects and urban development, differ from other projects because they are characterised by higher complexity and many uncertainties (Flyvbjerg, 2014; Sanchez-Cazorla et al., 2016). Uncertainty is a lack of certainty, ambiguity, lack of clarity, and lack of data and knowledge that makes accurately forecasting the future benefits, costs, and impacts of megaprojects difficult (PMI, 2021; Ward & Chapman, 2003). In project management studies, underestimating complexity and ignoring uncertainties are considered to be a main cause of poor megaproject performance (Ahiaga-Dagbui et al., 2017; Denicol et al., 2020; Welde & Odeck, 2017). Uncertainty management is of growing importance to improve megaproject performance (Atkinson et al., 2006; Bergsma et al., 2019; Machiels et al., 2021a).

A first step of uncertainty management is determining which uncertainties a megaproject must be prepared for (Jahanshahi & Brem, 2017; Machiels et al., 2021a). Stakeholders however have different perceptions of uncertainty and therefore also differing views about the scope of uncertainty management (Atkinson et al., 2006; Lehtiranta, 2014). The scope of uncertainty management is determined by which uncertainties are identified and the strategies that are designed to manage the identified uncertainties. A perception of uncertainty is a stakeholder's viewpoint about the determinants, outcomes, and impacts of uncertain project elements (Lyons & Marsden, 2021). Views about the future differ among stakeholders based on differences in the knowledge and information stakeholders possess, and the positions, interests, and values stakeholders have (Aaltonen & Kujala, 2016; Daniel & Daniel, 2018). Megaprojects are characterized by many stakeholders with different interests (Aaltonen, 2011; Di Maddaloni & Davis, 2017; Erkul et al., 2016), and differing perceptions of uncertainty can be a main determinant of conflict (Mok et al., 2015; Y. Wang et al., 2021). Therefore, identification of perceptions of uncertainty through stakeholder analysis must be a part of uncertainty management.

To our knowledge, no empirical studies exist about perceptions of uncertainty in megaprojects, in contrast to, for example, risk perception research in the field of environmental hazards and policies (Jacobson & Adams, 2017; Urquhart et al., 2017). Additionally, attention for stakeholder management and engagement in megaprojects is increasing, but understanding and empirically identifying stakeholder perceptions in preparation of stakeholder dialogue and engagement remains a key challenge for stakeholder management (Cuppen et al., 2016; Yu & Leung, 2015). There is a need for innovative approaches to assess uncertainty in megaprojects (Daniel & Daniel, 2018), and stakeholder analysis approaches are needed that help understand megaproject complexity and stakeholder heterogeneity by empirically investigating stakeholder perceptions (Mok et al., 2015; Yang, 2014). We address these gaps by integrating uncertainty management and stakeholder management research with the objectives to research how perceptions of uncertainty in megaprojects can be identified, how perceptions align or differ within and between stakeholder groups, and how exposing perceptions of uncertainty can add value project management research and practice.

We adopt Q methodology as a stakeholder analysis approach for project management research and practice to reveal perceptions of uncertainty among stakeholders. Q methodology is a mixed method to study subjectivity (McKeown & Thomas, 2013; Stephenson, 1953; Watts & Stenner, 2012). The purpose of Q methodology is to discern patterns among individual perceptions (Van Exel & De Graaf, 2005; Webler et al., 2009). The value of Q methodology has been demonstrated in energy (e.g. Bjørkan & Veland, 2019; Cotton & Devine-Wright, 2011; Díaz et al., 2017), water (e.g. Rittelmeyer, 2020; Snel et al., 2019; Vugteveen et al., 2010), and environmental studies (e.g. Cuppen et al., 2010; Curry et al., 2013; Forrester et al., 2015), and has been applied in only a few project management studies (Cuppen et al., 2016; Gijzel et al., 2020; Koops et al., 2016).

We contribute to (mega)project management research and practice in four ways. First, we propose a definition of perception of uncertainty to broaden the scope and understanding of uncertainties in megaprojects (Section 2.1). Second, we explain the limitations of conventional stakeholder analysis methods in stakeholder management (Section 2.2), and propose the use of Q methodology (Section 3) as a stakeholder analysis tool for stakeholders to evaluate uncertainties, and as a tool to expose stakeholder heterogeneity about perceptions of uncertainty. Third, we provide empirical evidence from a Q methodology application to the A102 highway megaproject in Flanders, Belgium, revealing four perception groups of uncertainty and explaining the Q methodology process step-by-step (Section 4). Fourth, we discuss how project researchers and managers can use the results to advance uncertainty and stakeholder management in megaprojects (Section 5).

5.2. Uncertainty management and stakeholder management in megaprojects

5.2.1. Uncertainty and perceptions of uncertainty

We focus on the concept ‘uncertainty’ instead of its related concept ‘risk’. Uncertainty and risk are often used interchangeably in project management research and practice, but are theoretically different concepts (Atkinson et al., 2006; Koppenjan et al., 2011; P. E. D. Love et al., 2022; Ward & Chapman, 2003). In leading project management guidelines, such as the ISO 31000 standards for risk assessment (ISO, 2009) or the Project Management Institute’s (PMI) PMBOK Guide (PMI, 2021), risk is defined as ‘an uncertain event or condition that, if it occurs, has a positive or negative effect on one or more project objectives’ (PMI, 2021, p. 53). Uncertainty is a general situation of incomplete knowledge and unpredictability that can lead to risk events (Atkinson et al., 2006; Daniel & Daniel, 2018; Perminova et al., 2008; PMI, 2021; Sanderson, 2012).

Based on Knight (1921), risk and uncertainty are distinguished by the ability to assign probabilities to future events or outcomes (Sanderson, 2012). Risks are events that impact project performance of which the probability of occurrence can be statistically quantified based on empirical data from a class of past events (Daniel & Daniel, 2018; Knight, 1921; Sanderson, 2012; Spencer, 1962). Uncertainty is what Knight (1921) calls estimates, a range of possible future outcomes that can be identified but their probabilities cannot be quantified. Risk management techniques in project management mainly rely on statistical models and quantitative probability approaches, which are inadequate to manage uncertainties that are hard to quantify and have a higher degree of incomplete knowledge (Koppenjan et al., 2011; P. E. D. Love et al., 2022). Knight (1921) further distinguishes between reducible and irreducible uncertainties. The former could be (partly) reduced by gathering more information, whereas the latter cannot be eliminated and require different uncertainty management strategies such as preparing for multiple outcomes (Giezen, 2013; Koppenjan et al., 2011; Machiels et al., 2021a). Uncertainty can also be divided into known unknowns and unknown unknowns. Known unknowns are Knight's (1921) estimates, foreseeable uncertainties we know but with unpredictable outcomes, while unknown unknowns are completely unforeseen or unexpected events (De Meyer et al., 2002; Giezen, 2013; Sanderson, 2012).

Following this difference between risk and uncertainty, we consider uncertainty as general situations of incomplete knowledge with multiple possible outcomes that are difficult or impossible to predict and of which the probabilities are non-quantifiable estimates (Atkinson et al., 2006; Daniel & Daniel, 2018; Perminova et al., 2008; Sanderson, 2012; Spencer, 1962). Uncertainty can either be (partly) reducible or irreducible, and either be a known unknown or unknown unknown. Uncertainty is a consequence of complexity in megaprojects, which is defined as project elements that interact, are difficult to manage and hard to quantify, and dynamically change over time in an uncertain way due to vagueness, ambiguity, and a lack of perfect knowledge or data and experience from the past (Daniel & Daniel, 2018; PMI, 2021; Salet et al., 2013). Forecasting the future is further complicated because uncertainties are interrelated, meaning the outcome of one uncertainty can impact others (Williams, 2017; Williams & Samset, 2010).

Estimates of uncertainty and the future are thus more difficult to quantify, but can still be based on data or knowledge. However, estimates about uncertainty involve a higher degree of judgment, which implies situations in which uncertainty is subject-dependent and can be interpreted in different ways (G. M. Winch & Maytorena, 2012; Zandvoort, van der Vlist, Klijn, et al., 2018). Different stakeholders with different interests mean that there are different perceptions of uncertainties, as different individual opinions about the determinants, outcomes, and impacts of various project elements (Lyons & Marsden, 2021). Perception of uncertainty is an important concept for project management because stakeholders make decisions based on their perceptions and judgements (Jahanshahi & Brem, 2017; A. Wang & Pitsis, 2020). Both experts and laypeople cannot accurately predict the outcomes of uncertainties, which means their forecasting efforts are inevitably prone to bias and error (Flyvbjerg, 2013, 2021; P. E. D. Love et al., 2022). Forecasts inform decision-making but are to some extent influenced by the forecaster's perception about the uncertain future, which means perceptions about uncertainty determine decisions made about the scope of uncertainty management, and general megaproject objectives and actions (Böhle et al., 2016; Lehtiranta, 2014; A. Wang & Pitsis, 2020).

Ignoring or misunderstanding different perceptions of uncertainty among stakeholders can lead to conflict in later project phases and a narrow view on uncertainties (A. Wang & Pitsis, 2020; Y. Wang et al., 2021). Hence, uncertainty management must draw on stakeholder management approaches to identify stakeholders' perceptions of uncertainties, in order to anticipate potential conflicts and to broaden the scope of uncertainty management by including multiple stakeholder viewpoints during the ex-ante evaluation of megaprojects.

5.2.2. Stakeholder analysis and engagement in megaprojects

The value of researching perceptions of uncertainty is reflected by the increasing attention in project management research and practice for inclusive stakeholder analysis and engagement. Stakeholder engagement entails communicating with internal and external stakeholders through stakeholder involvement and constructive conflict to make planning and decision-making processes more democratic, collaborative, and transparent (Erkul et al., 2016; Yang et al., 2011). Constructive conflict is 'an open exploration and evaluation of competing ideas and knowledge claims in order to achieve new ideas, insights and options for problem solving' (Cuppen, 2012, p. 26). It requires dialogue and expression of different perceptions among stakeholders (Cuppen, 2012; Cuppen et al., 2016). Stakeholder engagement must be preceded by stakeholder analysis, which entails building a correct view of the heterogenous stakeholder environment and learning about stakeholders by identifying stakeholder interests and concerns (Aaltonen, 2011; Yang, 2014; Yang et al., 2011).

Conventional stakeholder analysis methods to research stakeholder viewpoints are either quantitative or qualitative. Quantitative survey methods rely on a priori assumptions to classify stakeholders (Nost et al., 2019; Vugteveen et al., 2010), reducing the heterogeneity of perceptions into predefined stakeholder categories (Cuppen et al., 2016). Even qualitative approaches such as focus groups are often composed of homogenous groups, with the assumption that such groups will have similar interests and perceptions (Yang et al., 2011; Yu & Leung, 2015). Conventional approaches tend to simplify stakeholders into experts (e.g., project team) versus lay people (e.g. local communities). This can lead to misperceptions about the complex and heterogenous nature of stakeholder interests, values, and perceptions (Cuppen et al., 2016; Urquhart et al., 2017), which can result in conflict during later project phases. Empirical studies in environmental sciences already showed that risk perceptions differ among experts (Urquhart et al., 2017), and among members of local communities (Jacobson & Adams, 2017). Individuals do not simply define their perceptions based on the organization or group to which they belong (Urquhart et al., 2017). Qualitative interviews generate richer information about stakeholder perceptions than surveys, but it is more difficult to structure purely qualitative data and to manage individual perceptions in megaprojects with many stakeholders.

By facilitating the expression of a variety of perceptions, stakeholder engagement about uncertainties can be enriched with the consideration of future outcomes that might otherwise go unnoticed. Hence, an approach is needed for stakeholders to make their perceptions of uncertainties explicit, and for project managers to empirically research stakeholder perceptions to prepare stakeholder dialogue about uncertainties in megaprojects. The approach must allow project managers to structure perceptions into a manageable number of perception groups without simplifying stakeholder complexity. We research the use of Q methodology as a mixed-method to study perceptions of uncertainty in megaprojects.

5.3. Q methodology

Q methodology has received increasing attention from scholars as an approach to research stakeholder perceptions in complex decision-making problems (Eden et al., 2005; Molenveld, 2020), recently also in project management studies (Chantal C. Cantarelli et al., 2021; Cuppen et al., 2016; Gijzel et al., 2020; Koops et al., 2017). Koops et al. (2016) study project managers' perceptions of project success and show how the approach prompts respondents to relate different project success criteria to each other. In a study of sustainability perceptions in tunnel megaprojects, Gijzel et al. (2020) empirically show how the revealed perceptions can explain conflict and raise awareness about different perceptions of sustainability. Cuppen et al. (2016) discuss how revealing perceptions in a Dutch shale gas megaproject helps project managers to anticipate unforeseen stakeholder issues and initiate participation with external stakeholders. They further illustrate that Q methodology generates richer results concerning perceptions than stereotypical assumptions about stakeholders (Cuppen et al., 2016).

Q methodology is a mixed method that was developed by William Stephenson in the 1930s in the field of psychology to study human subjectivity (Stephenson, 1953). Q methodology reveals patterns among individual perceptions of study participants in a structured and systematic way (Molenveld, 2020; Rajé, 2007). Data about a person's perception is gathered through a sorting exercise, referred to as the Q sort. The researchers design a set of statements – in this study uncertainties – that participants must sort during an individual interview on a normal shaped distribution from mostly disagree to mostly agree, or mostly unimportant to mostly important, as shown in Figure 5.1. A factor analysis is then performed to determine which individual Q sorts are correlated. The factor analysis results in a non-predefined number of factors or perception groups, consisting of participants who sorted the statements in a similar fashion and have a similar perception about the topic. A Q methodology application is performed in five steps: (1) the concourse and defining of the set of statements (Q set), (2) the selection of participants (P set), (3) the Q sorting exercise (interviews), (4) factor analysis, (5) and the interpretation of extracted factors (perception groups). The five steps are explained in Section 4. The strength of Q methodology as a mixed method lies in the statistical rigor of the quantitative data from the Q sorts and factor analysis, while also collecting rich qualitative data by asking participants additional questions during the Q sorting exercise (Curry et al., 2013; Jaligot & Chenal, 2019).

The Q-sorting exercise requires respondents to place all statements (uncertainties) on a forced normal-shaped distribution with limited space at the extreme ends of the distribution (Figure 5.1). The hierarchical ordering prevents respondents from simply naming all statements as important or unimportant. It requires respondents to make a thoughtful assessment about all statements, especially the most (un)important ones (Bischof, 2010; Koops et al., 2017; McKeown & Thomas, 2013). In contrast, during interviews or focus groups, respondents might focus only on a few statements or topics, or get lost when asked questions about too many statements or topics. If stakeholders are presented with a broad set of uncertainties, the set likely contains uncertainties that participants might not consider on their own, especially if uncertainty management is not yet a common practice as is the case in many megaprojects (Lehtonen et al., 2017b; Machiels et al., 2021a). Participation in the Q-sorting exercise itself facilitates learning about a complex topic among participants (Curry et al., 2013). The Q-sorting format also ensures that respondents do not express their viewpoint about isolated statements, but about all statements presented to them as one set (Bischof, 2010). The distribution shape forces respondents to make trade-offs between the relative importance about the statements presented to them, contrary to Likert-scale surveys and questionnaires, where all items are scored individually and independent of each other. The distribution shape also allows respondents to visually group items close together, which gives them an opportunity to consider relationships between statements, as has been shown in previous studies (Koops et al., 2016; Koops et al., 2017).

Previous studies have extensively demonstrated Q methodology as an approach for stakeholder analysis and engagement. Q methodology does not make use of predefined stakeholder types or stereotypes to group or classify stakeholders (Durose et al., 2016; Robbins & Krueger, 2000). Stakeholders express their perceptions when performing the Q sort, after which all Q sorts are subjected to factor analysis to reveal perception groups of stakeholders with similar perceptions. Perception groups are based on similarities between individual perceptions, rather than similarities between sociodemographic characteristics of stakeholders (Cuppen et al., 2016; Rajé, 2007). This helps to understand heterogeneity of stakeholder viewpoints in situations that are more complex and nuanced than simply proponents versus opponents (e.g., Ellis et al., 2007; Nost et al., 2019). Because all respondents use the same distribution during the sorting interview, patterns among perceptions can be revealed in a structured and statistical way. Q methodology results can be used to prepare stakeholder dialogue and engagement, and facilitate learning among stakeholders about other viewpoints if the revealed perception groups are shared among all stakeholders. The results furthermore help identify areas of conflict and consensus, and anticipate stakeholder issues or concerns (Cotton & Devine-Wright, 2011; Díaz et al., 2017; Raadgever et al., 2008).

We now apply Q methodology to the early phase of an actual megaproject to empirically validate the use of Q methodology as a stakeholder analysis approach for project management to study stakeholder perceptions of uncertainty.

5.4. An application of Q methodology in megaprojects

We first introduce the A102 highway megaproject, after which we describe how the five Q methodology steps were applied in this study. Additionally, we explain how the results were disseminated among stakeholders and what the follow-up steps of this research are. Additional information about each step can be found in Appendix 3.

5.4.1. Single case study: The A102 highway in Flanders

Because uncertainties and stakeholders are specific to each megaproject, perceptions of uncertainty are difficult to research for megaprojects in general. Megaprojects must be understood within their own specific context (Ahiaga-Dagbui et al., 2017). We therefore adopt a single in-depth case study approach, an empirical method to research complex issues such as megaprojects in depth (Flyvbjerg, 2006; Yin, 2018), to provide evidence of how perceptions of uncertainty can be identified.

The A102 is a six kilometres long planned tunnel road infrastructure project east of Antwerp, the largest city in Flanders. The tunnel has an early estimated construction cost of at least 1 billion Euros, a time horizon of at least a decade, and will cross multiple municipal borders. We are engaged in the A102 project as part of a larger research project to advise the project team and stakeholders on coping with uncertainties. The A102 is part of a portfolio of transport infrastructure, environmental and urban development projects with the objective to improve the accessibility and liveability of the Antwerp metropolitan region. The A102 is the largest of several infrastructure projects along the R2 ring road – or 'Port Route' – north of Antwerp. The objective of the Port Route is to become the main access point for the Port of Antwerp and to divert traffic away from the highly congested Antwerp city ring road (R1).

The Flemish Government is the decision maker who officially initiated the A102 project in December 2020. This marked the start of the project's research and planning phase, the ex-ante evaluation during which alternative plans for the A102 are developed, researched, and compared using instruments such as a social cost-benefit analysis and an environmental impact assessment. The Q methodology application was performed between August 2020 and April 2021, and the Q sorting interviews were conducted in January and February 2021. This gave us the opportunity to identify perceptions of uncertainty in an early-phase megaproject to prepare further stakeholder dialogue about uncertainties during the project's research and planning phase. All Port Route infrastructure projects have a strong collaborative component. General stakeholder sessions are organized each year to inform stakeholders about the Port Route's progress. These sessions involve about 100 people who represent municipal governments, citizen groups, Flemish government administrations, and private sector interest groups.

5.4.2. Step 1: The concourse and the identification of uncertainties (Q set)

The first step of a Q methodology application is constructing the concourse and the Q set. The concourse is a term used in Q methodology to describe a longlist of statements that captures the existing discussions, debates, expressions of perspectives, and discourses about the research topic (Van Exel & De Graaf, 2005; Webler et al., 2009). In our study, the concourse is a longlist of individual expressions and statements about the A102 that can be interpreted as uncertainties – project elements for which there are different opinions about the determinants, outcomes, and impacts on the A102. The main source from which we deducted statements was an open question survey organized by the Port Route stakeholder session's chairmen in 2018. The survey was completed by 58 stakeholders. Other sources used to define the concourse were newspaper articles, reports and minutes from the general stakeholder sessions, and previous planning and policy documents about the A102. Academic literature was used to define additional uncertainty statements relevant for the A102. A concourse is complete when a saturation point is reached and statements become repetitive (Eden et al., 2005). The concourse consisted of 194 statements, and is included in Appendix 3.

Next, the concourse was aggregated into the Q set, the final list of statements for participants to sort (Webler et al., 2009). It is important to have a workable number for participants to sort, while keeping a valid set of uncertainties that represents all statements from the concourse. This was done with structured sampling and axial coding by designing a matrix with uncertainty types as columns and project elements as rows. The rows and columns were inductively created, and a row or column was added when a new uncertainty type or project element came up from the concourse. Once all statements were sorted in the matrix according to uncertainty type and project element, we had an overview of uncertainties about similar topics that were placed in the same cell. Next, we aggregated and reformulated similar uncertainties into a smaller number of uncertainties for the Q set. This way, the Q set remains a valid representation of the concourse. We chose general descriptions for the uncertainties that do not include assumptions about the determinants, outcomes, and impacts of the uncertainties. This way, we avoid manipulation by the researchers of the participants' perceptions of uncertainty.

The first author defined the Q set. Next, the Q set was refined during a discussion with all authors, resulting in a Q set of 28 uncertainties. Five pilot Q sort interviews were conducted to validate the Q set. The pilot interview participants were familiar with the project context but only one was a project stakeholder. This allowed for an outside perspective about the composition of the Q set. According to the participants, the Q set was comprehensive, but some uncertainties required rephrasing or clarification. Adjustments were made and discussed by all authors to generate the final Q set of 28 uncertainties (Table 5.1). The uncertainties are thus phrased by the researchers, but they are drawn from sources that reflect the stakeholders' combined visions about uncertainties and concerns.

The uncertainties were grouped into five uncertainty types that were deductively identified during the analysis of the concourse. The Q set contains 11 market and transport uncertainties, four technical uncertainties, four political and policy uncertainties, six societal and stakeholder uncertainties, and three environmental impact uncertainties. These uncertainty types are frequent in megaproject studies (Machiels et al., 2021b; Priemus, 2010; Salet et al., 2013). The ratio of uncertainty types in the Q set is similar to the ratio of uncertainty types in the concourse, which explains the higher number of market and transport uncertainties. It became apparent from the concourse that there are important differences (in opinion) between uncertainties about modal split and general traffic evolution, and passenger and freight transport, which is why these were defined as separate uncertainties. In contrast, the impact of the A102 on its spatial, human, and ecological environment was aggregated into one uncertainty because these elements were never explicitly distinguished in the concourse, but always named as part of impact on liveability.

5.4.3. Step 2: Selection of participants (P set)

The second step is selecting participants (P set) to perform the Q sorting exercise. Large numbers are not required to generate statistically valid results (Watts & Stenner, 2012). Participants in a Q methodology application are selected through purposive sampling (Sneegas et al., 2021), which means they are selected because they have a clear viewpoint that is significant in relation to the research topic (Van Exel & De Graaf, 2005; Watts & Stenner, 2012). As Eden et al. (2005, p. 417) state, 'participants are chosen for comprehensiveness and diversity, rather than representativeness or quantity'. Participants in our study were selected based on two criteria: they are regular participants in the Port Route's general stakeholder sessions; and they represent a stakeholder internally involved in the planning process (e.g. project team members), or a stakeholder that could be impacted by the A102 project (e.g. citizens, municipalities, or interest groups). The P set included 32 stakeholders: four interest groups, 11 citizen groups, nine municipalities, and eight project team members who represent Flemish or provincial government administrations. Interest groups are private stakeholders such as economic actors (e.g. the Port of Antwerp) or environmental associations. Citizen groups are local citizens who organize themselves as representatives of a place related to the project area. Municipalities were represented by either the mayor, an alderman, or a senior official.

Table 5.1. *Q set, list of A102 uncertainties*

**Oosterweel is a multi-billion road infrastructure project to close the R1 ring road in Antwerp. Construction is planned from 2020 to 2030. It highly influences mobility and other (infrastructure) projects in the Antwerp region.*

No.	Item. Uncertainty about…	Uncertainty type
1	the evolution of the modal split of passenger transport in the Antwerp region	Market and transport
2	the evolution of the modal split of freight transport in the Antwerp region	Market and transport
3	the evolution of passenger transport on the Antwerp ring road	Market and transport
4	the evolution of freight transport on the Antwerp ring road	Market and transport
5	the societal necessity of the A102	Societal and stakeholder
6	the societal support for the A102	Societal and stakeholder
7	the composition of future political administrations	Political and policy
8	the political priority of the A102 compared to other policies and projects	Political and policy
9	the effect of Oosterweel* on transport in the Antwerp region	Market and transport
10	the effect of the A102 on the modal split in the Antwerp region	Market and transport
11	the effect of the A102 on passenger transport demand	Market and transport
12	the effect of the A102 on freight transport demand	Market and transport
13	the impact of the A102 on its direct spatial, human, and ecological environment	Environmental impact
14	the effect of the A102 on economic growth	Market and transport
15	the effect of toll roads on transport demand (on the A102)	Market and transport
16	the effect of the A102 on the underlying road infrastructure network	Market and transport
17	the correct completion of legal and administrative procedures	Societal and stakeholder
18	the availability of financial resources for the A102	Political and policy
19	the availability of financial resources for liveability projects in the context of the A102	Political and policy
20	scope changes because of additional requirements of stakeholders	Societal and stakeholder
21	reaching consensus with all stakeholders	Societal and stakeholder
22	the sum of the societal costs, benefits, and effects of the entire Port Route	Societal and stakeholder
23	the construction time of the A102	Technical
24	the impact of the A102 on reaching climate goals	Environmental impact
25	the environmental impact during the construction of the A102	Environmental impact
26	the technical feasibility of the joint construction of the A102 and the second freight rail line.	Technical
27	the cost of an A102 tunnel constructed with a tunnel-boring machine	Technical
28	the route choice and connection of the A102 with existing road infrastructure	Technical

5.4.4. Step 3: Q-sorting interviews

The third step is the Q-sorting interview, during which participants were asked to rank the 28 uncertainties on a forced nine-point normal distribution from mostly unimportant (−4) to mostly important (+4) by answering the question 'which uncertainties do or do not have an important impact on the A102 decision-making?' (Figure 5.1). Importance (or unimportance) was clarified as whether the respondent believed the uncertainty of a project element has a large (or small) influence on decision-making and project objectives, and therefore whether its uncertain determinants, outcomes, or impacts (do not) must be part of the scope of uncertainty management of the project. Similar to the uncertainties in the Q set, the question for the participants was broad and excluded expressions of project goals or objectives. The interviews were conducted shortly after the initiation of the project's research and planning phase, when the stakeholder and project ambitions, and the project (research) scope were not yet clear or formalized. A broad question can help gain insight in stakeholder positions and can help adopt a broad view about uncertainties, and the project ambitions and scope of the research and planning phase.

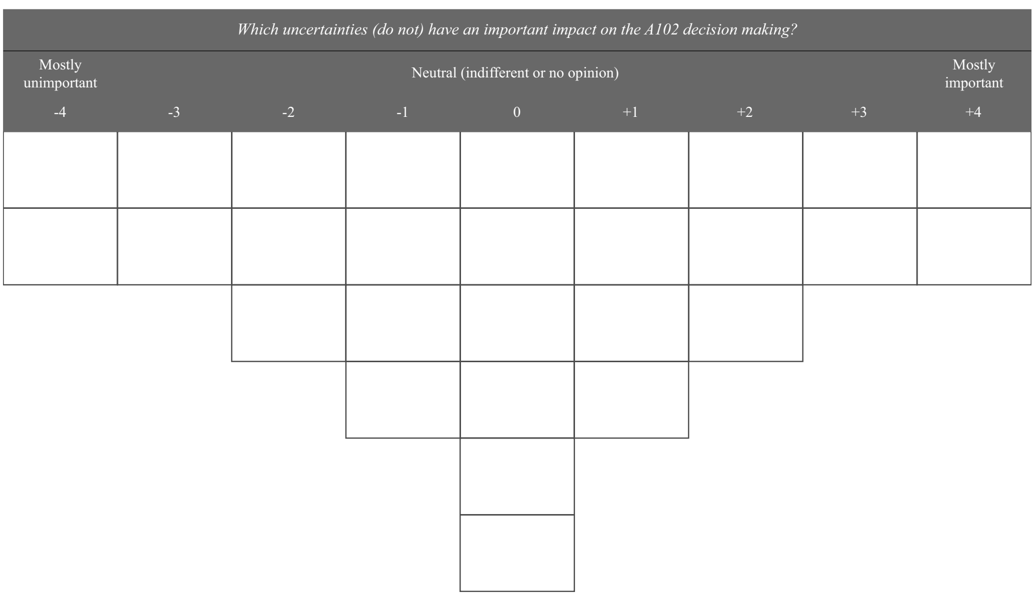


Figure 5.1. *Forced normal shaped distribution to perform the Q sort*

The Q sorts were performed during 32 individual face-to-face interviews, either physically with uncertainties printed on cards or during a video call with an Excel spreadsheet. There were no significant differences in the process or results between physical or digital interviews. The sorting procedure was performed in three steps. Respondents were first asked to assess the degree of uncertainty for each item on a scale from 1 (certain) to 5 (uncertain) to familiarize them with the 28 uncertainties. Respondents then pre-sorted the uncertainties into three groups – unimportant, neutral, and important – after which each group was further sorted on the distribution. When the Q sorts were completed, respondents were asked questions about the final ranking to collect additional qualitative data. Stakeholders were asked to explain their sorting choices, primarily about the uncertainties sorted at the extreme ends (−/+4 to −/+2). As a closing question, respondents were asked whether they believed other important uncertainties were missing from the Q set. This allowed for additional uncertainties to emerge, and served as an additional validation check of the Q set. New uncertainties were only mentioned by five participants, and they can all be considered as related to uncertainties from the Q set. A possible explanation for the few additional uncertainties identified could be that participants were already mentally fatigued after the sorting exercise. Another explanation could be that participants simply lacked creativity or a broader understanding of uncertainty to identify more uncertainties beyond the list of 28, which could be due to the general lack of attention for uncertainties and experience with uncertainty management in Flemish megaprojects.

5.4.5. Step 4: Factor analysis (results)

The fourth step is the statistical factor analysis, for which the free software Ken-Q Analysis was used (Banasick, 2019). Extracted factors are distinct perception groups of uncertainty, composed of participants who performed the Q sort similarly. All 32 Q sorts were valid and were used in the analysis. Factor analysis was performed with Principal Component Analysis (PCA), a standard technique for factor analysis in Q methodology applications (Watts & Stenner, 2012; Webler et al., 2009). After performing PCA, we applied varimax rotation. Varimax rotation shifts the perspective but not the consistency or relationships between the Q sorts, to ensure that each Q sort highly correlates with only one factor (Van Exel & De Graaf, 2005; Watts & Stenner, 2012; Webler et al., 2009). The extent to which a participant correlates with each factor is determined by the factor loading of the Q sort, ranging from 1 (positive correlation) to 0 (no correlation), and to −1 (negative correlation) (Watts & Stenner, 2012; Webler et al., 2009).

It is up to the researcher(s) to decide how many factors to retain for further analysis. There is no single optimal statistical solution. A good factor solution is statistically valid and theoretically significant based on the quantitative and qualitative data (Watts & Stenner, 2012). There are statistical criteria and guidelines that help determine a good factor solution (see Table 5.2). We experimented with various factor solutions. A solution with five or more factors was not statistically valid. A three-factor and four-factor solution were statistically valid, with statistical criteria in favour of and against each factor solution, as shown in Table 5.2.

Two factors were similar in the three- and four-factor solution. The third factor in the three-factor solution was split into a third and fourth factor in the four-factor solution (P1 and P3 in Table 5.3). Based on a first reading of the interview transcriptions of the P1 and P3 stakeholders, it became apparent that the viewpoints were significantly

Table 5.2. *Statistical criteria to determine how many factors to extract (For this study, a check mark means the factor solution satisfies the statistical criterion. An 'x' means the factor solution does not satisfy the statistical criterion)*

Statistical criterion	Explanation	A102 three-factor solution	A102 four-factor solution
Kaiser-Guttman criterion	Select only factors that have Eigenvalues > 1 (Watts & Stenner, 2012).	✓	✓
Two pure loadings	Select only factors that have two or more significantly loading Q sorts at the P < 0.01 level (Brown, 1980; Watts & Stenner, 2012). A significant factor loading = 2.58 * (1/√(no of items in Q set))	✓	✓
Humphry's rule	Select only factors if the cross-product of their two highest loading Q sorts exceeds twice the standard error (Brown, 1980; Watts & Stenner, 2012). The standard error = 1/√(no of items in Q set)	✓	✓
Factor correlations	Select only factors for which the correlation with factors is lower than the threshold of significance at P < 0.01 (Watts & Stenner, 2012).	×	✓
Factor variance	Select only factors that have a variance > 3 (Minkman & Molenveld, 2020; Webler et al., 2001).	✓	✓
Cumulate factor variance	Select a solution that has a total variance of 35–40% or higher (Watts & Stenner, 2012).	✓	✓
Cattel's Scree test (only with PCA)	The Eigenvalues of a maximum factor solution (eight factors) are plotted. The point at which the slope of the line connecting the Eigenvalues changes indicates the number of factors to extract (Watts & Stenner, 2012).	✓	×
Simplicity	Fewer factors are better, as the viewpoints at issue are easier to understand. Simplicity should not be taken too far. This might lead to losing interesting information or viewpoints (Webler et al., 2009).	✓	✓
Clarity	The best factor solution is one with a minimum number of non-loaders (participants who do not load significant on any factor) – and confounders (participants who load significant on multiple factors) (Webler et al., 2009).	✓	×
Distinctness	Lower correlations between factors are better. Highly correlated factors mean similar viewpoints (Webler et al., 2009).	×	✓
Stability	Good factors are those with a group of respondents that occur in various factor solutions. This indicates those participants really share a perception (Webler et al., 2009).	✓	✓

different between stakeholders from P1 and P3. The quantitative data also showed that correlations between factors were lower in the four-factor solution, meaning the factors are more distinctive. Therefore, the four-factor solution was retained. Table 5.3 provides a statistical summary of the four factors. Twenty-eight of the 32 Q sorts loaded significantly on one of the four perceptions. There were two non-loaders – Q sorts that do not load significantly on any factor – and two confounders – Q sorts that load significantly on more than one factor. Three different stakeholder types align with perception groups 1, 2, and 3. Perception group 4 represents respondents from each stakeholder type.

Table 5.3. *Statistical summary of the four extracted perceptions of uncertainty*
[a] *Significant at the $P < 0.01$ level, which means all Q sorts load significantly on the $P < 0.01$ level.*
[b] *Significant at the $P < 0.05$ level; seven Q sorts load significantly at the $P < 0.01$ level, two Q sorts load significantly at the $P < 0.05$ level*

	Number of respondents	P1 [a]	P2 [a]	P3 [a]	P4 [b]	Number of non-loaders	Number of confounders
Interest groups	4	0	0	2	2	0	0
Citizen groups	11	2	5	1	2	0	1
Municipalities	9	1	3	2	2	1	0
Flemish and Provincial government administrations	8	2	1	0	3	1	1
Total			5	9	5	9	2
Eigenvalue		4,48	5,12	3,84	5,12		
Variance		14%	16%	12%	16%		
Cumulative variance		14%	30%	42%	58%		

Confounders were excluded before the final extraction of the factors to avoid higher correlations and similarity between factors. Confounders are respondents that align with more than one perception group (Koops et al., 2016; Nost et al., 2019). To not lose the perspectives of the confounders altogether, the qualitative data gathered during their interviews was used after the factor analysis to aid the interpretation of the perception groups (factors) with which they significantly correlate.

Non-loaders were excluded from the analysis altogether, which is standard practice in Q methodology (Sneegas et al., 2021). Excluding non-loaders means their perceptions are not further considered when the factors are interpreted. We analysed the interview transcriptions of the non-loaders, from which we learned that their perceptions do not deviate entirely from the four perception groups. They are excluded from factor interpretation, but the perception groups are not entirely unrepresentative for the non-loaders' perceptions.

5.4.6. Step 5: Factor interpretation

Three sources were used to interpret and compare the four perception groups. First, the factor analysis generates a factor array for each factor, an idealized Q sort that represents the viewpoint of a factor as the weighted average of its individual Q sorts (McKeown & Thomas, 2013; Watts & Stenner, 2012). Second, three statement types were used to understand each perception (Van Exel & De Graaf, 2005; Webler et al., 2009): characterizing statements are uncertainties scored most (un)important (−4/+4); distinguishing statements are uncertainties that were sorted significantly differently than in other factors; consensus statements are uncertainties that were sorted similarly across all factors. Third, qualitative data collected during the Q-sorting interviews was used to interpret each perception, and were coded and analysed in NVivo. A simple codebook was defined a priori based on the structure of the interview transcripts and the factory analysis results, including a code for each uncertainty (28 codes), a code for each factor (four codes), and one code for all uncertainties mentioned by participants during the interviews that were not part of the Q set. For each factor, a short narrative was written based on interview sections that were coded on the most (un)important uncertainties of each factor (−/+4 to −/+2), and based on summarizing sections coded on the factor codes. Interview sections that were coded on two or more uncertainties helped understand how stakeholders perceive relationships between uncertainties in the sense that an uncertainty might impact or influence the outcome of other uncertainties.

We describe the perception groups by referring to the uncertainty number in the Q set and its score on the factor array of that perception as '(statement number, score)'. Table 5.4 gives an overview of the sorting patterns of uncertainty types for each perception.

Table 5.4. *Sorting patterns of uncertainty types for the factor arrays (U = unimportant, sorted −4 to −1; N = neutral, sorted 0; I = important, sorted +1 to +4)*

	Perception 1			**Perception 2**			**Perception 3**			**Perception 4**		
11 market and transport uncertainties	U	N	I	U	N	I	U	N	I	U	N	I
4 technical uncertainties	8	2	1	2	3	6	6	4	1	7	2	2
4 political and policy uncertainties	2	1	1	3	0	1	1	0	3	3	0	1
6 societal and stakeholder uncertainties	1	1	2	3	0	1	1	1	2	0	0	4
3 environmental impact uncertainties	0	1	5	3	1	2	2	1	3	0	2	4

Perception group 1: Uncertainty about liveability as a driver for legal action

There is a relation between the six most important uncertainties in the first perception. Uncertainty about legal action is considered as one of the most important sources of uncertainty, significantly affecting decision-making as legal action could delay decision-making or block the project (17, +4). Stakeholders believe the degree of legal action depends on the availability of funding for liveability projects in addition to the A102 infrastructure (19, +4). Because the funding for liveability projects is considered highly uncertain, the long-term environmental impact (13, +3) and the impact during construction (25, +2) are also perceived as highly uncertain and important. Respondents expect citizen groups to demand serious investments in liveability as compensation for the A102 infrastructure. If funding levels do not meet these expectations, finding consensus about the A102 may be difficult (21, +3), societal support for the project will decrease (6, +2). In turn, there might be an increase in the chance of legal action from opponents. At the other extreme of Perception 1, the seven most unimportant uncertainties are all market and transport uncertainties. Transport uncertainties are believed to be less important because traffic models can calculate traffic evolution (1, −4; 2, −2; 10, −2) and the effect of new infrastructure on traffic (11, −4; 12, −3; 9, −3).

To summarize Perception group 1, societal and stakeholder uncertainty, political uncertainty, and environmental impact uncertainties are perceived as uncertainties that influence each other and that are most determinant for decision-making about the A102, while market and transport uncertainties are expected to impact decision-making to a lesser extent. Uncertainty about available funding for liveability projects as compensation for the A102 infrastructure increases uncertainty and concern about environmental impacts, which may decrease societal support and stakeholder consensus, which in turn may lead to more legal action. Stakeholders of perception group 1 will pressure decision-makers to ensure the environmental impact receives sufficient attention and funding.

Perception group 2: Potential project redundancy driven by future modal split uncertainty.

The most important uncertainties in Perception group 2 are market and transport uncertainties. The ranked uncertainties are related and include the evolution of the modal split for passenger (1, +4) and freight traffic (2, +3), and the effect of the A102 on the modal split (10, +2) and the underlying road network (16, +3). Respondents believe the modal split is a relatively new concept that is difficult to predict with traffic models, especially the behaviour and transport mode choices of individuals. Respondents also believe the effect of the A102 on the underlying road network is difficult to predict, with different opinions between stakeholders of Perception 2. The modal split uncertainties are important because an evolution of the modal split towards less passenger or freight road transport might make the A102 unnecessary. From another perspective, respondents believe the A102 conflicts with the 50−50 modal split objective for the Antwerp metropolitan region, because new road infrastructure increases car and truck use due to induced demand.[1] As within in Perception group 1, the long-term environmental impact of the A102 is a major concern (13, +4), again related to the availability of funding for liveability projects (19, +2). Respondents are concerned that the A102 may be so expensive that little funding may be left for liveability projects.

The two most unimportant uncertainties are the construction time (23, −4) and the cost price of the A102 (27, −3). These can be estimated with high accuracy and should not have an influence on decision-making. If the project is good, delays are not a problem, and the cost price should not be important. Respondents also believe politicians will not have a great deal of influence on the project (7, −4; 8, −2). Politicians will simply base their decision on the societal support for the project. Lastly, the effect of the A102 on

1 50−50 modal split means 50% of passenger trips are made by privately owned cars, and 50% are made by alternative modes (e.g., bike, public transport, walking, car-sharing).

the economic growth (14, −3) and the effect of toll roads (15, −2) on traffic levels in the A102 tunnel are considered irrelevant for the A102.

To summarize perception group 2, politics, construction time and cost price uncertainties are less determinant for decision-making. The most important concern is the environmental impact of the A102, while the most important question or uncertainty is whether new road infrastructure is really needed, depending on how various uncertainties of traffic volumes and the modal split will evolve. Stakeholders of perception group 2 could be critical about traffic-model forecasts, and opponents might challenge traffic forecasts.

Perception group 3: Technical and cost uncertainties influence project impact and design

Three of the four most important uncertainties of Perception group 3 are technical uncertainties because they will determine the long-term impact of the A102 on its environment (13, +3) and the A102's effect on the underlying road network (16, +2). These effects are primary concerns and important uncertainties because design choices and the construction method – such as the connection of the A102 to existing infrastructure (28, +4) – are still uncertain and are expected to the most debated issues. There are contrasting opinions about whether the A102 should have additional intermediate entrance and exit points. This decision will influence the construction method, either a cut-and-cover tunnel or a construction with a tunnel boring machine. Many stakeholders favour a deeper boring alternative because a cut & cover requires a trench to be excavated, destroying open green space. Respondents however fear a boring alternative may be too expensive and believe the Flemish Government may choose the cheaper cut-and-cover alternative, which is why the yet to be estimated boring alternative's cost price is an important uncertainty (27, +4). There is also a lot of uncertainty about a federal freight rail tunnel project planned along the same route as the A102 (26, +3). A decision in one project might limit the construction possibilities of the other. Aside from technical discussions, uncertainty about the societal necessity (5, +2) and societal support (6, +2) for the A102 are important because many stakeholders are not yet convinced of the A102's necessity, especially stakeholders in the direct environs of the A102. The lowest ranked uncertainties include various types and are unimportant because they are either not considered uncertain and can be eliminated or calculated, or the A102 does not affect these project elements.

To summarize perception group 3, the main discussions are about technical issues that are related to environmental concerns. The outcomes of these discussions are still uncertain but will be decisive for the environmental impact of the A102 and the effect on the underlying road network. With perception group 3, project managers have a better view of how technical decisions and design choices may influence stakeholder positions, with conflicting opinions inevitably leading to 'winners' and 'losers'.

Perception group 4: Uncertainty about societal and political support drive the project priorities

The fourth perception group prioritizes societal and stakeholder uncertainties, and political and policy uncertainties, with eight of the highest ranked uncertainties. Respondents believe the search for societal support will remain a difficult task throughout the entire project (5, +4) and could block the project. Reaching a consensus with every stakeholder is considered impossible (21, +2), but consensus with a large group of stakeholders will increase societal support. Research must still prove whether the A102 is necessary (6, +3), and these results will directly influence the degree of support for the project. Even when the research is completed, the societal necessity of the A102 will still be questioned by several stakeholders. Next to societal support, the A102 is also dependent on political support, with doubts among respondents about the political priority of the A102 (8, +4) and the availability of funding for the A102 infrastructure (18, +3). Antwerp has already been given nearly five billion Euro (2020 price level) until 2030 for the construction of Oosterweel and liveability projects around the R1 ring road. In addition, the A102 has fallen down the list of transport investment priorities, mainly due to a lack of societal support in the past. Construction of the A102 will not begin sooner than 2030, when the Oosterweel will be completed. Respondents believe politicians in 2030 may have no further interest in the A102.

Three of the most unimportant uncertainties are technical ones, along with uncertainty about the environmental impact during construction, followed by market and transport uncertainties which fill up columns −2 and −1. The respondents believe technical issues can be solved, market and transport uncertainties can be eliminated with models, and the environmental impact during construction can be calculated, mitigated, and controlled.

To summarize perception group 4, the realization of the A102 will depend on various related political and policy, and stakeholder and societal uncertainties, including the degree of societal support, if research can prove its societal necessity. It will also depend on how long transport investments in the Antwerp metropolitan region will receive political priority and public funding from the Flemish Government.

Comparison of the four perceptions

Table 5.3 shows that none of the perception groups is dominated by a single stakeholder group, and that none of the stakeholder groups only align with one perception group. Each perception group has representatives from at least three stakeholder groups. Citizen groups and municipalities appear in all four perception groups, while regional government administrations and interest groups appear in respectively three and two perception groups. The results further show that 'experts' (project team members) and 'lay people' (citizen groups) can share views about uncertainties, while views can also differ among experts and among local communities. A possible explanation for differing perceptions between local municipalities are the different political coalitions that are in office in each municipality. Similarly, there are 11 citizen groups that represent different places and therefore different interests. Even the differences in opinion between project team members should not be surprising because they represent different government administrations. This shows that stakeholder perceptions are heterogenous and not simply based on the stakeholder group they represent. Perceptions can differ both between and within stakeholder groups.

Table 5.4 gives an overview of the sorting patterns of each perception group. The factor arrays show patterns of one or two uncertainty types on at least one end of the grid. Uncertainty about the long-term impact of the A102 on the human, spatial, and ecological environment was always ranked among the three most important uncertainties. Impact uncertainties in the first three perceptions were ranked high in combination with another uncertainty type: societal and stakeholder uncertainties in perception group 1, market and transport uncertainties in perception group 2, and technical uncertainties in perception group 3. Market and transport, and technical uncertainties were only ranked as important in perceptions groups 2 and 3 respectively. Perception group 4 differs from the other ones with the combination of highly ranked political and policy uncertainties, and societal and stakeholder uncertainties. Finally, the narratives and Table 5.4 show that the uneven representation of uncertainty types does not impact the results. The 11 market uncertainties do not dominate the perceptions, contrary to the three environmental impact uncertainties that rank highly in perception groups 1, 2, and 3.

5.4.7. Dissemination of the results among stakeholders and follow-up steps

We wrote a report about the Q methodology application and study results that was disseminated among all members of the Port Route's general stakeholder session. We also presented the results at a meeting with the project team members (April 2021) and a general stakeholder session (November 2021). We will continue our collaboration with the project team, and the set of uncertainties and the revealed perception groups will be used as input for workshops with project team members and stakeholder session members. During the workshops, we will give room for stakeholders to identify additional uncertainties; collaboratively assess the determinants, outcomes, and potential impacts of uncertainties through qualitative and quantitative methods; further explore the relations between uncertainties; and develop flexible decision-making strategies under uncertainty. These follow-up steps will be formalized in an official project document that defines the scope of the ex-ante evaluation. We hope this will help project managers and decision makers to make more informed decisions that show increased awareness of megaproject uncertainties.

5.5. Discussion

5.5.1. Implications for uncertainty management and stakeholder management in megaprojects

Understanding perceptions of uncertainty broadens uncertainty management in various ways. First, the narratives of each perception group show that stakeholders perceive uncertainties as a dynamic network with relations between uncertainties. Because of complexity, the future is an outcome of the interactions between uncertainties. For example, transportation uncertainties in perception 2 all contribute to the outcome of an overlaying uncertainty: traffic volumes and the consequential necessity of new infrastructure. In perception 1, relations between important uncertainties act more as a chain reaction, in which currently uncertain political decisions about funding for liveability will determine concerns about environmental impact, which will impact stakeholder consensus and in the end the extent of legal action. Because of megaproject complexity, uncertainty management must keep a broad perspective of the larger dynamic network of interrelated uncertainties and uncertainty types. This requires going beyond individual iron triangle criteria (impact on schedule, cost, benefit) as is often the case in risk management (Lehtonen, 2014), and paying attention to general sources of incomplete knowledge such as environmental externalities, political decision-making, multiple drivers of traffic outcomes in transportation infrastructure, stakeholder consensus and support, and overall societal utility of megaprojects. Approaching uncertainty through systems or network thinking can facilitate thinking about encompassing and strategic approaches to manage complexity and uncertainty (Williams, 2017; Williams & Samset, 2010). Q methodology is a good approach to gauge stakeholders' understandings of relations between uncertainties. The structured approach facilitated stakeholders to keep an overview of all the uncertainties they had to sort, and avoided that participants would only focus on a handful of individual uncertainties.

Second, whether an uncertainty is reducible or irreducible can also be perceived differently. In some perception groups, for example, technical uncertainties, market uncertainties, or environmental impact uncertainties are considered as knowledge gaps that can be reduced through modelling and studying, while in other perceptions, stakeholders are less convinced that outcomes can be understood before an outcome occurs. So, not only estimating the future involves judgement, also assessing whether or to what extent an uncertainty can be reduced, and determine how it should be managed, involves judgment. Developing strategies to manage uncertainties requires the consideration of multiple viewpoints to consider a wide range of future outcomes and possible strategies to manage uncertainty. Accepting that estimating the future or assigning probabilities to future outcomes in megaprojects involves judgment and is therefore prone to bias and error is a condition to better prepare megaprojects for uncertain changes.

For stakeholder management, the results show that stakeholder analysis in megaprojects should not rely on a priori assumptions about stakeholder types, but it must try to understand stakeholder heterogeneity. The composition of each perception group shows that there are differences in opinion between and within stakeholder groups. Revealing perceptions of uncertainty also serves as a predictor for conflict. It became clear during the interviews that a stakeholder's most important uncertainties will likely become the stakeholders' scope of attention during project discussions. Understanding these perceptions can help project managers to gain insights into conflicting opinions about uncertainties, and project desirability and feasibility, which is important information to prepare stakeholder dialogue about uncertainties and improve stakeholder management and inform decision-making. Project management research should be aware of the limited ability of conventional stakeholder analysis methods to understand stakeholder heterogeneity. Q methodology is a valuable stakeholder analysis tool that can be used in project management research and practice to allow stakeholders to make their perceptions about a topic explicit in an accessible way, and to reveal stakeholder heterogeneity.

5.5.2. Research limitations

Our empirical study has several research limitations. First, this study did not include a long term evaluation of the Q methodology results, which would unveil potential drawbacks of Q methodology and differences between perceived uncertainties and actual impacts of uncertainties. Second, the results are a snapshot of uncertainties and perceptions of uncertainty at a specific point in time. Uncertainties and stakeholder views are dynamic. Some uncertainties may be (partly) resolved with new information while new uncertainties may arise at different moments during a megaproject (Machiels et al., 2020). New stakeholders may enter the arena in later project phases – such as contractors, engineers and designers, financiers, or new citizen groups – and stakeholder positions and perceptions might shift throughout a project. Uncertainty assessments should be initiated as early as possible but must also updated frequently with new insights during different project phases. More empirical research is needed on how uncertainties and stakeholder perceptions of uncertainty evolve during different megaproject phases, for example, by replicating the Q methodology study at later moment during the project. Third, the study is a single case study and the revealed perceptions themselves must not be generalised and must be understood within the specific context of this Flemish infrastructure project. Finally, this study has only evaluated known unknowns or foreseeable uncertainties, uncertainties that we can identify but which have unpredictable outcomes. More research is still needed about methods to help megaprojects cope with unknown unknowns, such as adaptive or flexible approaches.

5.6. Conclusion

High complexity in megaprojects leads to uncertainty that makes forecasting the future prone to bias and error, and different perceptions of uncertainty among stakeholders. Understanding perceptions of uncertainty through stakeholder analysis must be a part of uncertainty management because these perceptions determine the scope of uncertainty management and influence megaproject decision-making. We integrated uncertainty management and stakeholder management by using Q methodology as a mixed method for stakeholder analysis to study perceptions of uncertainty. An empirical application of Q methodology revealed four distinct perception groups among 32 stakeholders in the A102 megaproject. The key findings from this study are: (i) uncertainty management must be broadened by considering uncertainties as a dynamic network with relations between uncertainties; (ii) assessing whether uncertainties are irreducible or reducible and consequently how they should be managed can be perceived differently and involves judgement; (iii) stakeholder analysis must aim to understand stakeholder heterogeneity and avoid classifying stakeholders based on a priori assumptions; and (iv) revealing perceptions of uncertainty can help project managers anticipate conflict and better prepare for stakeholder dialogue and engagement.

Further research is needed about how revealing perceptions can be used to facilitate stakeholder dialogue and engagement about uncertainties; to initiate a process of learning among stakeholders about uncertainties in future forecasts, and to study how this process impacts uncertainty management, and planning and decision-making over the duration of a megaproject. Further research is also needed to better understand relations between uncertainty through network or systems thinking, and to improve our understanding of how perceptions determine distinct management strategies to cope with irreducible and reducible uncertainties.

6. Creating flexible plans for an uncertain future: From exploratory scenarios to adaptive plans with real options

Thomas Machiels, Robert Goodspeed, Tine Compernolle & Tom Coppens

Revision submitted to *Planning Theory & Practice*

Abstract

Scenario planning is increasingly used to manage uncertainty, but such planning often struggles to influence decision-making and help communities navigate multiple futures. This article proposes a framework for planning practice that integrates scenario planning and real option theory to identify adaptation options that make plans or projects responsive to multiple futures. The framework is explained through a hypothetical case, Plan Bay Area 2050 and Link21, based on document content analysis and expert interviews. The findings show that exploratory scenarios generate opportunities for real options reasoning and adaptive planning by making uncertainties explicit when thinking about the future.

6.1. Introduction

Planning nowadays faces the challenge of considering decisions with long-range consequences in an environment of uncertainty caused by climate change, the energy transition, digitalization, economic and sociodemographic change, among others. Long-range plans often rely on forecasts, an approach sometimes called predict-and-plan (Berke & Lyles, 2013; Quay, 2010). Future predictions are often based on extrapolations of historical data, ignoring uncertainties in these predictions which can result in decisions that waste public resources, ignore emerging threats and opportunities, and inappropriately embed past values and assumptions into current issues (Nadin et al., 2021; Skrimizea et al., 2019). There has been a recognition among scholars that planning practice must move from predicting-and-plan to incorporating uncertainty (Machiels et al., 2021a; Rauws, 2017; Skrimizea et al., 2019).

A well-established method to facilitate this shift is scenario planning, a method to better inform decision makers about the future by creating multiple plausible future states (scenarios) based on descriptions of key uncertainties (Chakraborty & McMillan, 2015; Goodspeed, 2020; Hopkins & Zapata, 2007). Within scenario planning, there is a growing interest in moving from normative scenarios (defining preferred futures) to exploratory scenarios (creating multiple plausible futures), or a mix of both (Avin & Goodspeed, 2020; Goodspeed, 2020). Despite its increased use, scenario planning has been criticized for its limited impact on decision-making and its vague guidance for preparing communities for multiple futures (Abou Jaoude et al., 2022; Avin & Goodspeed, 2020; Zapata & Kaza, 2015). To address these challenges, more than a decade ago, Quay (2010) proposed planners use scenarios to prepare adaptive plans by providing examples from water supply planning. Despite Quay's Quay (2010) persuasive theoretical argument, the planning field has lacked specific guidance for how to implement adaptive planning outside of the water planning domain, such as land use and infrastructure planning.

One challenge that planning practitioners face, is the lack of a conceptual bridge between scenario planning, which outlines multiple plausible futures, and the specific decisions communities must make, which are often analyzed through conventional methods that rely on a single best-estimate future (Abou Jaoude et al., 2022; Knaap et al., 2020), such as cost-benefit analysis. Real option theory (ROT) can serve as a complementary method to scenario planning and fulfills the need to show how individual decisions can be made at different times in the future in light of uncertainty described by scenarios (Lyons & Davidson, 2016; Miller & Waller, 2003). ROT is an approach that aims to capture the value of flexibility when there is uncertainty about the future (Trigeorgis, 1996). It offers planning a toolkit of generic adaptation options to develop adaptive decision-making strategies in a structured way. ROT's value for planning has been discussed in recent literature (Coppens et al., 2021; Machiels et al., 2021b), but its potential remains underutilized (Herder et al., 2011; Machiels et al., 2021b). The integration of scenario planning and ROT has been proposed in previous studies (Alessandri et al., 2004; Lyons

& Davidson, 2016; Miller & Waller, 2003), but a specific approach for planning has not been developed.

The main contribution of this article for planning theory and practice is an integrated framework that outlines how ROT can be used to extend scenario planning practice to prepare adaptive plans for multiple futures that incorporate uncertainty. We question how the framework can support planning and prepare decision making in uncertain contexts. We offer guidance with a hypothetical application of the framework to Plan Bay Area 2050 (PBA2050), a scenario planning initiative and long-term planning vision for the San Francisco Bay Area, and one of its specific strategies, Link21, a rail infrastructure program. The case provides a context where high-quality exploratory scenarios were created for PBA2050 for which there is a need to incorporate an analysis of uncertainty and adaptive strategies into the particular project, i.e., Link21. In the following sections, we first provide a literature overview of scenario planning, adaptive planning, and ROT. We then briefly introduce our framework. Next, we present the research method and case study, after which we discuss the steps of our framework in detail through the findings from the case. In the discussion, we reflect on the framework's potential and limitations for adaptive planning and decision making.

6.2. Background

6.2.1. Scenario planning and adaptive planning

Scenario planning methods can make uncertainties transparent (Goodspeed, 2020), inform debates about addressing the future (Avin & Goodspeed, 2020), and lead to more thoughtful plans and decisions by explicitly incorporating uncertainties (Avin & Goodspeed, 2020). Scenario planning was first developed as a tool for military strategic planning in the 1950s, and became widely known in futures studies when it was adopted in business management in the 1970s, most notably by the Shell company (Goodspeed, 2020; Zapata & Kaza, 2015). Scenario planning pioneered in urban planning in the 1990s (Chakraborty et al., 2011; Goodspeed, 2020; Zapata & Kaza, 2015), and is related to alternative planning approaches that expanded during the second half of the 20th century, including forecasting, strategic spatial planning, and visioning (Abou Jaoude et al., 2022; Goodspeed, 2020).

Forecasting downplays uncertainties by focusing on a single future or trend forecast, and relies on the false belief that the future is controllable (Abou Jaoude et al., 2022). Scenario planning is, however, an approach that encourages planners to envision multiple plausible futures that are new realities in addition to current trends (Chakraborty & McMillan, 2015; Zapata & Kaza, 2015). Strategic spatial planning focuses on the balancing of long-term goals and short-term implementation actions (Albrechts et al., 2017). Although emphasizing uncertainty, strategic spatial planning focuses more on short-term actions than long-term future uncertainty (Goodspeed, 2020). Visioning is the practice of creating desirable community visions and focuses on a single preferred future. Normative scenario planning has its roots in visioning, but with the important difference that normative scenario planning starts with creating multiple futures before narrowing down on a preferred future (Abou Jaoude et al., 2022). Following the popularity of visioning and utopian urban plans (Couclelis, 2005), normative scenario planning has become the dominant scenario planning practice in urban planning (Avin & Goodspeed, 2020; Chakraborty et al., 2011; Goodspeed, 2020). Because of its emphasis on a single desirable future, normative scenarios provide little aid about how to prepare for multiple futures.

There is a growing interest in exploratory scenario planning that uses multiple plausible scenarios as a basis for planning (Avin & Goodspeed, 2020). Actively considering multiple futures through exploratory scenarios avoids over-reliance on single future forecasts or preferred plans, and offers opportunities to create adaptable plans and identify robust strategies (Abou Jaoude et al., 2022). Exploratory scenarios are not meant to replace normative ones, but can be used to keep different futures under consideration while at the same time planning for normative objectives (Avin, 2007; Banister & Hickman, 2013; Zapata & Kaza, 2015). That way, decisions and plans with normative objectives can be formalized, while changes in the external environment can be anticipated through exploratory scenarios.

Previous studies on scenario planning have already connected exploratory scenarios to adaptive planning, but lack specific guidance for domains such as land use and transportation planning. Chakraborty et al. (2011) and Knaap et al. (2020) developed scenarios for the Baltimore-Washington region and discuss how these scenarios can be used to create robust and contingent strategies, provide guidance for how practitioners can create similar strategies for land use and infrastructure planning. Quay (2010) introduced the concept of anticipatory governance for climate change adaptation planning. Anticipatory governance consists of three steps: anticipate the future by developing and analyzing a range of possible scenarios; create flexible adaptation strategies; and monitor and act in response to indicators of change or events. Flexible adaptation strategies include actions that preserve future options, contingency plans, no regret strategies, worst case strategies, and robust strategies (Quay, 2010). Despite Quay's convincing theoretical argument, most US local climate adaptation plans still rely on predicting-and-plan, and few use scenario planning and flexible adaptation strategies (Stults & Larsen, 2020).

Similarly, in planning domains such as land use and infrastructure planning, there remains a missing link between the increasing use of (normative) scenario planning and actual adaptive planning. Scenarios describe what the future could look like, but are still a long way from concrete planning actions that can be undertaken to navigate multiple futures, and scenario planning studies have not explained how to develop adaptive planning strategies based on scenarios (Avin et al., 2022; Knaap et al., 2020). Adaptive planning is an umbrella term for approaches to make plans adaptive to multiple future conditions.

Examples of adaptive planning practice remain scarce due to a lack of hands-on adaptive planning tools and successful precedents (Machiels et al., 2021a). In addition, scholars have outlined broader changes that might be required before adaptive planning can be more widely implemented: awareness of uncertainty and change (de Roo et al., 2020; Machiels et al., 2021a; Zandvoort et al., 2018); responsiveness or the willingness to anticipate change within planning (de Roo et al., 2020); and the institutional and organizational capacity to make changes (Machiels et al., 2021a; Nadin et al., 2021).

Building on previous concepts, we propose ROT as a more explicit approach to create adaptive strategies based on scenarios.

6.2.2. Real option theory

Scenario planning's strength is its ability to identify and analyze uncertainties, but, as noted, practitioners have struggled to apply scenarios to specific planning actions. Relatedly, scholars have recognized a lack of tools to prepare plans that are adaptable to changing conditions. To address both challenges, we turn to real option theory (ROT) as a source of ideas for how uncertainty and adaptive planning can be considered in the planning process. ROT originated in the fields of finance and economics in the 1970s, with the main premise that flexibility has value in situations of uncertainty and when there is flexibility in the timing of decisions (Trigeorgis, 1996). Applied to adaptive planning, this means removing the need to make every decision early in a planning process by embedding options in a plan or project that allow for making changes in response to changes in the planning environment (Coppens et al., 2021; de Neufville, 2003; Machiels et al., 2021b).

ROT originated as a quantitative method to measure the value of flexibility, but it can also be implemented as a qualitative method. Because quantitative ROT methods typically narrow the focus to only one or two uncertainties and adaptation options, and are mathematically complex (Coppens et al., 2021; Geltner & De Neufville, 2012; Machiels et al., 2021b), they are difficult to apply to the greater complexity that is typical in scenario planning contexts, which is our focus here. The qualitative approach, also named real options thinking (Trigeorgis & Reuer, 2017), involves a more creative thinking exercise to envision flexibility strategies, and has already been applied in studies about health care (Krystallis et al., 2020; van Reedt Dortland et al., 2012, 2014) and infrastructure development (Gil, 2009). Planning practitioners may already informally conduct real options thinking at times, but not in a systematic way (Coppens et al., 2021). A qualitative real options approach might lower the barrier for applying ROT, while also offering a tool for a more systematic discussion about flexibility (Alessandri et al., 2004; Lyons & Davidson, 2016; van Reedt Dortland et al., 2012). Quantitative valuations should, however, be pursued if possible because they offer more rigorous results (Coppens et al., 2021; Geltner & De Neufville, 2012). Overall, ROT should be tailored to each specific planning context.

ROT literature proposes a generic set of adaptation option types that can be used as a toolkit to identify flexibility strategies for plans and projects. Based on the typology introduced in the classic work on ROT by Trigeorgis (1996), the different option types have been reinterpreted for urban planning and transportation (Coppens et al., 2021; Machiels et al., 2021b). Table 6.1 gives an overview of the different option types. Each option is further described in the findings.

Table 6.1. *Adaptation option typology, based on Trigeorgis (1996), Coppens et al. (2021), and Machiels et al. (2021b)*

Adaptation option	**Description**
Defer or stage	Delay decisions or parts of a plan/project until more information becomes available, implement plans and projects in phases
Growth	Design and implement a plan/project in a way that allows for additional functions and/or capacity in the future
Scale (expand or contract)	Design a project in a way that allows expansion or contraction of the design or operations to minimize permanent overcapacity or undercapacity
Switch	Design or implement a plan/project that allows for changing the functional use of (parts of) the plan/project
Abandon or suspend	Abandon or temporarily suspend (parts of) a plan/project

6.3. From exploratory scenarios to adaptive planning with real options: An integrated framework

Scenarios, adaptive plans, and ROT are in themselves not new concepts. We bring them together in an innovative planning framework that incorporates uncertainty throughout the entire planning process. Scenario planning can help describe what the future might look like but offers little guidance for planners on how to define strategies to cope with the multiple scenarios identified (Knaap et al., 2020; Miller & Waller, 2003), aside from perhaps focusing on “robust” or “no regrets” strategies that analysis suggests will work well under any future scenario. Using ROT and its typology of adaptation options can be considered as a follow-on process, offering a structured way to develop adaptive strategies appropriate for different scenarios (Alessandri et al., 2004). Vice versa, ROT requires the scenario planning process to first understand critical uncertainties and plausible futures in planning, and scenarios can guide planners in determining the future need for flexibility (Van Reedt Dortland et al., 2014).

We developed our framework based on the frameworks for scenario planning of Avin and Goodspeed (2020), Goodspeed (2020), and Stapleton (2020); the ROT process for adaptive urban design of Coppens et al. (2021); the anticipatory governance framework of Quay (2010); and the PBA2050 case that is considered a high-quality example of exploratory scenario planning. The resulting framework is therefore the product of both theoretical translation and consideration of a real-world context typical of many planning practice contexts. Figure 6.1 gives an overview of the framework that consists of eight steps that are part of three phases: scenario development, strategy development, and implementation and monitoring. We first introduce the PBA2050 and Link21 case and explain the research method for the hypothetical application of the framework. We then explain each step of the framework in detail based on the application to and findings from the case. The framework is a cyclical one, which means revisiting previous steps might be required. As time passes, new uncertainties might emerge, or new information might require rethinking scenarios and subsequently rethinking strategies and adaptation options.

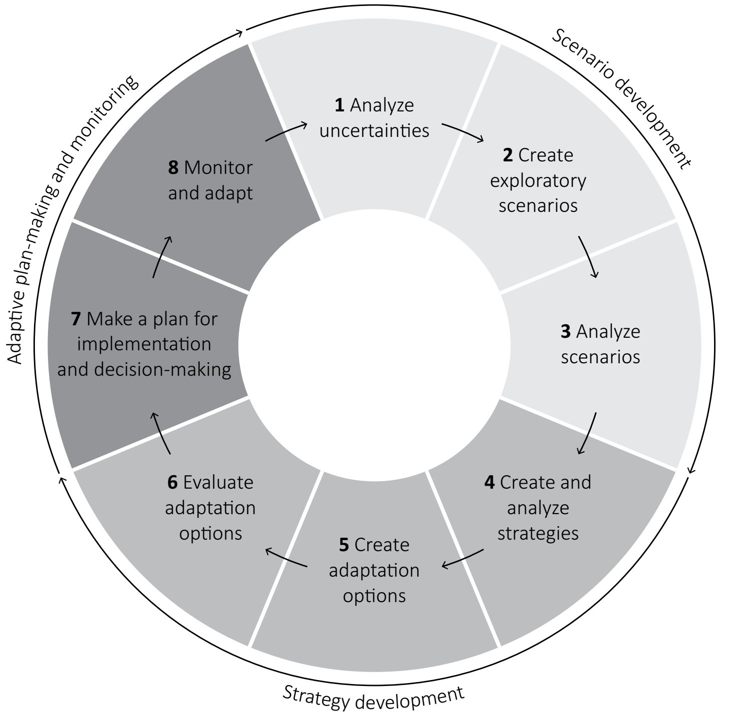


Figure 6.1. *Adaptive planning framework based on scenario planning and real option theory*

6.4. Research methods

In response to calls for more guidance on adaptive planning methods and the use of scenarios to make adaptive plans (Abou Jaoude et al., 2022; Knaap et al., 2020; Skrimizea et al., 2019), we use an existing scenario planning project as a demonstration case to provide a hypothetical application of the framework. We developed the case in two steps. First, we used case documents to report on an existing project that had previously completed steps 1–4 in our framework, the creation of exploratory scenarios and strategies as part of the Plan Bay Area 2050 (PBA2050) process. Second, we conducted interviews with practitioners involved in Link21, one of the strategies contained within PBA2050 where ROT can be used to develop and evaluate hypothetical adaptation options with stakeholders (steps 5-6). Because Link21 was in an early phase at the time of writing, we use literature to provide some pointers on how to translate scenarios and adaptation options into an adaptive plan (steps 7-8).

6.4.1. Plan Bay Area 2050: Document analysis

We performed a document content analysis using PBA2050's scenario exercise and planning process to illustrate how exploratory scenarios can be developed and used to create planning strategies and actions, in line with steps 1-4 of our framework. The main sources are the approved plan document—Plan Bay Area 2050 (ABAG & MTC, 2021)—and the report of the scenario planning exercise called Horizon (2018–2020) that preceded the plan—Horizon, Futures Final Report (ABAG & MTC, 2020). PBA2050 is a $1.4 trillion (2019 USD) long-term planning vision for the San Francisco Bay Area, in the state of California. PBA2050 was approved in October 2021 and created by the Metropolitan Transportation Commission (MTC) and the Association of Bay Area Governments (ABAG). The plan consists of 35 strategies and 80 implementation actions in four areas: housing, economy, transportation, and environment. The plan's objective is to make the Bay Area more affordable, connected, diverse, healthy, and vibrant for its residents by the year 2050.

6.4.2. Link21: Expert interviews

For the illustrative purposes of this research, we selected the Link21 program as a specific case to show how the adaptation option typology (Table 1) can be applied in planning, in line with steps 5-6 of our framework. Link 21 is part of PBA2050's transportation strategy to expand and modernize the regional rail network. The focus on one specific program and strategy allows for a detailed illustration of adaptation options.

Link21 is a rail infrastructure program to make the passenger rail system better connected and more efficient, sustainable, and affordable. Link21 refers to the 21 counties of the Northern California Megaregion, including the nine Bay Area counties. Phase 0 (program definition) of Link21 was completed in April 2022, and Phase 1 (program identification) was ongoing at the time of this writing. The final project will include improvements to existing infrastructure and new rail infrastructure to extend the network. Link21 is a joint program managed by two rail operators: BART (San Francisco Bay Area Rapid Transit) with rail services in five Bay Area counties, and Capital Corridor, a passenger regional rail service in the Northern California Megaregion. The project aims to better integrate connections between both networks. Link21's centerpiece project is a New San Francisco–Oakland Crossing, or New Crossing, a rail tunnel for either BART or regional rail to increase capacity and connections between East Bay and West Bay, in addition to the existing BART crossing (Figure 6.2). The New Crossing is one of the transportation projects in PBA2050, with early cost estimates of $29 billion (2019 USD).

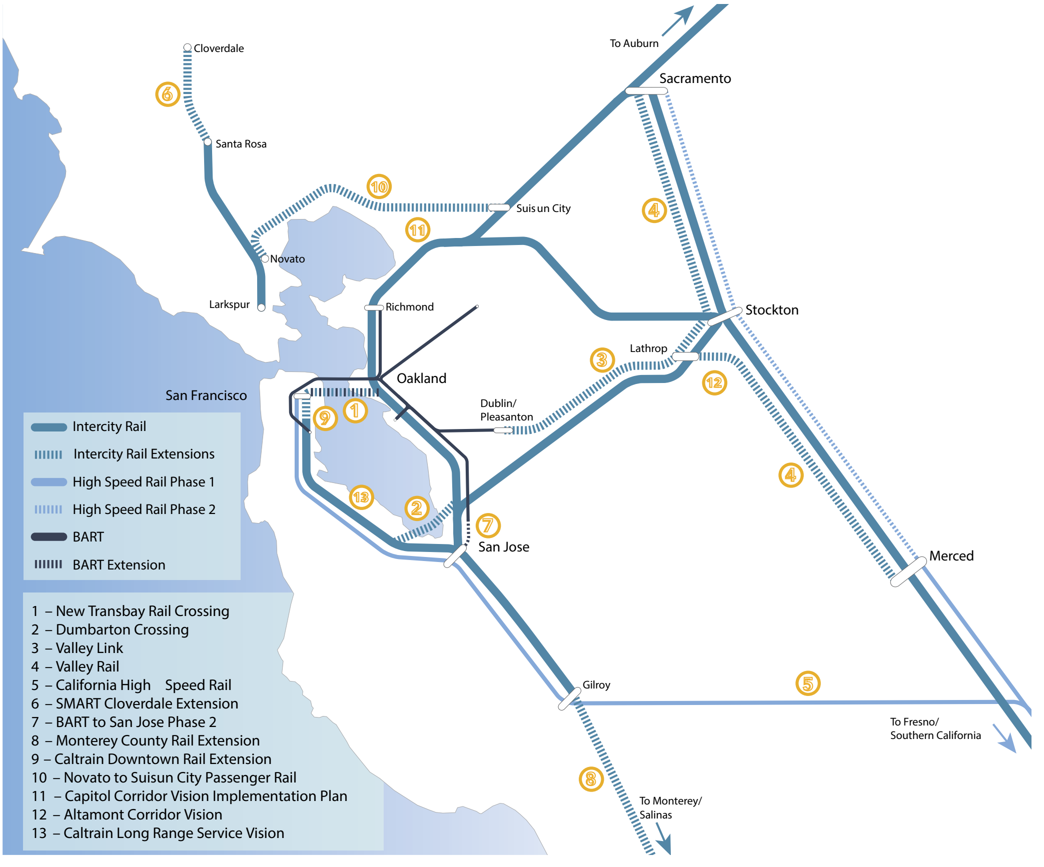


Figure 6.2. *Proposed rail infrastructure projects for the Northern California Megaregion, including Link21's New San Francisco–Oakland Crossing (No. 1) (Bay Area Council Economic Institute 2021).*

We performed a brainstorming exercise during interviews conducted in January 2022 with eight leading members from the Link21 team, including three people from BART, one person from Capital Corridor, and four consultants from three international transportation and infrastructure consultancy firms. We contacted interviewees through snowball sampling following suggestions from the first interviewee, the Link21 program evaluation manager. We started each interview with an introduction of the framework (Figure 6.1) and the adaptation options typology (Table 6.1). Next, we asked the respondents to assess which scenarios (Futures) from PBA2050, or which specific uncertainties, would be most determinant for the decisions and projects of Link21. Then, we asked respondents to envision which adaptation options from Table 6.1 could create flexibility for the scenarios and uncertainties. Last, we asked the respondents to assess the value of each adaptation option in a qualitative way by describing the adaptation option's feasibility.

We recorded the interviews and coded and analyzed the transcriptions using NVivo, a software for qualitative data analysis. After three rounds of open and axial coding by two authors, the final codebook contained five main code groups: Link21 (information about Link21), uncertainty (uncertainties and related Futures), adaptation options, flexibility value and costs/constraints, and PBA2050 (information about PBA2050). We used transcription sections coded on both uncertainty and adaptation options to generate an overview of the adaptation options for Link21. We only evaluated the adaptation options in a qualitative way because necessary quantitative data and a more defined set of options were not available.

After performing the coding and analysis, we returned the results and a first draft of the paper to the respondents, giving them the opportunity to review it and provide feedback. We then conducted a second interview with two respondents - the manager of program evaluation of Link21, and the manager of planning of Link21 to discuss comments collected from all respondents, which led to a few corrections about Link21.

6.5. Explanation and demonstration of the framework through Plan Bay Area 2050 and Link21

The following section explains and illustrates the steps of the adaptive planning framework through our case study. Steps 1 to 4 had already been conducted within the region through PBA2050, and we co-developed with Link21 practitioners a hypothetical and qualitative demonstration of steps 5 and 6 to demonstrate the value of ROT for adaptive planning.

6.5.1. Steps 1-3: Scenario development (PBA2050)

Step 1: Analyze uncertainties. The first step in the framework and of the scenario development phase is analyzing uncertainties. In keeping with exploratory scenario planning methods, key uncertainties are identified that are believed to have the biggest impact on plans and decision making, or that are expected to have major implications for plausible futures in a specific planning context.

The plan-making of PBA2050 was preceded by an exploratory scenario planning phase called Horizon, an exercise initiated because the main stakeholders believed that embracing uncertainty should be a central element of the planning process. The scenario development phase started with an overview of external forces (uncertainties) of which the outcomes would be beyond the Bay Area’s control. In total, 26 external forces were identified in five areas: environment, politics, economy, land use, and transportation.

Step 2: Create exploratory scenarios. Once key uncertainties are identified, in step 2 of the framework, exploratory scenarios are created as multiple plausible futures by combining different assumptions about uncertainties. Exploratory scenarios are usually described through narratives, visualizations, and/or quantitative modeling.

In 2018, MTC and ABAG created exploratory scenarios called Futures during workshops in collaboration with experts from various disciplines and Bay Area stakeholders. They created three Futures through consistent combinations of different assumptions for the identified uncertainties, and wove them together by a narrative. Future 1, Rising Tides, Falling Fortunes, is defined by the worst-case sea level rise scenario, and slow growth as a consequence of the elimination of federal funding programs from social services to infrastructure. Future 2, Clean and Green, is defined by an aggressive federal carbon tax to cut emissions. Clean technologies thrive, virtual reality increases the share of telecommuting, and there is a greater preference for urban housing. Future 3, Back to the Future, is defined by increased public investment in infrastructure and a thriving technology sector, leading to a broad adoption of low-cost autonomous vehicles, enabling residents to commute longer distances, generating a greater preference for dispersed housing. Table 6.2 summarizes the key assumptions for each Future.

Table 6.2. *Summary of the Plan Bay Area 2050 Futures. Adapted from the full table in Futures final report (ABAG & MTC, 2020, p. 9)*

External forces (Uncertainties)	**Futures (scenarios)**		
	Rising Tides, Falling Fortunes	Clean and Green	Back to the Future
Immigration and trade	Reduced, +20,000 immigrants annually	Similar to today, +80,000 immigrants annually	Increased, +240,000 immigrants annually
National growth	Limited, +1.6% annual productivity, +0.4 annual U.S. population	Similar to today, +2.8% annual productivity, +0.7% annual U.S. population	Rapid, +1.6% annual productivity, +1.1% annual U.S. population
National taxes and funding	Lower funding due to tax cuts	Higher funding via carbon tax	Similar to today
Land use preferences	Housing more urban, jobs similar to today	Housing more urban, jobs more dispersed	Housing more dispersed, jobs more urban
National environmental policy	Relaxed regulations, +3-feet sea level rise, 10% electric vehicles	Stricter regulations, +1-foot sea level rise, 95% electric vehicles	Stricter regulations, +2-foot sea level rise, 75% electric vehicles
New technologies	More limited, 10% automated vehicles, 10% telecommute share	Widespread, 95% automated vehicles, 30% telecommute share	Widespread, 75% automated vehicles, 15% telecommute share
Natural disasters	Earthquake magnitude 7.0, Hayward Fault	Earthquake magnitude 7.0, Hayward Fault	Earthquake magnitude 7.0, Hayward Fault

Step 3: Analyze scenarios. When the exploratory scenarios are completed, they are analyzed in step 3 of the framework by determining the impact of each scenario on a region, city, or community if no new plans, projects, or policies are adopted (business-as-usual). This can be done in a qualitative and descriptive way, or quantitative way with, for example, land use and travel demand models.

MTC and ABAG conducted an analysis of how the Bay Area would perform in 2050 in each of the three Futures with current policies and strategies from the previous Plan Bay Area 2040. Performance criteria were the five guiding principles: affordable, connected, diverse, healthy, and vibrant. They performed the analysis by using three primary models: a regional-level economic and demographic model, a land use model, and a transportation model. They used conditions in the Bay Area in the year 2015 as baseline conditions for each Future. The analysis provided insight into how the Bay Area would fare and perform under the previously understudied uncertainty described by each Future.

6.5.2. Steps 4-6: Strategy development (PBA2050) and adaptation options (Link21)

Scenarios developed throughout the first three steps of the framework provide insight into the effects of key uncertainties in different plausible futures. This is an important starting point for developing and evaluating strategies and policies that help prepare a region, city, or community for multiple futures.

Step 4: Create and analyze strategies. The strategy development phase commences with step 4, during which new strategies are created and their performance analyzed, similar to step 3. In the scenario planning field, strategies or policies are often categorized as follows: mitigating strategies to avoid undesirable outcomes, normative strategies to reach specific goals or objectives, contingent strategies that only perform well under some scenarios, and robust strategies that perform well in all scenarios (Abou Jaoude et al., 2022; Avin & Goodspeed, 2020; Chakraborty et al., 2011).

During workshops in 2019 with elected officials, stakeholders, and Bay Area residents, MTC and ABAG received input on new strategies in four areas—housing, transportation, economy, environment—that might improve the performance of the Bay Area in each of the three Futures for the five guiding principles. MTC and ABAG identified a final set of 35 strategies and reanalyzed them following the same procedure as in step 3, with the difference that the strategies from Plan Bay Area 2040 were replaced by the new set of strategies. MTC and ABAG conducted analyses about the impact of individual strategies and the integrated impacts of combined strategies. The strategies in PBA2050 were nearly similar to the ones identified during the Horizon process, as they proved effective in multiple futures. These strategies were identified as robust strategies that perform well across all three Futures.

The final PBA2050 has an estimated cost of $1.4 trillion (2019 $) but does not fund specific strategies or projects, and the plan makers, MTC and ABAG, do not have any decision-making or land use authority. Half of the plan's costs relies on new funding sources that must be secured through new policies and legislation. The plan's implementation and funding is dependent on the willingness and cooperation of public authorities at local, county, state, and federal level. The plan does not include a timing for the implementation of the strategies, and none of the strategies can be implemented right away. Transportation projects, for example, require lengthy planning, engineering, and environmental review procedures, while many strategies require changes to legislation. Finally, the Future Rising tides, falling fortunes, excludes certain high-cost transportation infrastructure projects because this scenario assumes a decrease in federal support for infrastructure. The initial performance assessment of the plan's transportation infrastructure projects further shows that not all projects have a positive net present value in every Future, including Link21's New Crossing. Therefore, these infrastructure projects should be considered as contingent strategies because they are either not included or do not perform well in every scenario, and are therefore not robust. These conditions are exemplary for many land use and transportation planning contexts.

Even if strategies are robust in terms of performance, in most planning contexts, a plan itself does not guarantee its implementation. In the case of contingent (and mitigation) strategies, options must be preserved that prepare a plan to adapt in response to a specific scenario (Berke & Lyles, 2013; Hopkins, 2001). An adaptive plan is responsive to changing situations following the exploratory scenarios identified and the conditions on which the plan's implementation depends. At this stage, ROT's value for planning comes into play by offering planning a typology of adaptation options that can be used to make plans adaptive.

Steps 5 and 6. Create and evaluate adaptation options. In step 5 of the framework, the real option typology (Table 6.1) is used to create adaptation options that can be embedded within the strategies identified during step 4. Adaptation options are not new strategies – policies or projects – but options that are embedded within strategies that grant flexibility to make changes to those strategies. In step 6, the adaptation options are evaluated quantitatively through real options models or qualitatively through a descriptive assessment of an option's (un)feasibility. Quantitative valuations provide more detailed information about an adaptation option's value, which is important because the flexibility value does not always outweigh the flexibility cost (Geltner & De Neufville, 2012). However, a qualitative approach to steps 5 and 6 can already in itself help to increase the responsiveness of a plan, and is a more accessible approach for practitioners who are not familiar with quantitative ROT (Lyons & Davidson, 2016; Miller & Waller, 2003). The scenarios created during the scenario development phase determine the range of possible futures for which strategy implementation should be made responsive through adaptation options.

Table 6.3 provides an overview of adaptation options identified for Link21, and more specifically the New Crossing—part of PBA2050's strategy to expand and modernize the rail network—and their associated uncertainties. Table 6.3 also includes the qualitative evaluation of each of the options provided by the interviewees, either feasible (✓) or infeasible (✗). The study participants were unanimous in their evaluations. We asked participants to relate adaptation options to PBA2050's exploratory scenarios. Respondents referred in total to over half of the external factors (uncertainties) of the three Futures, but indicated that Link21 will need to reassess assumptions for uncertainties to reflect their project-specific impacts.

Table 6.3. *Adaptation options for Link21 identified during expert interviews*

Option type	**Link21 adaptation option**	**Uncertainties**	**Feasible (✓) or Infeasible (×)**
Defer or stage	Delay the decision to build or no-build	Travel demand scenarios related to, e.g., transit recovery after COVID-19 pandemic and telecommuting	✓
	Flexible phasing and implementation of Link21 projects	Available funding, funding scenarios (when, how much, from whom)	✓
Growth	Build one two-track tunnel with the option to build a second two-track tunnel	Travel demand scenarios for 2090	✓
	Build one large tunnel with two tracks and additional space for two additional tracks		×
	Build rail infrastructure with additional space to accommodate future technologies	Technology evolutions	✓
	Build a rail connection with the option for additional stations along the connection	Travel demand, land use, funding	✓
Scale	Design the New Crossing for more trains/hour than initially needed to allow expanding operations	Travel demand, implementation of feeder lines	✓
Switch	Option to change the functional use of rail lines (e.g., Bart to commuter rail or vice versa)		×
Abandon or suspend	Temporarily suspend or abandon parts of Link21	Funding, travel demand, societal and political support	✓

Defer or stage. The option to defer or stage is the flexibility to delay decisions until more information becomes available and to divide plans and projects in phases so they can be implemented incrementally, without delaying the overall process.

Various respondents indicated that the decision to build the New Crossing would not be made before 2028, because the phases of program identification and project selection of Link21 are not expected to be completed before that time. If in 2028 it appears a new rail crossing is not needed until a certain year, the decision to build could be further postponed. The build or no build decision is dependent on travel demand evolution, which became a major uncertainty during the coronavirus disease 2019 (COVID-19) pandemic. Prior to COVID, the existing BART crossing was overcrowded, creating a window of opportunity for a political decision for a new rail tunnel. Ridership levels on both BART and regional rail have dropped to 20%–30% of pre-COVID numbers and had not recovered by early 2022. This drop in ridership levels has, for now, removed the pre-pandemic overcrowding problem, therefore also removing the sense of urgency to immediateluy build a new tunnel. The related increase in telecommuting might also influence long-term travel demand. This led to high uncertainty about future ridership levels and has alleviated the political pressure to make a fast and final decision, which makes the flexibility to delay decisions an attractive and valuable option. The need to adapt the decision timing to the travel demand as it evolves is further facilitated by Link21's approach, with multiple decision-making points at which adjustments can be made.

The final build or no-build decision can be delayed, but other decisions must be made on a shorter term. A ballot measure (referendum) is expected to be organized among the region's residents to ask for a tax increase (e.g., sales tax) to fund one or more projects of Link21. This sets a deadline to decide on the projects that must be part of Link21 to inform the people about what they are voting for. For the New Crossing, it must be decided whether it will be a tunnel for BART, for regional rail, or for both. This decision has major implications for the future rail network in the larger region.

The final Link21 program will consist of a list of projects, including the New Crossing. Our interview respondents indicated that the program would benefit from flexible phasing rather than a rigid implementation strategy, mainly because of funding uncertainty. Funding for public transportation infrastructure can come from various public authorities and funding programs at varying levels, depending on the project objective, effects, and characteristics. Related to different assumptions about (federal) funding for infrastructure in the PBA2050 Futures, the availability of funding sources at specific times determines which projects can or cannot move forward. Link21 must be prepared to adapt its phasing to take advantage of uncertain funding opportunities, which could result in pushing projects up or down the list of priorities.

Growth. The option to grow means projects are designed and implemented in a way that allows growth in terms of the implementation of additional functions in the future. The specific future function of the growth option is not predefined.

Interview respondents indicated that this option is actively researched for potential project alternatives for the New Crossing. The New Crossing could be constructed as a two-track tunnel—one track in each direction—in a way that it accommodates the construction of an additional two-track tunnel in the future, so it can adapt to increased travel demand. To have this flexibility, the landing sites of the first two-track tunnel must be designed so that the first tunnel does not preclude the connection of a second two-track tunnel to the existing network. This way, the first two-track tunnel could be built for one rail technology (e.g., BART) and the second tunnel for another rail technology (e.g., regional rail). Contrary to Plan Bay Area's time horizon of the year 2050, Link21 considers travel demand scenarios until 2090 to determine whether four new tracks might ever be necessary.

Similarly, interview respondents stated that the idea of building one larger tunnel so that two tracks can be inserted and two extra tracks could be added in the future is infeasible. The cost difference of building two separate two-track tunnels versus one larger tunnel is negligible. It would be hard to justify the cost of building one large tunnel when it would initially be used for only two tracks. Also, because BART and regional rail are different technologies that require their own specific tracks, a single large tunnel creates more technical complexity to make the connections at the landing sites. Thus, building a two-track tunnel with the growth option to build an additional two-track tunnel is more feasible because the costs are then more equally divided among two separate projects, and it avoids having an oversized tunnel if travel demand in the long term does not require four tracks.

A few respondents also mentioned the importance of building rail infrastructure with the general provision of additional space for new technological infrastructure, given the uncertain evolution of technologies to operate public transportation, citing difficulties that have been encountered retrofitting BART with new control systems.

A final growth option for Link21 is to build new rail connections between two points, and have the opportunity to build extra stations in between, such as after land use change. Many transit systems, including BART, have added infill stations after initial system construction. Being able to adapt to such circumstances and to build these stations at a later point can be facilitated by design choices like reserving space within the right-of-way at strategic locations.

Scale. The option to scale means having the flexibility to expand or contract the design or operations of an infrastructure. In contrast to the growth option, scaling means expanding or contracting within the same function, having more or less of the same. It seemed likely to design the New Crossing for a certain number of trains per hour but to start operations with fewer trains. Travel demand might not require the tunnel to operate at full capacity from the start. Also, the potential number of trains per hour depends on progression made in other Link21 projects that serve as feeder lines for the New Crossing.

Switch. The option to switch is the flexibility to change the functional use of a project or infrastructure. The option to change the functional use of rail infrastructure from BART to regional rail or vice versa was considered impossible because of technical constraints. BART and regional rail each have different technologies, and one cannot run on tracks of the other.

Abandon or suspend. The option to abandon or suspend means considering the possibility to temporarily suspend or abandon parts of a program or a project. Respondents stated that this option is always on the table, and it relates to delaying certain decisions. The New Crossing could be suspended because certain forces might abruptly change travel demand patterns and render the New Crossing (temporarily) unnecessary, such as technologies that increase the share of telecommuting. Lack of funding or necessary political support could lead to a forced suspension or abandonment of parts of the program that are, for example, dependent on the outcome of a future ballot measure.

6.5.3. Steps 7-8: Adaptive plan-making and monitoring

Strategies and adaptation options developed and evaluated in steps 4 through 6 show how a region, city, or community can prepare for the multiple futures identified in steps 1 through 3. The adaptation options embedded within the strategies allow implementation and the specificities of the strategies (e.g., the design) to be adapted to various scenarios and avoid planning for a single best estimate or preferred future.

Step 7 integrates the scenarios, strategies, and adaptation options from the previous steps in an adaptive plan. Adaptive plans are designed based on the assumptions that conditions change and plans should be adapted through a continuing process of revision (Berke & Lyles, 2013). Therefore, indicators of change such as signposts, events, thresholds, or specific conditions must be identified based on the uncertainties and scenarios identified during steps 1 through 3 (Quay, 2010), to determine the thresholds or conditions for executing certain strategies or adaptation options. An adaptive plan is a set of strategies and actions that can be incrementally implemented, monitored, and adapted through adaptation options. Step 8 involves monitoring, which is crucial because it allows to respond in time to changing conditions (Berke & Lyles, 2013; Coppens et al., 2021; Quay, 2010).

For Link21, a plan for implementation and decision making (step 7) could be a road map that shows the possible courses of action (strategies with embedded adaptation options) based on the PBA2050 Futures and additional project-specific uncertainties or scenarios. In Figure 6.3, we show what an adaptive plan for Link21 could look like, and we illustratively compare step 7 of our framework with what a predicting-and-plan and conventional scenario planning approach for PBA2050 would have looked like. A predicting-and-plan or forecasting approach would probably result in the proposition of a single course of actions – projects and policies – that were created and evaluated based on a trend forecast that extrapolates historical data towards 2050 and determines future needs. Forecasting may be well-suited for short term planning, but not for long term planning visions such as PBA2050 that face long-term uncertainty. A conventional normative scenario planning approach following Federal Guidelines for US land use and transportation planning would have resulted in the selection of a preferrable future based on an initial set of scenarios, for example, the Clean and Green Future. Similar to forecasting, a single course of actions would be proposed that includes projects and policies to create the desirable future by 2050. Although based on an analysis of uncertainties, a

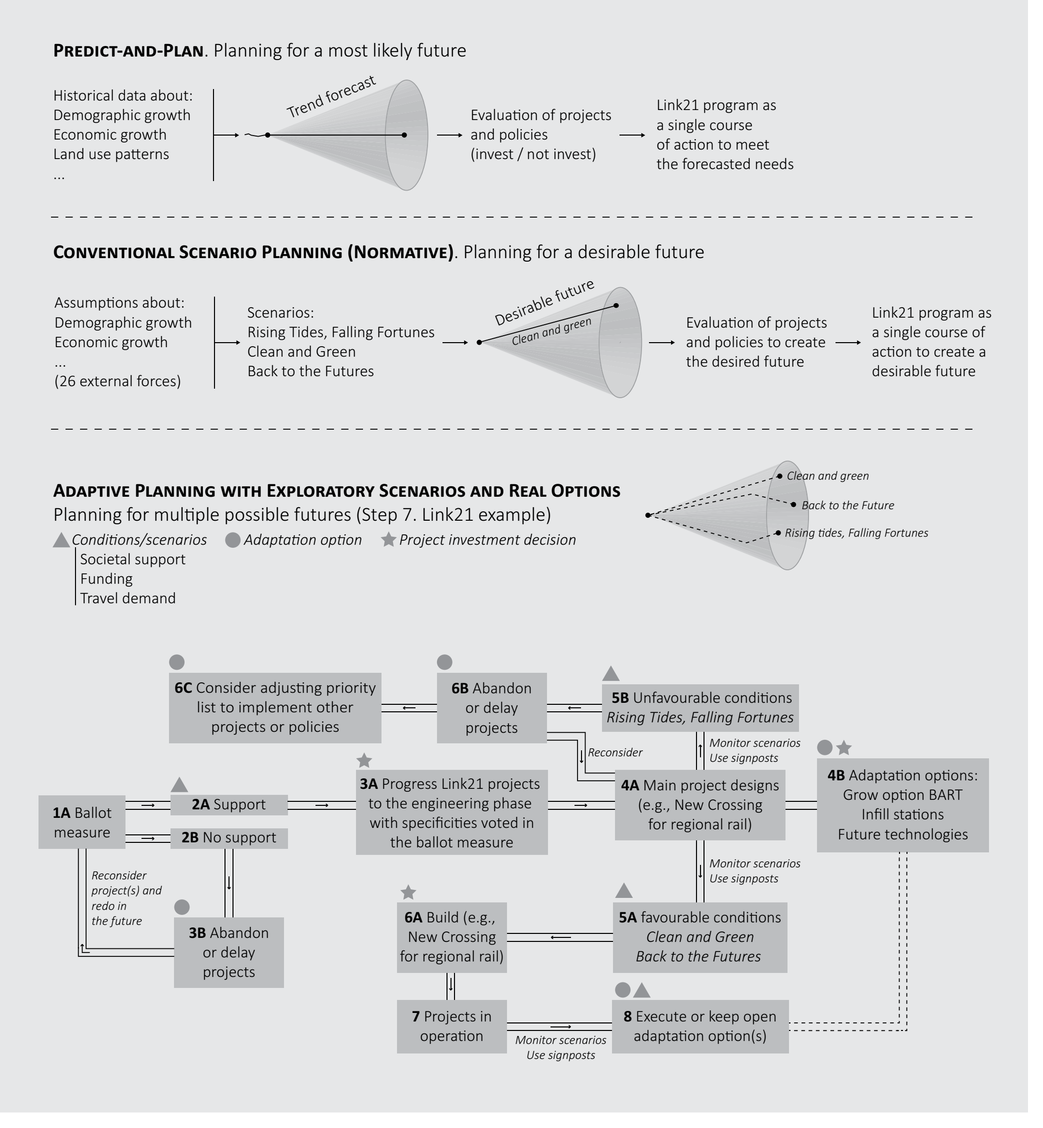


Figure 6.3. *Example of an adaptive plan for Link21 in comparison with plan-making following traditional approaches.*

normative plan also remains static once a preferred future direction is chosen.

An adaptive plan (Figure 6.3) following our framework instead is like a road map that integrates scenarios, decision-making moments for strategies, and adaptation options that can be executed or kept open while monitoring conditions. An adaptive plan can inform decision makers about multiple courses of action for multiple futures grounded on scenarios and adaptation options previously identified in steps 1-6. The adaptive plan shows how decisions, and the execution of adaptation options are related to specific conditions or scenarios, following signposts – e.g., public transportation travel statistics, political announcements… – that indicate what future scenario an area is (currently) heading towards. The effectiveness of projects and policies once implemented remains uncontrollable to some extent and depends on which scenario will eventually materialize. At least, an adaptive plan backs up decisions with richer information about scenarios for long-term uncertainties and flexibility possibilities.

6.6. Discussion

The challenge of coping with uncertainty in planning became apparent during the interviews, and respondents indicated they were still searching for what they believe is the right method to analyze uncertainties in Link21. The adaptive planning framework and the adaptation option typology were appreciated by the respondents for their clarity and structure. Overall, the respondents believed the ROT-based typology to be a valuable tool as a starting point to consider how Link21 can adapt to changing circumstances. An adaptive plan for Link21 is required because most of the adaptation options discussed referred to uncertainties from the PBA2050 scenarios and conditions that generally remain unspecified or unconfirmed in regional plans, such as funding, or project phasing and design. The option typology and the framework provided a more structured approach to identifying adaptation options and considering their relation to uncertainties.

At the onset of our research, we assumed that the Link21 project could use the scenarios created by PBA2050. However, although respondents referred to these scenarios and perceived them to be helpful, they stated that Link21 would need its own uncertainty analysis, possibly even its own scenario planning process. In this case, there was too big a difference between project-specific uncertainties of Link21 and scenario-specific uncertainties of PBA2050. Both PBA2050 and Link21 have their own uncertainties, geographic scales, project teams and stakeholders, approaches, and decision-making procedures. Regional plans such as PBA2050 are important because they provide a shared vision for the future(s) of a municipality or region, but do not necessarily secure funding, change policies, or execute projects. Consequently, individual strategies benefit from being adaptive because the overall regional plan does not guarantee all strategies' implementation and effectiveness, and changes along the way might be required that strategies or projects must be prepared for.

Despite this distinction between scenarios for long-range regional plans and specific projects, the interview respondents were well informed about the PBA2050 Futures and were aware of the many uncertainties affecting the region. More than half of the external forces from the PBA2050 Futures were mentioned during the interviews, mainly those that would influence travel demand and funding. The interviews provided evidence that individual scenario planning processes can contribute to the conceptual and institutional shifts described as necessary for greater adoption of adaptive planning. The scenario planning process itself can be a source of inspiration on how to analyze uncertainties, illustrate the steps of a scenario planning process, and tell which uncertainties have been analyzed. PBA2050's exploratory scenario planning exercise is a break with the two previous normative long-term visions. The growing awareness that the outcome of uncertainties is beyond the control of planners and decision makers can disrupt the context of predicted plans and have a spillover effect on other regional or local planning initiatives and projects in the region.

Our study and framework helped to address important challenges in planning practice today: the lack of hands-on adaptive planning tools, and a conceptual bridge between (exploratory) scenario planning and its use for adaptive planning in actual planning and decision making for uncertain futures. Two main limitations require further research. First, our application was limited to a single qualitative case study of a large-scale regional plan and project. More empirical studies are needed to help understand how scenarios can be used to increase flexibility following our framework within and between different scales of planning initiatives, such as regional plans, local municipal plans, and specific strategies, policies, and local or regional projects. This also calls for more attention to the differences between regional plans and (local) projects to better understand the difficulty of turning scenario-based plans into adaptive plans, projects, and implementation actions. We believe that our framework's steps are generic enough to be applicable in various planning situations with a long-term planning horizon, but more empirical research is needed to verify this, including applications to small- and large- (or mega)-scale scenario planning initiatives, e.g., regional vs municipal plans, and applications to transportation and land use development projects.

Second, land use and transportation planning and decision making is not only based on technical knowledge, but is political in nature and takes place within a broader context of local and regional power relations (Albrechts, 2003). Planning and the decisions made in the end will never only be the result of approaches like our framework. Rather, our framework should be viewed as a support tool that can offer specific information about possible strategies to navigate multiple futures, information not found in predicting-and-plan or normative scenario planning approaches. The emphasis of this paper was on introducing and illustrating the framework's applicability. More research is needed about how to embed alternative frameworks like ours within existing planning systems and cultures, to maximize its potential use for planning and decision making.

6.7. Conclusion

Uncertainty remains a persistent challenge for planners and decision makers who must decide on policies and spatial interventions that determine the future of cities and regions. Prediction-based and normative planning approaches do not aid decision making about how to navigate future uncertainty in the dynamic environment of today's planning contexts. Despite the increased use of exploratory scenario planning to cope with uncertainty, scenario planning still struggles to offer explicit guidance about how to navigate multiple futures, and hands-on adaptive planning tools are lacking. We contribute to planning theory by integrating existing concepts of scenarios, adaptive planning, and ROT into a novel and practical framework to leverage scenarios into adaptive plans with adaptation options. We contribute to planning practice by illustrating the framework's applicability in a hypothetical case of the regional PBA2050 and one of its transportation strategies, Link21. The case illustrated that the framework provides a systematic approach to identifying opportunities for adaptive strategies in relation to uncertainties and scenarios, illustrating how it can be used to produce an adaptive plan which differs from previous paradigms. Further research will be needed of the application in real life cases to assess its added value, specifically focusing on how to embed the framework in existing planning cultures and systems to maximize its impact on actual decision making. The results also suggest that regional plans and its projects might each require their own specific scenarios and uncertainty analyses, complicating the straightforward use of a single set of regional scenarios for project planning. Nevertheless, regional scenario planning can set the stage for greater consideration of uncertainty in other projects in the region, potentially fostering the adoption of adaptive planning approaches.

7. A real options approach to value flexibility in transportation infrastructure: The New Crossing case study

Thomas Machiels, Kris Welkenhuysen, Tine Compernolle & Tom Coppens

Submitted to *Transportation Research Part A: Policy & Practice*

Abstract

Ignoring uncertainty and the ability to adapt to changing conditions in dominant ex-ante project evaluation approaches remains an important cause for persistent underperformance of large-scale transportation infrastructure projects. Real options theory (ROT) is increasingly proposed as an alternative approach to value flexibility under conditions of uncertainty, but its mathematical complexity and a lack of empirical examples inhibit its practical use. We develop a real options model called TIPROE that integrates traditional discounted cash flow methods with scenarios and limited foresight to incorporate uncertainties, and a decision tree to incorporate flexibility options. We apply the model to New Crossing, a multibillion rail infrastructure project in the San Francisco Bay Area. The model numerically compares the value of different project alternatives while considering flexibility options in the timing of decision making and phasing of project alternatives, and cost and benefit uncertainty. The results support New Crossing decision makers to advance the regional rail alternative and the grow option for BART to the engineering phase without making a final decision yet. The key findings show that: (i) including flexibility options increases the project value and significantly changes the decisions made for New Crossing; (ii) the consideration of (likely) cost overruns impacts the probability of investing and increases the value of waiting; (iii) the combined use of scenarios and a decision tree allows to tailor real options approaches to the context of complex transportation infrastructure projects; (iv) and communicating with stakeholders from the case strengthens the empirical data and results.

7.1. Introduction

An urgent challenge in large-scale transportation infrastructure planning today is coping with uncertainty and change in the project and decision-making environment (Atkinson et al., 2006; Lyons & Davidson, 2016; Machiels et al., 2021a). Decisions about the allocation of public budgets for transportation infrastructure are usually made during early project phases, when information is limited and uncertainty highest (Samset & Volden, 2016; Williams et al., 2019). Over the long period – often multiple decades – between a first decision and actual project implementation and operation, the project environment can change in such a way that actual cost and benefit outcomes do not match initial estimates. Ignoring uncertainty and change remains an important cause of widespread project underperformance in terms of cost overruns, benefit shortfalls, delays, or unexpected externalities (Ahiaga-Dagbui et al., 2017; Denicol et al., 2020; Flyvbjerg, 2017a; Patanakul et al., 2016).

Conventional decision-making procedures and ex-ante project evaluation tools are not fit to cope with uncertainty or to prepare projects to adapt to changing conditions (Daniel & Daniel, 2018; Davies et al., 2017; Williams & Samset, 2010). Dominant approaches rely on linear-rationalist discounted cash flow methods, such as net present value, that falsely assume that project outcomes can be clearly identified and predicted (Ramjerdi & Fearnley, 2014; Samset & Volden, 2016; Verweij, 2017). At best, sensitivity analyses are performed to check the robustness of project outcomes, but overall, projects are still mainly perceived as now-or-never decisions, and uncertainties and the value of adapting to emerging opportunities are ignored (Giezen, 2012; Lehtonen et al., 2017b). Scholars are increasingly advocating approaches that incorporate uncertainty and adaptability in ex-ante project evaluation (Lyons & Marsden, 2021; Nadin et al., 2021; Ramjerdi & Fearnley, 2014; Salet et al., 2013). An approach that has received increasing attention is real options theory (ROT), an economic and financial approach that uses mathematical models to quantify uncertainty and the value of flexibility (Herder et al., 2011; Lyons & Davidson, 2016; Machiels et al., 2021b).

Real option applications in transportation infrastructure research have increased in the past two decades (Machiels et al., 2021b), but the use of ROT in public transportation planning practice lags behind. Various reasons inhibit the adoption of ROT in practice: (i) the mathematical complexity and opacity of the real option models in combination with a lack of understanding of ROT among practitioners (Geltner & De Neufville, 2012; Lyons & Davidson, 2016; Machiels et al., 2021b); (ii) the lack of empirical evidence from real-life examples and ex-ante applications (Herder et al., 2011; Machiels et al., 2021b; van den Boomen et al., 2019); (iii) the difficulty of adapting real options models from their original context of valuing financial options to the context of valuing options in complex transportation projects (Garvin & Ford, 2012; Herder et al., 2011; Oliveira et al., 2021); and (iv) the difficulty of quantifying and modelling uncertainties from complex real-world contexts (Di Maddaloni et al., 2022; van den Boomen et al., 2019).

To address these gaps and advance the use of ROT in transportation infrastructure project evaluation, an approach is needed that avoids advanced mathematics while being able to simulate the complex and uncertain reality of public transportation infrastructure as best as possible. Additionally, the approach's strengths and weaknesses must be showcased with empirical evidence and compared with the traditional NPV approach. In this paper, we aim to fulfil these requirements and contribute to transportation infrastructure research and practice by developing a real options analysis spreadsheet model and applying it to New Crossing, an early phase multibillion rail infrastructure project in the San Francisco Bay Area. We use actual data and information about flexibility options and cost and benefit uncertainty from various sources, including project documents and interviews with project team members. We also show how the results of a real options approach leads to different decisions compared with a traditional NPV approach. The theoretical and methodological contribution of this paper lies in the integration of multiple existing concepts – decision tree, Monte Carlo simulation, limited foresight, and scenarios – into a project evaluation tool that is tailored to the context of complex transportation infrastructure projects.

In section 7.2, we provide an overview of research about performance issues in rail infrastructure projects, and real option applications in transportation infrastructure research. Next, we introduce our real options approach and the case study New Crossing in Section 7.3. In section 7.4, we describe the model application step-by-step. The results are presented in Section 7.5. Section 7.6 discusses the implications for the case of New Crossing and transportation infrastructure research and practice more generally. Section 7.7 concludes the paper.

7.2. Background

7.2.1. Performance issues in rail infrastructure projects

Underperformance in transportation infrastructure projects world-wide, has been well-documented in the past two decades. Pioneering studies about cost overrun and traffic forecast inaccuracy in public transportation projects are Wachs (1987, 1989, 1990), Pickrell (1990, 1992), and Skamris holm and Flyvbjerg (1997). The largest early documentation of cost overrun and benefit shortfalls is Flyvbjerg et al.'s (2002) analysis of rail, road and fixed link (tunnels and bridges) infrastructure projects. The study analysed 258 projects implemented throughout the 20th century in Europe, North America and other parts of the world. The study found that costs are underestimated in 9 out of 10 projects, and that rail infrastructure projects had an average cost overrun of 44.7% and an average benefit shortfall of 51.4% (Flyvbjerg et al., 2002). Although recent studies provide evidence of project success in transportation infrastructure in different countries (Rokicki, 2022; Siemiatycki, 2013; Volden & Welde, 2022), plenty of evidence still points to the fact that many projects in various areas still underperform.

Table 7.1. *Cost overrun (CO) data for rail infrastructure projects*

Study	Sample size	Area	Period	Mean CO	Remarks
Booz (2006)	28	USA	1984-2002	36.3%	
Dantata et al. (2006)	16	USA	1994-2004	30%	13/16 projects had cost overruns
FTA (2003)	21	USA	1989-2002	20.9%	
FTA (2008)	23	USA	2002-2007	40.2%	
Gao and Touran (2020)	81	USA	1980-2018	31.2%	Major projects had a mean cost overrun of 48.5%
Pickrell (1990, 1992)	10	USA	1986-1989	52%	
C. C. Cantarelli, Flyvbjerg, et al. (2012)	26	The Netherlands	1980-2010 (?)	10.6%	55% of projects had cost overruns
Flyvbjerg (2007)	44	World	1966-1997	44.7%	75% of the projects have at least 25% cost overrun, 25% of the projects at least 60%
Lundberg et al. (2011)	65	Sweden	1997-2009	21.1%	
Lee (2008)	16	South-Korea	1985-2005	25%-50%	10/16 projects had cost overruns
Peter E. D. Love et al. (2017)	16	Australia	2011-2014	23%	
Odeck (2019)	579	World	Unknown	36.3%	Based on data from 48 studies
Park and Papadopoulou (2012)	7	Southeast Asia	1983-2010	13.46%	
Singh (2010)	122	India	1992-2009	94.84%	82.79% of the projects had cost overruns; 98.36% had time overruns

Research about project underperformance has mainly focused on cost overruns. Table 1 provides an overview of studies on cost performance in rail infrastructure projects in different countries. A trend that many studies find is a lack of improvement of cost forecasting accuracy throughout time (Dantata et al., 2006; Flyvbjerg, 2007, 2014; Gao & Touran, 2020). Gao and Touran (2020) compared cost performance data in US rail infrastructure from recent projects with data found in earlier studies, including Pickrell (1990, 1992), Dantata et al. (2006), FTA (2003, 2008), and Booz (2006), generating a sample of 81 projects executed between 1980 and 2018. The study shows that the projects had an average cost overrun of 31.2%, and 70 projects (86,5%) had cost overruns (Gao & Touran, 2020). While they found evidence that cost estimate accuracy improved over time, this finding remains inconclusive and statistically insignificant because projects throughout time have also increased in size and implementation time, and these factors have a negative impact on cost performance (Gao & Touran, 2020). The bigger a project and the longer it takes to implement a project, the higher the average cost overrun. When singling out 22 major projects (>$500 million), Gao and Touran (2020) found an average cost overrun of 48.5%.

7.2.2. Real options theory for transportation infrastructure project evaluation

Real options theory is a quantitative approach that originated in the 1960s in finance and economics as a critique against static discounted cash flow methods such as NPV-based methods (Dixit & Pindyck, 1994; Trigeorgis, 1996). NPV-based methods assume a single line of development for a most likely future that excludes the possibility of changing decisions if conditions in the project environment change (Cheah & Garvin, 2009; de Neufville, 2003; Pellegrino et al., 2013). A NPV becomes outdated if conditions change, especially in situations of high uncertainty, creating the risk of decision making based on outdated information. A 'real option' – an option in real assets – instead refers to a decision taken today that allows for actions to be undertaken in the future (Lyons & Davidson, 2016). A real option is the right, but not the obligation, to change courses in the future depending on how uncertainty unfolds (Dixit & Pindyck, 1994; Garvin & Ford, 2012). The flexibility to respond to changing conditions allows to benefit from unexpected upside opportunities and avoid losses of downside events or unfavourable conditions (Geltner & De Neufville, 2012; Gil, 2009; Trigeorgis, 2005). The higher the uncertainty, the more valuable flexibility becomes (Cheah & Garvin, 2009; de Neufville, 2003).

Real option applications in (transportation) infrastructure have been initiated in the early 1990s and have grown ever since (Machiels et al., 2021b; Martins et al., 2015; Trigeorgis, 1996). We discuss some applications relevant for this paper because they applied ROT to an actual transportation infrastructure project. Broader overviews can be found in Martins et al. (2015) and Machiels et al. (2021b). Thijssen (2015) applies dynamic programming, a real options valuation technique to determine the optimal timing of investments, to determine whether an investment should be made in the first phase of a high-speed rail link between London and Birmingham (UK). The study found that, contradictory to the positive NPV from the actual project, an economic case for the project cannot be made when considering construction cost and revenue uncertainty. Couto et al. (2012) applied dynamic programming to determine the optimal timing of investment in a Portuguese high-speed rail project under demand uncertainty. Their approach was later expanded to consider cost and benefit (demand) uncertainty in the same case in Pimentel et al. (2017). Couto et al. (2022) use dynamic programming to assess the optimal timing of investment for the new Montijo airport in Lisbon under future demand uncertainty. These four studies offer valuable empirical insights for actual decision making, but dynamic programming requires an understanding of advanced mathematical techniques (de Neufville & Scholtes, 2006; Machiels et al., 2021b), inhibiting the adoption of their approaches by practitioners.

Recent real option applications try to diminish the mathematical complexity and rely on simpler real option valuation methods than dynamic programming. Oliveira et al. (2021) use a binomial lattice approach with grow options to assess the real option value of expanding the Ponta Delgada airport in the Azores under conditions of future demand uncertainty. Di Maddaloni et al. (2022), based on Favato and Vecchiato (2017) and Collan et al. (2009), combine scenarios to quantify uncertainties with a fuzzy pay-off method to value real options, and apply their approach to an ex-post case study of the rail Line C extension project in Rome. The fuzzy pay-off method does not require advanced mathematics because it is based on NPV methods, while the scenario approach helps to better estimate changes and uncertainties in a real-world context (Di Maddaloni et al., 2022; Favato & Vecchiato, 2017).

While these studies provide empirical applications and some manate to downsize the modelling and technical complexity of real options, their applications remain limited to relatively easy projects (Di Maddaloni et al., 2022). Easy in these decision-making situations does not mean less complex, it means that the decision-making question at hand is straightforward: whether (and possibly when) to invest or not? As we will see in the case study, transportation infrastructure projects often present decision makers not only with the question of whether to invest, but also what to invest in. Transportation infrastructure planning may require comparing multiple project alternatives. In the case of rail infrastructure, alternatives could differ based on the route, the number and location of stops, the construction method (above- or underground), the rail type (light-rail, heavy rail), etc. Real option models developed so far for transportation infrastructure projects do not show how to value options in situations of multiple project alternatives.

7.3. Methods and materials

7.3.1. The TIPROE model

To analyse the project value of infrastructure projects under conditions of uncertainty and flexibility, we develop a simulation model derived from the PSS (policy support system) suite simulators developed by Welkenhuysen et al. (2018); Welkenhuysen and Piessens (2017); Welkenhuysen et al. (2013); Welkenhuysen et al. (2017). In its current version, PSS IV was developed as a techno-economic forecasting model to analyse the risk and value of investment decisions of CO2 capture, transport and geological storage, and CO2-enhanced oil recovery. PSS IV is not an analytical or optimisation model that calculates the exact solution like the classical real options approach following Dixit and Pindyck (1994), but a numerical simulation model that combines Monte Carlo simulations with limited foresight and a real options analysis in the form of a decision tree. The simulation model returns an average Net Present Value (NPV) that integrates the value of flexibility as the project value. We tailor the PSS IV method to the context of transportation infrastructure projects, and call it the TIPROE model (Transportation Infrastructure Project Real Options Evaluation model).

PSS IV incorporates uncertainties through Monte Carlo following a similar logic as the Datar-Mathews method (Mathews et al., 2007). Mathews et al. (2007) developed a real options approach that represents an extended NPV analysis using Monte Carlo simulations and spreadsheets to determine option values. Monte Carlo simulation is a method to simulate uncertainties as stochastic parameters, by performing hundreds or thousands of iterations during each simulation. The stochastic parameter values are randomly defined (from a pre-defined uncertainty distribution), returning a different parameter value and project value or NPV for each Monte Carlo iteration (Mathews et al., 2007; Welkenhuysen et al., 2013). In that way, a range of project values is generated that can be presented as a probability distribution. The option value is the mean of all the project values, multiplied by the probability of positive outcomes (Mathews et al., 2007), assuming that negative outcomes will be terminated.

Flexibility or optionality following real options logic is embedded in PSS IV as a decision tree with potential investment options for decision-making (Welkenhuysen et al., 2017). A decision tree consists of branches that are each unique and that each represent a different future or decision-making pathway. In each pathway, different consecutive decisions are taken throughout a decision-making period. Decision making in these branches can differ based on the specific investment option(s) in each branch (e.g., transportation infrastructure alternatives), and the timing of decision making.

PSS IV advances Monte Carlo simulations with the addition of limited foresight. Real options analysis assumes that there is a growing uncertainty towards the future for one or more parameters. In most real option models based on the analytical real options approach described by Dixit and Pindyck (1994), The amount of uncertainty is quantified a priori and is usually assumed to behave as a geometric Brownian motion. Such uncertainty gives rise to a limited foresight on decisions being taken. Such limited foresight can take different shapes. In the case of the classic real options approach by Dixit and Pindyck (1994), the uncertainty ranges are fixed based on assumptions and (historical) data, and project decisions can be made in an objective and analytical way. In reality, though, the range and nature of uncertainty is not always exactly known (Welkenhuysen et al., 2017), as is for example the case with large infrastructure projects. Real limited foresight means that the amount of uncertainty is not exactly known, and some variation on the outcome still exists beyond the pre-defined uncertainty ranges. This inevitably leads to imperfect decisions instead of optimal decisions, also called near-optimal decisions (Welkenhuysen et al., 2018; Welkenhuysen & Piessens, 2017; Welkenhuysen et al., 2017).

Limited foresight about the future is represented in the PSS IV simulator through the integration of two nested Monte Carlo simulation processes, a primary and secondary Monte Carlo simulation. The primary Monte Carlo simulation is the same as described earlier, each simulation containing hundreds or thousands of iterations, in which the stochastic parameter values assigned during each iteration are considered as the expected values or reality. During each primary Monte Carlo iteration, a secondary Monte Carlo process is run with a limited number of iterations (e.g. 25). During the secondary Monte Carlo process, it is assumed that the stochastic parameter value set during the primary Monte Carlo iteration can still rise or fall into the future. In PSS IV, these are called the outlook parameters that represent the real limited foresight with a growing uncertainty towards the future (Welkenhuysen et al., 2018; Welkenhuysen & Piessens, 2017; Welkenhuysen et al., 2017).

In the TIPROE model, because of the limited amount of detailed available data, a slightly different approach is taken. Instead of generating price paths or processes that vary over time, in the TIPROE secondary Monte Carlo, fixed price paths, though with an initial random component, are set (green lines in Figure 7.1). In the PSS IV simulator, near-optimal investment decisions are made based on the outlook parameter values in the secondary Monte Carlo process, after which the actual or average values from the primary Monte Carlo are used to calculate the project value of the decision made during the secondary Monte Carlo process. This means that the values that form the basis for

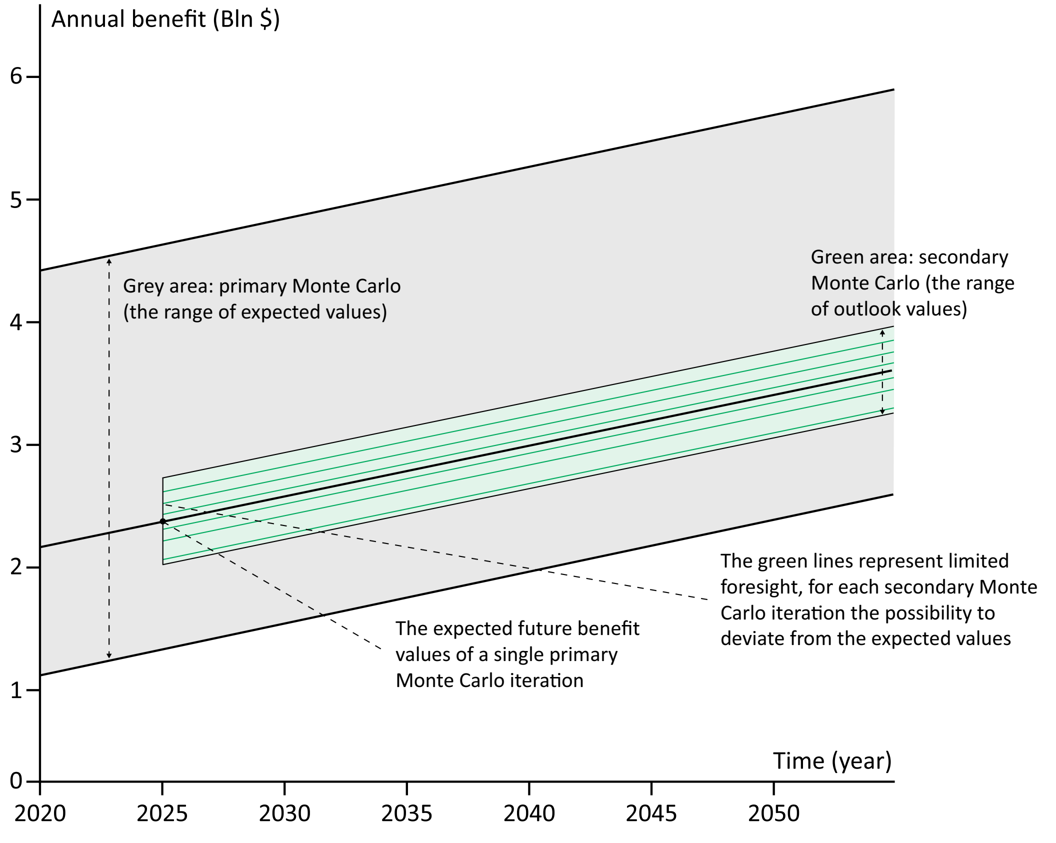


Figure 7.1. *Example of the concept of limited foresight, based on Welkenhuysen et al. (2017). Decisions for each decision-making year, in this case 2025, are based on the outlook values (green lines), but can differ from the expected future values that are used to value the investment*

the initial decision making differ from those used to calculate the project value in the end, reflecting a more realistic situation in which decisions are made based on limited information about the range of uncertainties.

In this study, we further tailor the PSS simulation method to transportation infrastructure planning by expanding it with scenario planning methods to determine the value distribution of the stochastic parameters, hence creating the TIPROE model. Scenario planning methods are defined as “methods that involve the analysis of key uncertainties and the creation of multiple alternative plausible scenarios” (Goodspeed, 2017, p. 1). Previous studies already proposed the integration of scenario methods and ROT in transportation infrastructure (Di Maddaloni et al., 2022; Lyons & Davidson, 2016). Scenario methods allow to quantify uncertainties from real world contexts, which can then be incorporated in real options models. For a more elaborate overview of how scenario planning methods and real options approaches strengthen each other, see Di Maddaloni et al. (2022), Miller and Waller (2003), and Alessandri et al. (2004).

7.3.2. Case study: Uncertainty and flexibility in New Crossing

We will apply the TIPROE model to New Crossing, a planned multibillion rail infrastructure project in the San Francisco Bay Area, California. The project includes a new underground Transbay rail tunnel crossing the water between Oakland and San Francisco to improve public transportation connections between East Bay and West the Bay. New Crossing is part of Link21, a rail infrastructure program with the aim to make the passenger rail system better connected and more efficient, sustainable, and affordable. Link21 is a joint program managed by two rail operators: BART (San Francisco Bay Area Rapid Transit), a light-rail system that serves five Bay Area counties, and Capital Corridor, a standard gauge passenger regional rail service that serves the Northern California Megaregion. New Crossing will be the core and most costly project of Link21. Link21 is in 2022 in the early phase of project identification. At the end of this phase, a decision will be made about whether New Crossing will be advanced to the next phase, and if so, whether New Crossing should be constructed for BART, regional rail, or both rail services.

New Crossing and Link21 are in turn part of Plan Bay Area 2050 (PBA2050), $1,4 trillion long-term planning vision for the San Francisco Bay Area. PBA2050 was approved in October 2021 and developed by the Metropolitan Transportation Commission (MTC) and the Association of Bay Area Governments (ABAG) (ABAG & MTC, 2021b). Prior to the creation of PBA2050, an exploratory scenario planning exercise was performed, during which three distinct scenarios (‘Futures’) were developed for the San Francisco Bay Area based on different combinations of assumptions for 26 uncertainties (ABAG & MTC, 2020). Uncertainties are external forces over which the Bay Area exerts no control, and include environmental, political, economic, land use, and transportation uncertainties. Based on the three Futures, three distinctive social benefit scenarios were calculated by MTC and ABAG for all transportation projects of PBA2050, including New Crossing, using their project performance assessment methodology (ABAG & MTC, 2021a).

Table 7.2 gives an overview of the project values for each Future for three most feasible project alternatives of New Crossing: a double track BART crossing, a double track regional rail crossing, and two double track tunnels, one for BART and one for regional rail (ABAG & MTC, 2019). Double track means one track in each direction. The three benefit scenarios are an aggregation of the 26 uncertainties. Table 7.2 shows that, for each alternative, there is the possibility to have a negative NPV in one or more Futures. In addition, we can also assume there is uncertainty about the project costs, specifically the initial capital costs. The cost figures shown in Table 7.2 are early estimates based on plans that lack a detailed technical design and an environmental impact assessment.

Table 7.2. *Net present value of New Crossing project alternatives in three Futures (scenarios). Numbers are discounted billion USD (2019 values). (ABAG & MTC, 2021a)*

Project alternative		**Future 1: Rising Tides, Falling Fortunes**	**Future 2: Clean and Green**	**Future 3: Back to the Future**
Double track regional rail tunnel	Total costs	52.8	52.8	52.8
	Total benefits	30.7	79.3	98.0
	NPV	-22.1	26.5	45.2
Double track BART tunnel	Total costs	43.3	43.3	43.3
	Total benefits	21.6	47.3	42.7
	NPV	-21.80	3.90	-0.70
Two double track tunnels (BART & regional rail)	Total cost	96.3	96.3	96.3
	Total benefits	47.1	121.0	114
	NPV	-49.20	24.70	17.70

Intuitively, we could assume that a decision maker with a risk taker personality would choose the regional rail alternative, while a risk-aversive decision maker would decide not to invest in New Crossing at all. If a decision would be made based the average NPV of each alternative across the three Futures, regional rail would be chosen with the highest average NPV of $16.5 billion. However, if we would increase the capital cost with 48.5%, the average cost overrun of major US rail infrastructure projects (Gao & Touran, 2020), and then calculate the average NPV, no project alternative would be chosen. The traditional NPV-based approach remains a static now-or-never comparison of different project alternatives in different scenarios, and offers little aid to decision makers in situations of cost and benefit uncertainty. Following real options reasoning, we can expect flexibility to have value under the uncertain conditions presented here. This value of flexibility should be integrated into the NPV calculation.

We identified flexibility options for New Crossing prior to this research during interviews with project team members of Link21 (Chapter 6). Based on the interviews, we designed a decision tree for New Crossing as shown in Figure 7.2. The first option is the option to not invest (NI). A decision maker always has a choice to not invest in a project if the expected benefits would not outweigh the expected costs. Options RR, BART and RR&BART are the three project alternatives shown in Table 7.2. Options RR+ and BART+ are similar as RR and BART, but with the important addition of a grow option that grants the right, but not the obligation, to implement an additional double track tunnel for the opposite rail type in the future. If the grow option embedded in RR+ and BART+ would be executed, an additional tunnel is implemented for BART (+BART) and regional rail (+RR) respectively. Options RR+ and BART+ are slightly more expensive than RR and BART respectively because the grow option has a cost for configuration of the tunnel mouths and connections to existing networks to not inhibit the implementation of an additional tunnel in the future.

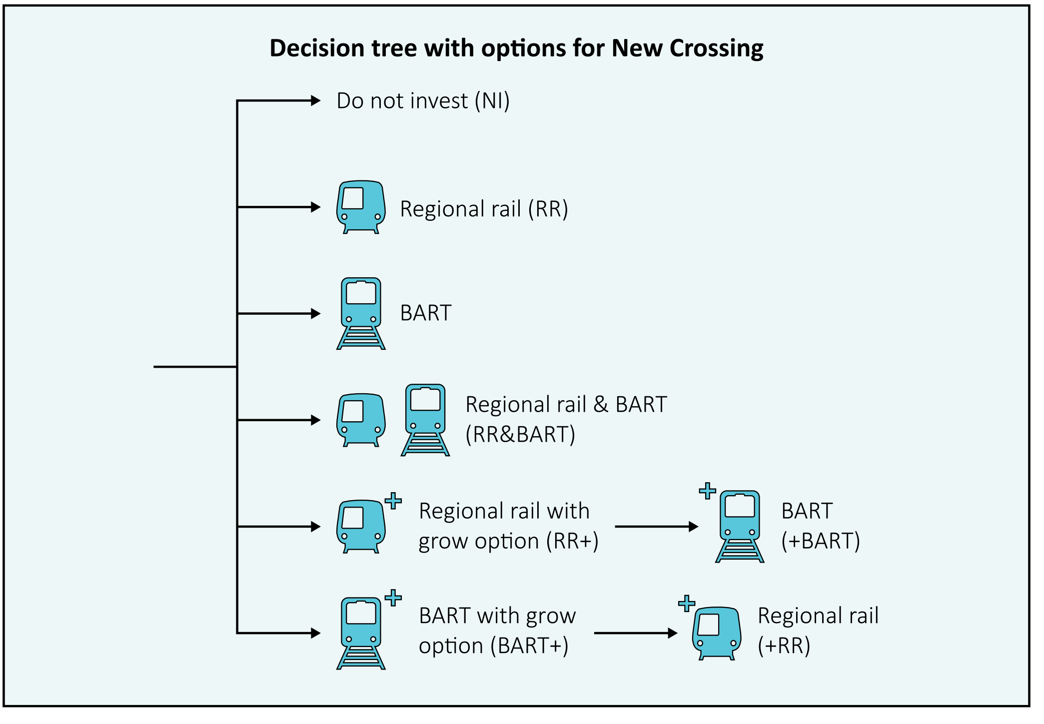


Figure 7.2. *Decision tree options for New Crossing. Source of icons: ABAG and MTC (2019)*

7.4. Application of the TIPROE model to New Crossing

We will showcase how the TIPROE model can inform New Crossing decision makers and project team members about the impact on the project value of uncertainties and flexibility options. The steps of a complete TIPROE model simulation are visualised in Figure 7.3. The text boxes in Figure 7.3 each represent a step in the process, and the arrows represent loops, meaning the steps within a loop are repeated for the duration of that loop. For example, steps 2-5 are each performed for one secondary Monte Carlo iteration, and thus have to be repeated for every secondary Monte Carlo iteration. We developed the model with Visual Basics for Applications in Excel spreadsheets. The model code can be found in the Appendix 4.

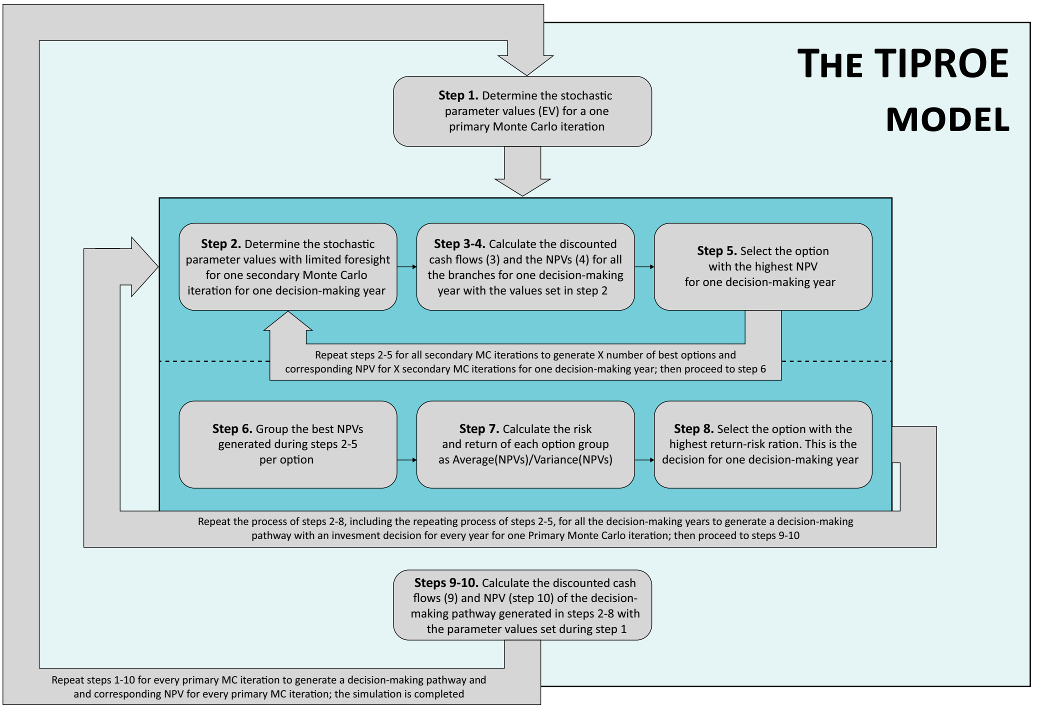


Figure 7.3. *The TIPROE model procedure*

7.4.1. Preparatory task: Build the decision tree

Before the simulation can be initiated, we had to redesign the decision tree from Figure 7.2 into an Excel table with the columns as decision-making moments and the rows as tree branches. The NPVs from New Crossing (table 7.2) are based on the assumption that construction would start in 2025. We implemented the flexibility option to delay investments (NI) until 2034 for options RR, BART, RR+, BART+, and RR&BART. This means that aside from a choice between these options – in addition to the option NI – there is also flexibility in the timing of decision-making, with ten decision-making moments during this first decision-making period (2025-2034). If a decision is made for a certain year, it is assumed that construction starts in that decision-making year. If a branch includes an investment during the first decision-making period for option RR+ or BART+, we assume another ten-year decision-making period between 2070 and 2079 during which the grow option can be executed, and an additional tunnel can be implemented for BART (+BART) and regional rail (+RR). If the grow option is executed, the branch's NPV is the sum of the NPVs of RR+ and +BART (or BART+ and +RR). This decision-making period is based on the assumption that it is unlikely for two projects of this size to receive funding and go through the same lengthy decision-making process shortly after each other. This generates a decision tree with 251 branches or unique decision-making pathways, including one branch with no investments at all (option NI). Figure 7.4 shows some possible branches of the decision tree.

Branch	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2070	2071	2072	2073	2074	2075	2076	2077	2078	2079
2	RR	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
9	NI	NI	NI	NI	NI	NI	NI	RR	/	/	/	/	/	/	/	/	/	/	/	/
15	NI	NI	NI	BART	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
16	NI	NI	NI	NI	BART	/	/	/	/	/	/	/	/	/	/	/	/	/	/	/
31	NI	NI	NI	NI	NI	NI	NI	NI	NI	RR& BART	/	/	/	/	/	/	/	/	/	/
33	NI	RR+	/	/	/	/	/	/	/	/	NI	NI	NI	NI	NI	NI	NI	NI	NI	NI
90	NI	NI	NI	NI	RR+	/	/	/	/	/	NI	NI	NI	NI	NI	NI	NI	NI	+BART	/
91	NI	NI	NI	NI	RR+	/	/	/	/	/	NI	NI	NI	NI	NI	NI	NI	NI	NI	+BART
165	NI	BART+	/	/	/	/	/	/	/	/	NI	NI	NI	+RR	/	/	/	/	/	/
218	NI	NI	NI	NI	NI	NI	BART+	/	/	/	NI	NI	NI	NI	NI	NI	+RR	/	/	/

Figure 7.4. *Examples of decision tree branches with decision-making pathways*

7.4.2. Preparatory task: Define the parameters

Table 7.3 gives an overview of the parameters and their values. The annual capital costs and annual benefits are considered uncertain and will be modeled as stochastic parameters. All other parameter values are fixed for the entire TIPROE model simulation. Monetary values are in billion US Dollars (2019 price value). Some parameter values are the same for all options, while others are option dependent. Cost and benefit data available from New Crossing are total discounted costs and benefits. Based on these totals, the construction and operational time, the discount rate, and the growth rate, we determined the annual capital cost and annual benefit. The minimum and maximum annual benefits reflect the lowest and highest benefit scenario from Table 7.2. A grow option cost of $0.5 billion was determined in communication with the Link21 project leader. This total cost was then annualised for the duration of the construction period. The annual growth rate was determined as the average of the annual population and job growth rate uncertainties of the three Futures. The mean cost overrun percentage is the mean cost overrun for major US rail infrastructure projects between 1980 and 2018 as found by Gao and Touran (2020). The parameter Annual capital cost CO is the Annual capital cost increased with the average cost overrun, generating the likely actual cost when considering cost overrun data for US rail infrastructure projects. All parameter values were presented for verification to the Link21 project leader during an interview.

Table 7.3. *Parameters for the TIPROE model application to New Crossing (A detailed description of all parameters can be found in Appendix 5)*

Parameters	NI	RR	BART	RR&BART	RR+	BART+	+BART	+RR
Construction time (year)	0	10						
Operational time (year)	0	45						
Annual capital cost (2019 $ bln)	0	6.2	5,6	11,8	6,2	5,6	5,6	6,2
Cost overrun (%	0	48.5						
Annual capital cost CO (2019 $ bln)	0	9.3	8,3	17,5	9,3	8,3	8,3	9,3
Annual capital cost_EV (2019 $ bln)	0	Stochastic random value (option dependent)						
Annual O&M (2019 $ bln)	0	0.5	0,3	0,8	0,5	0,3	0,3	0,5
Rehabilitation & replacement cost (2019 $ bln)	0	4.2	2,7	6,9	4,2	2,7	2,7	4,2
Residual value (2019 $ bln)	0	4.7	5,1	9,8	4,7	5,1	5,1	4,7
Annual grow option cost (2019 $ bln)	0	0	0	0	0,07	0,07	0	0
Min annual benefits (2019 $ bln)	0	1.6	1,1	2,4	1,6	1,1	1,1	1,6
Max annual benefit (2019 $ bln)	0	4.9	2,4	6,1	4,9	2,4	2,4	4,9
Annual benefits_EV (2019 $ bln)	0	Stochastic random value (option dependent)						
Annual benefits_LF (2019 $ bln)	0	Stochastic random value (option dependent)						
Growth rate benefits (%)	0	0.7						
Discount rate (%)	0	3						
Decision-making period 1	0	2025-2034					/	/
Decision-making period 2	0	/	/	/	/	/	2070-2079	
Primary Monte Carlo iterations	1000							
Secondary Monte Carlo iterations	25							

Cost uncertainty: Annual capital cost_EV

We assume that the expected value (EV) of the annual capital cost is uncertain, and therefore model it as a stochastic parameter in the TIPROE model. For each iteration of the primary Monte Carlo process, the stochastic parameter value of each project alternative or option is sampled randomly from a normal distribution with the Annual capital cost CO as mean value and a standard deviation of 15%. This way, we consider the likely possibility that capital costs will still increase, which is usually not done in early estimates of ex-ante project evaluations. Gao and Touran (2020) found that major projects have an average cost overrun of 48.5% with a standard deviation of 34.8%. If we would use the same standard deviation, the simulation would return values for the annual capital cost_EV with a 5%-10% likelihood of cost underruns between 25% and 100%, which are unrealistically low values. We therefore adopted a standard deviation of 15%. This way, outliers on both side – underrun and overrun – remain within a reasonable range. This way, the median becomes higher in our distribution than compared to Gao and Touran's (2020) findings, which may lead to an overestimation of cost overrun and a pessimistic view. However, New Crossing's project alternatives have significantly higher early total cost estimates during the project development phase than the early estimates ($0.088-$10.7 bln, 2019 values) of the projects in the sample of Gao and Touran (2020). Following their findings that cost overruns increase as project size increases, we can assume that New Crossing is more sensitive to higher cost overruns than the projects in Gao and Touran's (2020) sample.

Benefit uncertainty: Annual benefits_EV and Annual benefits_LF

We assume not only that the benefits are uncertain, but also that the uncertainty range of the benefits is not exactly known, based on the assumption that the external factors from the Futures that determine the benefits are outside the control of decision makers and cannot be exactly predicted. To simulate this, we use limited foresight as explained earlier, and need to sample the stochastic parameter value for the annual benefits twice from a probability distribution, first for the expected annual benefits (Annual benefits_EV) during the primary Monte Carlo process, and second for the limited foresight annual benefits (Annual benefits_LF) during the secondary Monte Carlo process.

The Annual benefits_EV of each project alternative or option are determined based on benefit scenarios from the Futures as shown in Table 7.2. The Futures generate a range of benefits for each project alternatives, with a minimum (Min annual benefits) and maximum (Max annual benefits) benefit scenario. Because PBA2050 was developed around the idea that each of the Futures have an equal likelihood of occurrence, the stochastic parameter Annual benefits_EV is a random value drawn from a uniform distribution between the minimum and maximum annual benefit for each project alternative. This means that each value within the distribution has an equal likelihood of being drawn.

Because we assume that the benefits become more difficult to predict the further into the future we go, the value drawn for the Annual benefits_EV is uncertain in itself. Limited foresight prescribes that future values (Annual benefits_LF) can still differ from the expected annual benefits because uncertainty about the future is not perfectly known. Therefore, for each single primary Monte Carlo process, a secondary Monte Carlo process is performed with 25 iterations to generate 25 values for the Annual benefits_LF that deviate slightly from the Annual benefits_EV. To assign this value, for each secondary

Monte Carlo iteration, a random value is drawn from a normal distribution with the Annual benefits_EV as the mean expected annual benefit and a standard deviation of 5%. The standard deviation is deliberately small such that the actual annual benefit value will only deviate slightly from the expected annual benefit.

7.4.3. The TIPROE model simulation procedure

Step 1: Initiate the first primary Monte Carlo iteration and determine the stochastic parameter values EV

The TIPROE model simulation starts by entering the first primary Monte Carlo iteration. At the start of the iteration, the stochastic parameter values for Annual capital cost_EV and Annual benefits_EV are set for the first iteration.

Step 2: Initiate the first secondary Monte Carlo iteration for the first decision-making year and determine the stochastic parameter value LF

For each primary Monte Carlo iteration and for each of the decision-making years (2025-2034, 2070-2079), the secondary Monte Carlo process is performed in steps 2-5. At the start of the simulation, we perform the secondary Monte Carlo process for the first primary Monte Carlo iteration and the first decision-making year (2025) to determine which decision to make in year 2025. Each secondary Monte Carlo process consists of 25 iterations. For each of these iterations, in step 2, a stochastic parameter value is sampled for Annual benefits_LF based on the sampled value for Annual benefits_EV of a single primary Monte Carlo iteration. This means that for each decision-making year, 25 iterations will be performed and thus 25 values will be determined for the Annual benefits_LF.

Step 3-4: Calculate the future discounted cash flows and NPVs of all the branches for the first secondary Monte Carlo iteration during the first decision-making year

In step 3, after a random value is assigned for Annual benefits_LF for each project alternative for the first secondary Monte Carlo iteration, the discounted cash flows are calculated of all the branches in the tree for the first decision-making year. This means that the discounted cash flows of each branch are calculated based on the investment option of the first decision-making year (or first column) of each branch, while also considering future investment possibilities. For example, branch number 9 in Figure 7.4 shows a sequence of decisions where there is no investment (NI) until 2031, and a decision to invest in regional rail (RR) in 2032. The calculations made for decision-making year 2025 of this branch will thus include the discounted cash flows of investing in option RR in year 2032. This way, the flexibility to delay an investment is considered by calculating the values of future possible investments if no investment would be made during the first decision-making year. In branches that include, for example, both options RR+ and +BART, as with branch numbers 90 and 91 in Figure 7.4, the discounted cash flows are calculated for two future investments.

In step 4, the NPVs are calculated for all the branches of the decision tree for the first decision-making year by calculating the sum of all the total discounted cash flows, wherein costs are expressed as negative values. We now have generated a NPV for all the 251 branches for a single secondary Monte Carlo iteration during the first decision-making year.

Step 5: Select the best option with the highest NPV for the first secondary Monte Carlo iteration during the first decision-making year

Once we have 251 NPVs, one for each branch, the option for the first decision-making year with the highest NPV will be chosen. Once this is done, we have generated a best option and a corresponding NPV for the first secondary Monte Carlo iteration. The best option will always have a NPV of 0 or higher, because not investing (NI) is better than investing in a project with a negative NPV. Step 2 to 5 are now repeated for every of the 25 secondary Monte Carlo iterations. By repeating the process of steps 2 to 5, the model generates 25 best options and 25 corresponding best NPVs for the first decision-making year.

Step 6-8: Group the best NPVs and make a decision for the first decision-making year

In step 6, the NPVs of the same best option are grouped per option. For example, if among the 25 best options, option RR is present eight times, then the eight corresponding NPVs of this option are grouped. In step 7, the NPVs in each option group are then compared to calculate the return-risk ratio as the average of the NPVs in an option group divided by the variance of the NPVs in an option group. The decision-making criterion in our model is to select the best option as the option with the highest NPV and the lowest risk. In step 8, the option group with the highest risk and return for its NPVs will be selected as the best option. This option is the decision made for the first decision-making year based on limited foresight about the benefits.

When a decision is made for the first decision-making year, steps 2-8 are then repeated for all subsequent decision-making years. At each next decision-making year, the model excludes branches from the process based on the decision made during the previous year. For example, if during decision-making year 1, a decision is made to not invest, only the branches are kept that include option NI in the first decision-making year, and all branches that include other options are excluded. For the examples shown in Figure 7.4, this would mean that branch 2 is excluded while the other branches are kept. Keep in mind that steps 2-8 are all performed and repeated for a single primary Monte Carlo iteration. When these steps are completed for all the decision-making years, the model has generated a decision-making pathway of best options and decisions made during each decision-making year. As such, this final decision-making pathway is always one of the branches of the decision tree (Figure 7.4).

Step 9-10: Calculate the expected discounted cash flows and NPV of the decision-making pathway for the first primary Monte Carlo iteration

The decision-making pathway generated at the end of step 8 includes the decisions made based on the values returned from the secondary Monte Carlo process. The decisions are thus made based on limited foresight about the benefits. In steps 9 and 10, similar as in steps 3-4, the discounted cash flows and total project value (NPV) of the investments in the decision-making pathway will be calculated based on the parameter values set at the start of the first primary Monte Carlo iteration. This means that the model uses the value of Annual benefits_EV instead of Annual benefits_LF to determine the project value, while all other parameter values remain the same between the primary and secondary Monte Carlo process. In case of branch 90 in Figure 7.4, the expected project value is the sum of the NPVs of option RR+ with the start of construction in 2029, and of option +BART with the start of construction in 2078. This is the decision-making pathway and project value of one primary Monte Carlo iteration. In total, 1000 primary Monte Carlo iterations are made, so the model will repeat the process of steps 1-10 for the remaining 999 primary Monte Carlo iterations. This means that for each of the 1000 primary Monte Carlo iterations, the secondary Monte Carlo process will be completed for every decision-making year (steps 2-5), followed by a decision for a best option in each decision-making year (steps 6-8). This will generate 1000 decision-making pathways with investment decisions and 1000 corresponding project values (NPVs) that can be analysed.

7.5. Results

We present the results of the application of the TIPROE model to New Crossing in three ways. First, we present the results of a traditional NPV approach with sensitivity analysis in which we calculated the project values of the three base alternatives (RR, BART, RR&BART) under conditions of uncertainty as a now-or-never decision in the year 2025, excluding the flexibility options. The NPVs of each of the three alternatives were calculated 1000 times using the primary Monte Carlo process as in the TIPROE model with Annual capital cost_EV and Annual benefits_EV as stochastic parameters. Table 7.4 shows a negative mean NPV for all project alternatives, except for regional rail if there is no capital cost uncertainty. Following the logic of a static NPV analysis, the decision would be to not invest in any of the project alternatives under conditions of both benefit and cost uncertainty.

Second, we present the results of the TIPROE model procedure from section 4, which we call the base case, and compare the results with the outcome of the static NPV analysis. By comparing the TIPROE results with the static NPV results, we can also calculate the real option value, i.e. the value of flexibility, which is the difference between the value

Table 7.4. *Static NPV analysis of New Crossing under conditions of uncertainty (2019 billion USD)*

Project alternative	Mean NPV	Median NPV	Min NPV	Max NPV	Q1 NPV	Q3 NPV
Average cost overrun of 48,5% to determine stochastic annual capital cost value						
Regional rail (RR)	-11.8	-12.1	-70.8	44.3	-28.4	5.0
BART	-31.3	-31.0	-66.1	2.0	-39.4	-23.3
RR&BART	-55.5	-56.1	-143.0	29.5	-75.0	-36.3
Average cost overrun of 31.2% to determine stochastic annual capital cost value						
Regional rail (RR)	-3.8	-4.2	-70.8	49.6	-20.3	12.8
BART	-24.2	-23.7	-56.2	5.5	-31.9	-16.5
RR&BART	-40.6	-40.9	-122.0	38.1	-59.5	-21.8
No cost overrun and no capital cost uncertainty. fixed annual capital cost value						
Regional rail (RR)	11.4	10.8	-40.1	60.5	-6.0	28.1
BART	-11.0	-10.8	-37.7	17.1	-17.7	-4.3
RR&BART	-13.4	-12.6	-85.7	47.2	-33.2	6.1

of the total project with and without flexibility options (Garvin & Ford, 2012; Geltner & De Neufville, 2012; Trigeorgis & Reuer, 2017). If the real option value is positive, then flexibility adds value to New Crossing:

Real option value = Mean NPV TIPROE - Mean NPV static

Third, we perform sensitivity analyses on the TIPROE model to see how changing some of the fixed parameter values would impact the results compared to the base case, specifically the discount rate, the decision-making periods, the grow option cost, and the cost overrun assumption. Table 7.5 provides an overview of the sensitivity analysis and the difference between the other model runs (Model IDs) compared to the base case. The run time of the base case and the other Model IDs was around 12 hours each.

We found that in none of the Model IDs, decision-making pathways were returned that include investments in options BART, BART+, +RR, and RR&BART. This means that investing in a New Crossing for BART during the first decision-making period is never an attractive option compared to other options. Also, investing immediately in full capacity with both regional rail and BART is not attractive. For these options, there is no difference between the real options analysis and the static NPV analysis (Table 7.4). We therefore only discuss the results for options NI, RR, RR+ and +BART. We do not discuss results about options that have an investment probability of less than 1%. The model results allow us to analyse (i) the probability of investing in an option (independent of the timing); (ii) the probability of executing a grow option; (iii) the timing of investing in an option; and (iv) the expected real option value and project value (NPV).

Table 7.5. Model runs of the TIPROE model for New Crossing and their difference from the base case

Model ID	Difference compared to the base case
DR	Increase the discount rate from 3% to 7% (suggested sensitivity test in (ABAG & MTC, 2021a))
DMPA	Lengthen both decision-making periods to 2025-2044 and 2060-2079, with a decision every two years
DMPB	Advance the decision-making period for executing the grow option to 2060-2069
DMPC	Advance the decision-making period for executing the grow option to 2050-2059
GOC1	Increase the total grow option cost from $0.5 bln to $1 bln
GOC2.5	Increase the total grow option cost from $0.5 bln to $2.5 bln
GOC5	Increase the total grow option cost from $0.5 bln to $5 bln
CO31.2	Decrease the mean cost overrun from 48.5% to 31.20%, the mean cost overrun of all projects between 1980 and 2018 in the sample of Gao and Touran (2020).
CO0	Decrease the mean cost overrun to 0% and remove capital cost uncertainty (fixed Annual capital cost_EV now equals Annual capital cost as described in Table 3).

7.5.1. The probability of investing in an option and executing a grow option

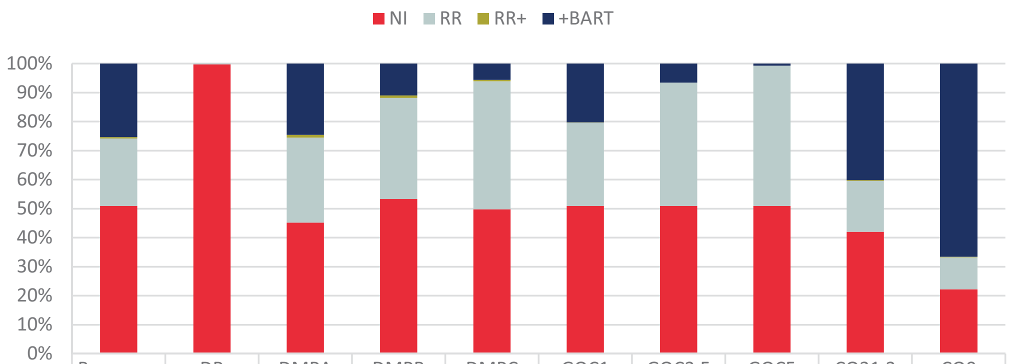
Figure 7.5 shows the probability of investing in an option. In the base case, there is a probability of 50.9% to not invest in any of the project alternatives (NI). Investments in RR and RR+ followed by +BART have a probability of 23.3% and 25.3% respectively. This means that if an investment is made, the first investment will always be the construction of a New Crossing for regional rail. Figure 7.5 also shows that, regardless of the probability to invest in a certain option, if an investment is made in RR+ during the first decision-making period, then the grow option will almost always be executed, varying between a probability of 92% and 100%, and an investment will be made in +BART. This finding shows that having the flexibility to phase investments in time is valuable, as purchased grow options are nearly always executed in the future, compared to the 0% probability investment in an immediate realisation of full capacity (RR&BART).

When comparing the probability to invest in an option in the base case with the other model IDs, we find that increasing the discount rate from 3% to 7% in DR leads to a probability of 99.7% to not invest. If the discount rate is higher, it becomes nearly impossible for the benefits that occur later in time to outweigh the construction costs that occur earlier. Because of this low investment probability, DR is not further discussed in the results that follow.

When expanding the decision-making periods in DMPA, we find a slightly lower probability of 45.2% to not invest, and mainly an increase in the probability to invest in RR (29.3%). In DMPB and DMPC, we find that gradually advancing the decision-making period of investing in +BART leads to less investments in +BART and therefore also in RR+. This shows that having the grow option in RR+ is only valuable if the opportunity to invest in +BART lies far enough into the future. Otherwise, investments will rather be made in RR, with a probability of 34.9% and 44.1% in DMPB and DMPC respectively.

As expected, increasing the grow option cost in GCO1, GCO2,5 and GCO5 makes investing in RR+ less attractive compared to the RR without the grow option. If the grow option cost is $5 billion, there is only a 0.7% probability to invest in RR+ and +BART. Based on this low probability, we find that the threshold where the NPV of a future investment cannot compensate the costs of having the flexibility of a future investment in the case of New Crossing is reached when the grow option cost is around $5 billion.

Finally, we find that, as expected, a reduced capital cost due to less or no cost overruns in CO31.2 and CO0 respectively leads to an overall higher probability of investing in New Crossing, with a large increase of the investment probability in +BART (40.2% in CO31.2 and 66.6% in CO0), contrary to a decrease of the investment probability to not invest (42% in CO31.2 and 22.2% in CO0) and to invest in RR (17.5% in CO31.2 and 11% in CO0). We thus find that a reduction of the capital cost through less or no cost overruns makes it more attractive to invest in both regional rail and BART, although phased with a grow option.



	Base case	DR	DMPA	DMPB	DMPC	GOC1	GOC2,5	GOC5	CO31,2	CO0
+BART	25,3%	0,0%	24,6%	11,0%	5,6%	20,3%	6,6%	0,7%	40,2%	66,6%
RR+	0,5%	0,0%	0,9%	0,8%	0,5%	0,1%	0,0%	0,0%	0,3%	0,2%
RR	23,3%	0,3%	29,3%	34,9%	44,1%	28,7%	42,5%	48,4%	17,5%	11,0%
NI	50,9%	99,7%	45,2%	53,3%	49,8%	50,9%	50,9%	50,9%	42,0%	22,2%

Figure 7.5. *The probability of investing in an option in the different model IDs. RR+ means that the grow option +BART is not executed. +BART means an investment in both RR+ and +BART.*

7.5.2. The probability of the timing of investment

To analyse the timing of decision making if an investment is made, we show in Table 7.6 the probability of investing in RR, RR+, and +BART during the first five decision-making moments (DMM 1-5) and the last five decision-making moments (DMM 6-10). The empty cells in Table 7.6 reflect investments in options that have an overall investment probability of less than 1%, and are thus non-representative. The main finding across all the model IDs is that if a single investment is made, i.e. investing only in RR, the investment will generally occur later; while if an investment is made in regional rail with the possibility of an additional investment, RR+ followed by +BART, the time to invest in regional rail will occur sooner. We find that most early investments are made during the first decision-making year of an option's decision-making period, while late investments are mostly made during the last decision-making year of an option's decision-making. It is difficult to provide a clear explanation for this finding, but we could assume that investments during the last decision-making year are made to not avoid missing out on the benefits of that investment at all. In the case of RR and +BART, it is more attractive to delay the investment. One exception can be found in CO0, where no cost overrun leads to sooner investments in +BART.

Table 7.6. *The probability to invest in an option during the first or last five decision-making moments (DMM) of an option*

Option	DMM	Base case	DMPA	DMPB	DMPC	GOC1	GOC2.5	GOC5	CO31.2	CO0
RR	DMM 1-5	0%	6%	22%	32%	28%	34%	36%	0%	0%
	DMM 6-10	100%	94%	78%	68%	72%	66%	64%	100%	100%
RR+	DMM 1-5	67%	79%	86%	95%	74%	95%		72%	82%
	DMM 6-10	33%	21%	14%	5%	26%	5%		28%	18%
+BART	DMM 1-5	10%	7%	16%	13%	12%	12%		29%	61%
	DMM 6-10	90%	93%	84%	88%	88%	88%		71%	39%

7.5.3. The project value and the real option value

The mean project values following the real options analysis were calculated as the mean NPV of each option multiplied by the probability of investing in that option, following Mathews et al. (2007). Consequently, we can compare these project values with the project values from the static NPV analysis (Tabe 7.4) to determine the real option value in all model IDs, as shown in Table 7.7. We find that although there are differences in the probability of investing in certain options, there are no large differences between the mean NPVs of nearly all Model IDs, ranging between $4.33 billion and $5.19 billion, except for CO31.2 and CO0. The slightly higher NPV of DMPA would imply that an even larger flexibility in the timing of decision making by extending the decision-making periods, not the number of decision-making moments, would generate a higher project value. Not surprisingly, the project value increases significantly in CO31.2 and CO0 if the capital costs are reduced due to less cost overrun, or no cost overrun and no capital cost uncertainty.

When comparing the results with the project value of regional rail, the best or least negative alternative from the static NPV analysis in Table 7.4, we have a positive real

Table 7.7. *The project value and real option value of New Crossing under conditions of cost and benefit uncertainty and flexibility (2019 USD billion).*

Model ID	Mean NPV RR (static NPV)	Mean NPV (TIPROE)	Real option value = TIPROE mean NPV – Mean static NPV RR
Base case	-11.8	4.8	16.6
DMPA	-11.8	5.2	17
DMPB	-11.8	4.3	16.1
DMPC	-11.8	4.8	16.6
GOC1	-11.8	4.7	16.5
GOC2.5	-11.8	4.7	16.5
GOC5	-11.8	4.7	16.5
CO31.2	-3.8	8	11.8
CO0	11.4	16.9	5.2

option value for all model IDs and we find that New Crossing becomes worth investing if there is flexibility in the timing and phasing of investments available. The real option value is the added value of flexibility, thus proving that flexibility increases New Crossing's value. The real option value only increases when comparing the TIPROE mean NPVs with the static NPVs of BART and RR&BART.

Figure 7.6 shows the value patterns of the mean Annual capital cost_EV and the mean Annual benefits_EV of the chosen options across all the model IDs. We find that investments in RR, RR+, and +BART are only made if, on average, the annual benefits lie closer to the high benefit scenario (Max annual benefits) than to the low benefit scenario (Min annual benefits), and if the annual capital cost remains below or close around the average cost overrun of 48.5%. This means that the future need to evolve towards the *Clean and Green* or the *Back to the Future* scenario for the investment to be valuable. In these scenarios, cost overruns do not immediately cause a negative NPV, but need to be kept under control so they do not surpass 48.5%. This relation between benefits and costs is similar across all model IDs.

Similarly, we find that investing in both RR+ and +BART is only worthwhile if the annual capital cost and annual benefit of RR+ are sufficiently low and high enough respectively. If not, no investment is made (NI) or an investment is made in RR. This finding changes slightly for CO31.2 and CO0, where lower capital costs allow for lower benefits to still generate a positive NPV. We do not find significant changes between the mean Annual capital cost_EV and the mean Annual benefits_EV of +BART if an investment is made in RR or RR+. This means that the value of a future investment in +BART depends on a sufficiently high NPV for RR+. This intuitively aligns with the NPVs for BART in table 2 and 4 that show that BART in itself is a less attractive investment. Vice versa, we find that no investments (NI) are made in RR/RR+ and +BART if the the mean Annual capital cost_EV slightly surpasses cost overrun of 48.5% (or 31.2% in the case of CO31.2), and if the Annual benefits_EV lie closer to the low scenario than the high scenario. Similar to the findings from the static NPV analysis, we find that investing in New Crossing does not generate a positive NPV if the future would evolve towards the *Rising Tides, Falling Fortunes scenario*.

Based on these findings, we conclude that both cost and benefit uncertainty have a strong impact on the investment decision for New Crossing, and that positive NPVs are dependent both on keeping cost overrun under control and being reliant on a future that unfolds towards a high benefit scenario (e.g., the Futures Clean and Green of Back to the Future as shown in Table 7.2).

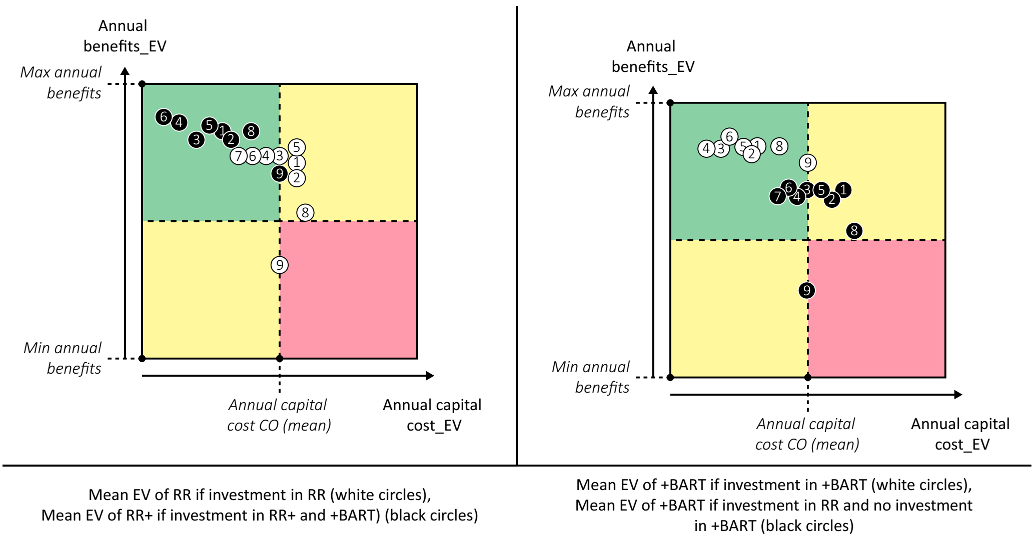


Figure 7.6. *The mean annual expected capital cost and benefit values of RR and RR+ if investments are made in RR and RR+ respectively (left figure), and of +BART if investments in +BART or investments in RR (and thus no RR+ and +BART). The numbers in the circles represent Model IDs (1 = base case; 2 = DMPA; 3 = DMPB; 4 = DMPC; 5 = GOC1; 6 = GOC2.5; 7 = GOC5; 8 = CO31.2; 9 = CO0). The figure does not show absolute values, but aims to show relative differences in value patterns.*

7.6. Discussion

7.6.1. Decision support for New Crossing

The real options model offers decision support from a cost-benefit perspective to the planners and decision makers of New Crossing. First, some findings from the static NPV analysis are reconfirmed by the TIPROE model results: a short-term investment in a BART tunnel or an immediate realisation of both a regional rail and BART tunnel are unattractive decisions. In the static NPV, regional rail is intuitively the most attractive investment alternative under conditions of benefit uncertainty when looking at Table 7.2, but becomes an unattractive decision if we also consider cost uncertainty and the possibility of cost overrun (Table 7.4). So, based on the results from Table 7.4, the static NPV approach informs the project team not to invest in New Crossing at all.

Once we embed flexibility options and evaluate New Crossing with the TIPROE model, the information to support decision making changes significantly. Not only do we find that regional rail (RR and RR+) becomes an attractive alternative, we also find that investing in a BART tunnel (+BART) on a longer term could also be a beneficial investment. There are, however, some important conditions that need to be fulfilled. First, capital costs need to be controlled to ensure that cost overruns do not exceed 48.5% compared to the current estimates for an investment in RR, while cost overruns compared to current estimates for investments in RR+ and +BART may not exceed 18%-31%, depending on the assumptions for fixed parameter values. Also, for an investment in RR+ and +BART, the grow option cost should not be too high, with a threshold around $5 billion. Second, expected future social benefits must lie closer to the high benefit scenario than the low benefit scenario from Table 7.2.

The real option analysis results can help decision makers to understand how to advance the project without the need to make a final now-or-never decision. The TIPROE model results suggest advancing the regional rail alternative to the engineering and design phase, and further research the grow option to design how a regional rail tunnel could be implemented so that it enables the construction of a second tunnel in the future, without requiring a detailed design for a BART tunnel. During the engineering phase and closer to construction, cost estimates become more accurate (Cantarelli, Flyvbjerg, et al., 2012; Cantarelli, Molin, et al., 2012; Cantarelli, van Wee, et al., 2012), although not entirely invulnerable to cost overruns, and the uncertainties of the Futures scenario planning exercise can be monitored to see in which direction the future is heading. A definitive decision about the implementation of a regional rail tunnel – with or without a grow option – only needs to be made after the design phase and prior to construction. This creates flexibility to further delay an investment if conditions are unfavourable.

7.6.2. Lessons learned for transportation infrastructure research and practice

The TIPROE model and the empirical application to New Crossing also provide general insights for transportation infrastructure research and practice. First, the empirical results show the value of real options over static NPV approaches in actual transportation infrastructure projects. This does not mean that flexibility will be beneficial or necessary in every project, but at least it is worth looking into, especially in complex multi-alternative projects such as New Crossing. Of course, we must accept that the actual outcomes are outside our control and uncertain, since there is still a period, in the case of New Crossing, of at least ten years of construction before the first benefits will materialise. Regardless of the outcomes, we can still make good and well-informed decisions, and the difference between the static NPV analysis and one that considers flexibility options from the start under conditions of uncertainty has shown that keeping options open does not require a now-or-never decision and can make investments more valuable.

Second, while the possibility of significant cost overruns is rarely considered in early project estimates, the results show that cost overruns decrease the project value and the probability of investing in a project, and increase the value of waiting. Decisions are often based on early estimates that advance one alternative and discard others, leading to a linear and vulnerable development pathway. Considering potential cost overruns as early as possible can help understand how much cost overrun a project could withstand to still have on average a positive NPV, given various benefit scenarios. This in combination with flexibility in the timing of decision-making allows to reconsider decisions and keep options open until more accurate information about costs is available.

Third, aside from the empirical contributions, the findings also offer some methodological contributions to transportation research and ROT. We have adapted an existing real options model and shown how various existing concepts, specifically scenarios, decision trees, limited foresight and Monte Carlo simulation, can be integrated to develop an ex-ante project evaluation model for transportation infrastructure under conditions of uncertainty and flexibility. The model is based on existing NPV-techniques familiar among transportation planners and infrastructure consultancy firms, avoiding advanced mathematics. Using scenarios helped to overcome the difficulty of quantifying uncertainties from a real-world context. The decision tree allowed us to compare multiple project alternatives in an integrated way, contrary to existing real option applications in transportation infrastructure that have focused mainly on projects with a single decision-making question or project alternative.

Finally, this research shows the importance of doing empirical research in collaboration with transportation planners and practitioners. The interviews conducted with the Link21 project team members allowed us to design the decision tree options from their point of view, offering an analysis about options that can be considered in the actual project. The empirical case was further strengthened by discussing the parameters with the project leader.

7.6.3. Research limitations

There are research limitations that provide opportunities to extend our approach and adapt it to other contexts in future research. First, data for the growth rate of the benefits, the decision-making periods, and the grow option cost were not available from the project information. We discussed the assumptions we made for these parameters with the Link21 project leader, and we performed sensitivity analysis for individual parameters through different model IDs.

Second, the PBA2050 Futures are visions of the Bay Area's future state in 2050, and the project information assumed 2025 to be the start of construction, meaning operations would end in 2080, whereas the flexibility of timing and phasing in our decision tree allowed the operations to run until 2129. We thus extrapolated the PBA2050 assumptions even further in the future. We tried to compensate this issue with limiting foresight, Also, the three Futures from PBA2050 were significantly different, offering a wide range in expected benefits.

Third, no data was available about the impact of competition between two rail operators – BART and Capital corridor (regional rail). In our model, we can still assume that the sum of their individual benefits could be larger than the benefits of RR&BART because we considered two phased investments over a longer period of time, as compared to the smaller total time period in RR&BART during which the two tunnels are both operational at the same time.

Fourth, we did not include shocks in our model. For example, the Covid pandemic has plummeted rail ridership in the Bay Area, and numbers have not yet recovered, especially on the existing BART tunnel. This is somewhat reflected in the negative Future (Rising Tides, Falling Fortunes) with lower growth figures of public transportation use, but future research can expand the model to include the impact of unforeseen disruptions.

Finally, we only approach decision making in New Crossing from the perspective of a socioeconomic cost-benefit analysis. Decision making in such projects is influenced by various elements, including multiple possible qualitative and quantitative criteria, stakeholder and power relations, the extent of consensus or conflict, political priorities and availability of public budgets, and existing institutions and decision-making procedures. One of the most important avenues for further research is finding out how approaches such as real options models can be embedded in such complex and political planning and decision-making contexts, and how tools like the TIPROE model can replace or complement static approaches and can be institutionalised in the ex-ante project evaluation of transportation infrastructure projects.

7.7. Conclusion

Coping with uncertainty and responding to changing conditions is an urgent challenge in transportation infrastructure projects to improve their cost and benefit performance. Static NPV-based approaches are not suited to address this challenge. We therefore developed the TIPROE model, a real options model to determine project values and compare multiple project alternatives under conditions of multiple uncertainties and flexibility options. To test the model, we applied it to New Crossing, a rail infrastructure project in the San Francisco Bay Area. The static NPV analysis resulted in negative values for all project alternatives under conditions of cost and benefit uncertainty. The real options analysis – for the base case – resulted in an average project value of $4.78 billion and a real option value of $16.6 billion under conditions of uncertainty and flexibility. Decision makers of New Crossing should advance the regional rail alternative to the engineering phase and further research the grow option for a future investment in BART, without the need to make a final decision yet.

The key findings from the empirical application show that: (i) having flexibility options compared with a static NPV-analysis with now-or-never decisions under conditions of capital cost and social benefit uncertainty increases the project value and significantly changes the decisions made; (ii) the consideration of (likely) cost overruns compared with early estimates significantly impacts the probability of investing in a project alternative, and increases the value of waiting until more accurate cost estimates are available; (iii) the integration of scenarios to incorporate uncertainties and a decision tree to incorporate multiple options helps to tailor real options approaches to complex transportation infrastructure projects; and (iv) collaborating with stakeholders from the case strengthens the value of the empirical data and results.

Further research must continue to explore the TIPROE model's potential in other transportation projects, allowing to further expand and adapt the model to different contexts. But most importantly, future research is needed to understand how alternative approaches to the static NPV-approach can become institutionalised and embedded in official transportation infrastructure planning and decision-making procedures.

8. Conclusion

In this final chapter, I will answer the main research question that I posed in Chapter 1, and I will present the main findings and contributions of this dissertation. Building on this, I will discuss research limitations and areas for further research; I will share some personal reflections from experiences throughout the research process of my PhD; and I will offer advice to practitioners about how they can use ROT in planning practice.

8.1. Answering the research questions

The main question of this dissertation is the following two-fold research question:

What is the current state of uncertainty management in complex spatial projects (CSPs) in Flanders, and how can uncertainty management be improved and adaptive planning be facilitated, with real options theory, in CSPs?

The current state of uncertainty management in Flemish CSPs was researched in Chapters 3 and 4 with a case study analysis of the Zeebrugge New Lock seaport infrastructure project. The main findings of these chapters were that while uncertainties are inevitable in CSPs, they are not managed proactively, uncertainty management is not a part of official CSP planning and decision-making procedures, and uncertainties are avoided as much as possible. To better understand what explains uncertainty avoidance, In Chapter 4, we developed a theoretical framework with three explanation models: the resource constraint model, the strategic behaviour model, and the planning institutions model. For the New Lock infrastructure project, we concluded that formal and informal planning institutions that determine the rules and procedures to be followed in CSPs dictate the most that uncertainties are to be avoided to not legally weaken the decisions and supporting project documents. The development and validation of this theoretical framework is an important contribution to planning research and practice, because understanding the causes of uncertainty avoidance allows us to understand what needs to change to proactively incorporate the impacts of uncertainties in CSPs.

Uncertainty management in Flemish CSPs is ad-hoc and nearly non-existent. When we compare this answer for the first part of the research question with the findings from Chapter 5, we can conclude that the current predict-and-plan approach used in Flemish CSP practices is in tension with the complex reality of CSP processes. The perceptions of uncertainty that were researched and revealed in Chapter 5 showed that stakeholders have heterogenous and different views about uncertainties and the future. In Flemish CSPs however, the dominant practice remains to search for agreed certainties, to rely on single future forecasts, and to narrow a CSP down to a single alternative early on. This exposes CSPs to two main vulnerabilities. First, the preferred alternative is considered most optimal based on estimates made about the future that do not consider how uncertainties and changes over time could impact the outcomes of each alternative. Second, each alternative is a linear development and does not consider adapting to change. The findings from Chapter 5 suggest that a different approach is needed, one in which uncertainties are proactively considered early on, and one in which adaptations to change are considered as much as possible through adaptive planning

The search for new approaches to improve uncertainty management and to facilitate adaptive planning in CSPs led to the development of ROT-based approaches in Chapters 6 and 7. In these chapters, ROT was applied qualitatively and quantitatively as a tool for adaptive planning to the US case study of Plan Bay Area 2050, more specifically its rail infrastructure program Link21 and Link21's largest project New Crossing. The availability of exploratory scenarios that had already been developed in preparation of PBA2050 allowed us to focus directly on the application of ROT. Departing from the available scenarios, in Chapter 6, we integrated ROT and scenario planning into an eight-step adaptive planning framework and applied it qualitatively to PBA2050 and Link21. Departing from available quantitative data and the exploratory scenarios, In Chapter 7, we developed the quantitative real options model 'TIPROE', and applied it to New Crossing to determine the project value under conditions of flexibility and cost and benefit uncertainty.

The empirical applications of these approaches in Chapters 6 and 7 prove that ROT can be used as a tool for adaptive planning in both a qualitative way and a quantitative way. The main contributions of Chapter 6 are the eight-step framework and the example of an adaptive plan as a visual road map in which the scenarios and real options come together. The main contribution of Chapter 7 is TIPROE, an Excel simulation model that avoids complex mathematics but still allow to consider the actual complexity of CSPs through the integration of multiple project alternatives and flexibility options. With the model, we proved that, for New Crossing, flexibility has value, and more importantly, that it potentially has more value than if flexibility options are not considered in a predict-and-plan approach. The empirical findings also show that ROT can be combined with other methods, in this case scenario planning and traditional net present value techniques used in cost-benefit analyses.

This dissertation's focus was on developing novel approaches for adaptive planning based on ROT. We successfully developed and tested these, but further research is needed to upscale the use of ROT and adaptive planning approaches in actual CSP practices, and in CSPs in different planning contexts. I will now offer some reflections for future planning research and practice.

8.2. ROT and adaptive planning in CSPs: The way forward

Based on the contributions of this thesis and my personal experiences, I will now discuss three related topics that must receive attention in future research and practice: contextual differences between planning cultures; how to transform planning practice from predict-and-plan to adaptive planning; and ROT within the bigger picture of institutions, politics, and power relations in CSPs. I will end with advice about how planning practitioners can already use ROT-based approaches for adaptive planning in practice today.

8.2.1. Context matters: Differences between Flanders and the United States

Initially, the research plan was to develop a real options approach for a CSP in Flanders. Because Flemish planning practitioners have few experience with uncertainties and adaptive planning, we first had to familiarize planning practitioners with these concepts. This step required more time than we expected. In the A102 case study, prior to the use of Q methodology, we sent out a preparatory survey to the study participants in which we asked them to provide an initial ranking of general uncertainty types, motivate their choices, and name specific uncertainties. The survey results were a disappointment. It seemed participants did not completely understand what uncertainty meant. Q methodology, although more time consuming, proved to be a better method to gauge perceptions of uncertainty because the list for the Q sorting interviews was prepared by the researchers. The Q sorting interviews themselves required sufficient time and patience to explain the ranking procedure and the contents of the uncertainty statements to the participants. Very few new uncertainties were added by the stakeholder themselves.

We overestimated – yes, we became victims of optimism bias – the knowledge about uncertainty available among practitioners and stakeholders in this case. For that reason, we selected PBA2050 and Link21 as an additional case study for which it was more feasible to immediately develop and apply a real options approach. The main (transportation) planning agencies of the Bay Area had already conducted two scenario planning exercises prior to PBA2050, and for the first time, they adopted an exploratory scenario planning approach in which many different stakeholders were involved. If we zoom out, we see that scenario planning has been in use in US urban planning since the 1990s, and the practice has become institutionalised and has been made mandatory for some planning processes by the Federal Transit Administration and multiple metropolitan planning organizations (Goodspeed, 2020). Since 2017, the US also has a Consortium for Scenario Planning that offers practitioners technical assistance, educational resources (Hopkins & Zapata, 2007; Stapleton, 2020), and a broad network. The consortium organizes a yearly scenario planning conference and, since 2023, also offers a scenario planning course for practitioners.

In the US, and specifically in the Bay Area, experience with uncertainty management was readily available, which made it 'easier' to piggyback and extend the scenarios of PBA2050 with ROT to develop a comprehensive adaptive planning approach. I experienced a large difference between the interviews that I conducted for the Flemish case studies and those that I conducted for the PBA2050 and Link21 case study. Because the Link21 members were familiar with scenario planning and knew the PBA2050 scenarios, they quickly understood the value of our approach and were able to qualitatively apply the real options typology without any difficulties.

The point of this comparison is that context matters. We cannot expect to achieve the same results as those from Chapters 6 and 7 for a Flemish CSP because experience with uncertainty of that extent was not present in our Flemish cases. The readiness level to adopt (new) uncertainty management and adaptive planning approaches differs between planning contexts and cultures. This dissertation has mainly focussed on developing and testing new approaches, rather than researching how to upscale these approaches in multiple contexts. To upscale adaptive planning approaches such as our real options framework and model, future research must first understand the readiness level for uncertainty management and adaptive planning of specific contexts, and understand local needs, opportunities, and obstacles for adaptive planning in planning cultures. This requires further empirical research and (comparative) case studies in different contexts.

8.2.2. Transforming practice: Incremental changes vs large jumps

To upscale the use ROT and adaptive planning approaches, we have to transform current planning practices. To do so, we must question how the required transformations should take place. Should transformations happen in one large jump or rather through incremental changes. There are scholars who believe that radical changes are required to replace existing institutions and practices completely (Moroni, 2014; Moroni et al., 2018; Moroni & Chiffi, 2021), while others propose that we should transform planning practice by embedding new approaches within practices (de Roo et al., 2020; Rauws et al., 2019). Considering the empirical findings from our cases, we would give the benefit of the doubt to incremental changes that try to embed adaptive planning approaches within existing planning institutions – procedures, instruments, practices – after which larger transformations can take place over time.

Looking once again at scenario planning in the US, we see that the use of scenario planning methods to cope with uncertainty has gradually expanded for almost 30 years now. As we explained in Chapter 6, even after almost three decades, scenario planning has become institutionalised but still struggles to impact actual planning and decision making. Only recently, the attention for exploratory scenarios and adaptive planning compared to normative scenarios has been increasing, and we were one of the first to develop and apply an integrated adaptive planning framework. In the Bay Area, the exploratory scenario planning exercise was preceded by two normative scenario planning processes.

Circling back to Flanders, we must accept that it will not be possible to radically transform planning practice in one day. An anecdote from my collaboration with the project team from De Nieuwe Rand illustrates this point. After the completion of our Q methodology study, we gained the approval from the project initiator (public administration) to develop a research proposal for further collaboration. The initial proposal was elaborate and had to be toned down in the end. One reason was financial, the other reason related to the content of the proposal. It was quickly decided to keep uncertainty outside the scope of the EIA, because of the legal reasons explained in Chapter 4. Afterwards, it appeared there was also no support to perform uncertainty or sensitivity analysis as part of the SCBA. The project initiator was convinced that many uncertainties that we identified in Chapter 5 would be solved and removed throughout the project's research phase. In the end, we selected one uncertainty from the list (Q set) of our Q methodology study, and one additional uncertainty was identified. These will be further researched in a qualitative way together with the project team members.

This anecdote illustrates the current reticence towards a more explicit incorporation of uncertainties in CSPs, but also shows that practitioners are interested to research uncertainties and to learn about it, which is a positive sign. There is an openness towards transforming practice in Flanders, but, for now, only through incremental changes. Pushing for radical changes might scare planning practice off. In contexts where the readiness level or experience with uncertainties and adaptive planning is low, it might be better to start with small steps. Fortunately, there are good examples and experiences available, such as in the US. This could accelerate the transformation of planning practice towards adaptive planning in other areas. In that regard, future research must also participate in the development of other tools and resources besides the approaches developed in Chapters 6 and 7. Using the Consortium for Scenario Planning as an inspiration, examples are educational resources such as guidelines, handbooks, or courses; events or media to share experiences such as conferences, newsletters or webinars. Additionally, future research should also look into the history of, for example, scenario planning in the US, to understand how transformations happened and what the conditions were for transforming planning practices.

8.2.3. Real options and adaptive planning for CSPs: The bigger picture

To understand how we can transform planning practice, we must also understand how approaches like ours fit within the bigger picture of CSPs. In this dissertation, we only tested our newly developed approaches in a single case study, and we are still a long way from widely adopting these approaches in CSPs in different contexts. To upscale such approaches requires a thorough understanding of how they can be embedded in broader CSP processes in different contexts, including planning institutions, the political culture and power relations.

We found in Chapter 4 that planning institutions play an important role in maintaining the predict-and-plan approach in Flanders. Predict-and-plan and uncertainty avoidance in Flanders has been strengthened with the introduction of the Decree for Complex Projects in 2014. The Decree was called to life because many CSPs faced delays as a consequence of stakeholder conflicts and legal procedures that blocked various CSPs.

The Decree contains a planning procedure with a streamlined and rigid approach with multiple decision making moments and multiple opportunities for stakeholder involvement. The guidelines of this procedure state that this approach will lead to more societal support, less legal action, and a more efficient and faster implementation of CSPs. In 2014, the Decree was officiated and since then, 13 projects have been initiated following this procedure, of which five have abandoned the procedure. None of the projects has yet reached the implementation phase, and stakeholder support has been proven equally difficult to achieve as in other planning procedures for CSPs.

Stakeholder conflicts or disagreements are in essence a result of differences in views about what stakeholders believe the future will look like, or what stakeholders want the future to look like. If CSP practices then rely on predict-and-plan approaches, conflicts or disagreements are inevitable, and projects can be turned into an 'I am right, no I am right!' situation. The revealed perceptions of uncertainty in Chapter 5 are an illustration of this. Narrowing down the project scope to a linear trajectory based on agreed certainties and a single alternative in the early stages disregards the multiple views that inevitably exist about the future. Rather, opening up the procedure to uncertainties and multiple perspectives of the future, and keeping multiple alternatives and futures open through adaptive planning, might lead to broader stakeholder support because stakeholders' viewpoints are considered and incorporated.

Planning institutions are composed of formal institutions – the official rules and procedures written down in laws or decrees – and informal institutions – the interpretation and application of formal institutions that lead to routinized practices and accepted norms. Following this distinction, the Decree for Complex Projects does not entirely exclude the use of adaptive planning or real options approaches. Through informal institutions, the Decree remains interpreted as an approach that must follow a linear sequence of procedural steps, and, in the end, uncertainties are avoided as a routine and norm to not legally weaken official project documents or decisions. On the side of the formal institutions, there are procedural steps and instruments in CSPs that have a zero tolerance towards uncertainty, such as the EIA or the decision-making moments and arguments for decisions made. However, the research that leads up to the drafting of EIAs or decision-making documents does not only follow strict rules. Additionally, in Flanders, for example, the SCBA is not an institutionalized instrument, there are only guidelines that can help draft an SCBA. Aside from the strict legal regulations and procedures that must be followed, there is room for creativity and freedom to decide how to conduct research in CSPs. In addition, there are no rules about how to organize informal stakeholder collaboration and involvement. This means that is possible to apply new approaches during the early stages of CSPs. This could already help to better inform decision makers about uncertainty and flexibility. For example, in Chapter 7, the results from our TIPROE model suggest a different decision for New Crossing than if flexibility and uncertainty would not have been considered, without the need to change current procedures.

Next to planning institutions, politics and power relations play an important role in CSP processes. The real options approaches that we developed must be considered as tools that practitioners can use to better assess uncertainties and flexibility. As a tool, it offers valuable information, but it does not offer solutions. The information that our approaches can generate are left open to interpretation, similar to the SCBA and EIA as shown in Chapter 3. Decisions still have to be made by politicians or decision makers based on their interpretation of the information generated. Furthermore, the decision maker has the final say about the research scope and approach, so it is the decision maker that determines whether uncertainty management and adaptive planning become part of the evaluation process. The availability of resources such as time or money can influence that decision. For example, in Flanders, CSPs are often scheduled in such a way that decision-making moments take place close before elections, which is the case in the New Lock Zeebrugge and De Nieuwe Rand projects. Our anecdote about the follow-up collaboration with the De Nieuwe Rand shows that the decision maker eventually decided to limit the scope of researching uncertainties. We had more support from the consultancy firm than from the decision maker to for our research.

Even if our real options approaches would be applied in actual CSPs, how it would be used will become subject to power relations and the different agendas of stakeholders. Stakeholders with a strong position or voice in a CSP could have a large influence on which uncertainties are selected for research, and which scenarios, outcomes of uncertainties, or real options will get more attention or more support. I mentioned earlier that adaptive planning creates an opportunity to open up the process to multiple views about the future, but power relations and the political culture will determine whether this will happen in a democratic way, and whose voices will be heard. Mind you, stakeholder conflict is not something that can (or should) be removed by adaptive planning.

Upscaling the use of novel approaches like ours will requires more research into how they can be embedded and become institutionalized in CSP processes. This requires researching obstacles and opportunities in current CSP processes, procedures, and instruments for the use of new approaches, and researching the possible downsides and limitations of using real options in CSPs compared to current approaches. More research is also needed into how politicians and decision makers could accept new planning approaches. Taking it another step further, if real options approaches would lead to decision making that would involve adaptive plans and real options, eventually, options have to be closed down and decisions must be made. In that regard, more research is needed about how planning and project flexibility can be balanced with legal certainty. Research must look into the institutional change that is required to allow for uncertainty and flexibility to be incorporated in official project documents and decisions.

To summarize, we developed what we believe are valuable tools to better inform planning and decision making about uncertainty and flexibility, but we do not yet know how and to what extent they be used in actual CSP processes and practices in different contexts, nor what the drawbacks of this approach in actual practice could be.

8.2.4. Planning with real options: Advice for planning practitioners

There is no reason why planning practitioners could not already use ROT or (parts of) the approaches that we developed in Chapters 6 and 7. I want to approach the end of this dissertation by offering four points of advice about how to initiate adaptive planning processes with real options. These advices are actions that can be undertaken regardless of the specific planning context (institutions, power relations, and politics), or the experience of practitioners with uncertainty and adaptive planning. Researchers can consider these advices as research approaches that could help to upscale the use of real options for adaptive planning in CSPs.

The first advice is to start small by applying ROT in a qualitative way like we did in Chapter 6. The real options typology on its own is clear and intuitive. Coppens et al. (2021) have shown with multiple examples that the different option types are already applied intuitively by planning practitioners. The real options typology brings structure to the table and gives a complete overview of the flexibility types that could be considered. Also, there are no quantitative models or complex techniques required to start drawing an adaptive plan like we showed in Figure 6.3 of Chapter 6. In workshop settings, stakeholders or project team members could collaboratively draw a road map with the possible decisions, plan or project directions, or scenarios, instead of the current practice of identifying isolated project alternatives or planning strategies. It could be a starting point to initiate a debate about adaptive planning opportunities in a CSP, These are actions that could be undertaken in the early stages of a CSP. Prior to such workshops, participants could be introduced first to examples like the ones in Coppens et al. (2021). This can help to make real option types more tangible and less abstract.

ROT is still an unfamiliar concept to most planning practitioners. The second advice is to combine ROT with familiar approaches, instruments, or planning and research methods. This might help to better understand the purpose of ROT and to make it less abstract. The integration of scenario planning and ROT in Chapters 6 and 7 is an example. This integration also helped managers of the Link21 team to understand the quantitative results and the TIPROE model procedure when we presented it to them in the aftermath of the research from Chapter 7. In Chapter 5, we have shown how Q methodology can be used to reveal perceptions of uncertainty, information which can then be used to initiate debates about uncertainties, the need for flexibility, and the use of ROT, leading back the first advice.

The third advice is to open up communication to a broad public of stakeholders beyond the project team about uncertainties and flexibility from the early project phases onwards, to familiarize them to concepts like uncertainty, adaptive planning, and even real options. This can be done in an accessible way, for example, by preparing specific what-if questions about uncertainties, or by pitching ideas about flexibility by using real-life examples or visualisations such as road maps. Chapter 5 has taught us that if we prepare a list about uncertainties and start asking questions about it, stakeholders are able to express valuable opinions about it. In De Nieuwe Rand (A102) project, collaboration with many stakeholders is organised through general stakeholder sessions and interactive sessions and workshops. These platforms offer opportunities to organize conversations about uncertainty and adaptive planning.

The fourth advice is to tailor uncertainty management, adaptive planning, and real options approaches to the needs of a specific CSP or planning context. The framework that we developed in Chapter 6 has been partly based on the exploratory scenario planning exercise of PBA2050, increasing the framework's value for PBA2050 and Link21. Depending on differences in the readiness level of planning practices, the characteristics of a specific CSP, the uncertainties or the flexibility needs, and the broader CSP and planning context, changes to approaches might be needed so that they better fit the needs of each specific situation.

8.3. Final thoughts

It has become somewhat of a tradition in the past few years for academic publications in planning to start an off with mentioning the many challenges that planning practice faces, including, but not limited to, growing urbanization, the energy transition, climate change, technological evolutions, growing polarization, geopolitical instability, and socioeconomic or sociodemographic changes. I did it myself in Chapters 6 and 7. Rightfully so, because what these challenges have in common is that they have a significant impact on the spatial needs of people and nature and thus impact planning practices and CSPs. What they also have in common is that the outcomes and implications of these challenges are uncertain and difficult or even impossible to predict, making it difficult to plan CSPs for the needs of today and the future. Uncertainty and flexibility have become important assets in planning that we cannot ignore any longer.

You may have read some chapters of this dissertation because you wanted to learn more about uncertainty, adaptive planning, or ROT. Whatever your reason was, I hope that this dissertation has impacted the way you look at CSPs and how they are planned, the way you look at certainty versus uncertainty in planning, that this dissertation convinced you of the value of flexibility in planning, and that my work inspires you to look more critically at current CSP practices. I cannot predict, but I imagine a plausible future state in which my dissertation impacts the way planning practice handles uncertainty through flexibility.

References

Aaltonen, K. (2011). Project stakeholder analysis as an environmental interpretation process. *International Journal of Project Management*, 29(2), 165-183.

Aaltonen, K., & Kujala, J. (2016). Towards an improved understanding of project stakeholder landscapes. *International Journal of Project Management*, 34(8), 1537-1552.

ABAG, & MTC. (2019). *Crossings. Transformative investments for an uncertain future* (https://www.planbayarea.org/sites/default/files/pdf/Horizon_Crossings_November2019.pdf)

ABAG, & MTC. (2020). *Futures final report. Resilient and equitable strategies for the Bay Area's future* (https://mtc.ca.gov/sites/default/files/Horz_Futures_Report.web_.pdf)

ABAG, & MTC. (2021a). P*lan Bay Area 2050. A vision for the future* (https://www.planbayarea.org/sites/default/files/documents/Plan_Bay_Area_2050_October_2021.pdf)

ABAG, & MTC. (2021b). *Performance Report* (https://www.planbayarea.org/sites/default/files/documents/Plan_Bay_Area_2050_Performance_Report_October_2021.pdf)

Abbott, J. (2005). Understanding and managing the unknown: The nature of uncertainty in planning. *Journal of Planning Education and Research*, 24(3), 237-251.

Abou Jaoude, G., Mumm, O., & Carlow, V. M. (2022). An overview of scenario approaches: A guide for urban design and planning. *Journal of Planning Literature*, 08854122221083546.

Ahiaga-Dagbui, D. D., Love, P. E. D., Smith, S. D., & Ackermann, F. (2017). Toward a systemic view to cost overrun causation in infrastructure projects: A review and implications for research. *Project Management Journal*, 48(2), 88-98.

Albrechts, L. (2010). More of the same is not enough! how could strategic spatial planning be instrumental in dealing with the challenges ahead? *Environment and Planning B: Planning and Design*, 37(6), 1115-1127.

Albrechts, L., Balducci, A., & Hillier, J. (Eds.). (2017). *Situated practices of strategic planning: An international perspective* (1st ed.). Routledge.

Alessandri, T. M., Ford, D. N., Lander, D. M., Leggio, K. B., & Taylor, M. (2004). Managing risk and uncertainty in complex capital projects. *The Quarterly Review of Economics and Finance*, 44(5), 751-767.

Allred, D., & Chakraborty, A. (2015). Do local development outcomes follow voluntary regional plans? Evidence from Sacramento region's blueprint plan. *Journal of the American Planning Association*, 81(2), 104-120.

Alonso-Conde, A. B., Brown, C., & Rojo-Suarez, J. (2007). Public private partnerships: Inventives, risk transfer and real options. *Review of Financial Economics*, 16, 335-349.

Annema, J. A. (2013). The use of CBA in decision-making on mega-projects: empirical evidence. In H. Priemus & B. van Wee (Eds.), *International Handbook on Mega-projects* (pp. 291-312). Edward Elgar Publishing Limited.

Annema, J. A., Frenken, K., Koopmans, C., & Kroesen, M. (2017). Relating cost-benefit analysis results with transport project decisions in the Netherlands. *Letters in Spatial and Resource Sciences*, 10(1), 109-127.

Ashuri, B., Kashani, H., Molenaar, K. R., Lee, S., & Lu, J. (2012). Risk-neutral pricing approach for evaluating BOT highway projects with government minimum revenue guarantee options. *Journal of Construction Engineering and Management*, 138(4), 545-557.

Asplund, D., & Eliasson, J. (2016). Does uncertainty make cost-benefit analyses pointless? *Transportation Research Part a-Policy and Practice*, 92, 195-205.

Atkinson, R., Crawford, L., & Ward, S. (2006). Fundamental uncertainties in projects and the scope of project management. *International Journal of Project Management*, 24(8), 687-698.

Avin, U., & Goodspeed, R. (2020). Using exploratory scenarios in planning practice. *Journal of the American Planning Association*, 86(4), 403-416.

Balducci, A., Boelens, L., Hillier, J., Nyseth, T., & Wilkinson, C. (2011). Introduction: Strategic spatial planning in uncertainty: Theory and exploratory practice. *Town Planning Review*, 82(5), 481-501.
Banasick, S. (2019). *Ken-Q analysis* (Version 1.0.6) https://shawnbanasick.github.io/ken-q-analysis/
Banfield, E. C. (1959). Ends and means in planning. *International Social Science Journal*, 11(3), 361-368.
Banister, D., & Hickman, R. (2013). Transport futures: Thinking the unthinkable. *Transport Policy*, 29, 283-293.
Bay Area Council Economic Institute (2021). *The megaregional case for a new transbay rail crossing* (http://www.bayareaeconomy.org/report/megaregionimpactsofnewtransbayrailcrossing/)
Beauregard, R. A. (2005). Introduction: Institutional transformations. *Planning Theory*, 4(3), 203-207.
Bergsma, E., Giezen, M., Schalkwijk, B., & Büscher, C. (2019). Adapting to new realities: An analysis of institutional work in three cases of Dutch infrastructure planning. *Journal of Environmental Planning and Management*, 62(1), 88-105.
Berke, P., & Lyles, W. (2013). Public risks and the challenges to climate-change adaptation: A proposed framework for planning in the age of uncertainty. *Cityscape*, 15(1), 181-208.
Bertolini, L. (2010). Coping with the irreducible uncertainties of planning: An evolutionary approach. In P. Healey & J. Hillier (Eds.), *The Ashgate research companion to planning theory: Conceptual challenges for spatial planning* (pp. 413-424). Routledge.
Bertolini, L. (2012). Integrating mobility and urban development agendas: A manifesto. *disP - The Planning Review*, 48(1), 16-26.
Bertolini, L., & Salet, W. (2008). *Coping with complexity and uncertainty in mega projects: Linking strategic choices and operational decision making* [Unpublished manuscript]. Barlett School of Planning, University College London
Beukers, E., Bertolini, L., & Te Brömmelstroet, M. (2012a). Why Cost Benefit Analysis is perceived as a problematic tool for assessment of transport plans: A process perspective. *Transport Research Part A*, 46, 68-78.
Beukers, E., Bertolini, L., & Te Brömmelstroet, M. (2012b). Why cost benefit analysis is perceived as a problematic tool for assessment of transport plans: A process perspective. *Transportation Research Part A: Policy and Practice*, 46(1), 68-78.
Biatour, B., Kegels, C., van der Linden, J., & Verwerft, D. (2017). P*ublic Investment in Belgium. Current State and Economic Impact*. Federal Planning Bureau. https://www.plan.be/admin/uploaded/201701270618330.WP_1701_11411.pdf
Biesenthal, C., Clegg, S., Mahalingam, A., & Sankaran, S. (2018). Applying institutional theories to managing megaprojects. *International Journal of Project Management*, 36(1), 43-54.
Bing, L., Akintoye, A., Edwards, P. J., & Hardcastle, C. (2005). The allocation of risk in PPP/PFI construction projects in the UK. *International Journal of Project Management*, 23(1), 25-35.
Bischof, B. G. (2010). Negotiating uncertainty: Framing attitudes, prioritizing issues, and finding consensus in the coral reef environment management "crisis". *Ocean & Coastal Management*, 53(10), 597-614.
Bjørkan, M., & Veland, S. (2019). Beyond consensus: Perceptions of risk from petroleum developments in Lofoten, Vesterålen, and Senja, Norway. *ICES Journal of Marine Science*, 76(6), 1393-1403.
Black, F., & Scholes, M. (1973). The pricing of options and corporate liabilities. *Journal of Political Economy*, 81, 637-659.
Böhle, F., Heidling, E., & Schoper, Y. (2016). A new orientation to deal with uncertainty in projects. *International Journal of Project Management*, 34(7), 1384-1392.
Bond, A., Morrison-Saunders, A., Gunn, J. A. E., Pope, J., & Retief, F. (2015). Managing uncertainty, ambiguity and ignorance in impact assessment by embedding evolutionary resilience, participatory modelling and adaptive management. *Journal of Environmental Management*, 151, 97-104.
Booz, A. H. (2006). *Managing capital costs of major federally funded public transportation projects*. E. National Academies of Sciences, and Medicine
Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures*, 38(7), 723-739.
Bosch-Rekveldt, M., Jongkind, Y., Mooi, H., Bakker, H., & Verbraeck, A. (2011). Grasping project

complexity in large engineering projects: The TOE (Technical, Organizational and Environmental) framework. *International Journal of Project Management*, 29(6), 728-739.
Bowe, M., & Lee, D. L. (2004). Project evaluation in the presence of multiple embedded real options: Evidence from Taiwan High-Speed Rail Project. *Journal of Asian Economics*, 15, 71-98.
Bowen, G. A. (2009). Document analysis as a qualitative research method. *Qualitative Research Journal*, 9(2), 27-40.
Brandao, L. E. T., Bastian-Pinto, C., Gomes, L. L., & Labes, M. (2012). Government supports in public-private partnerships contracts: Metro line 4 of the São Paulo subway system. *Journal of Infrastructure Systems*, 18, 218-225.
Brent, R. J. (2006). *Applied cost-benefit analysis*. Edward Elgar Publishing.
Bristow, A., & Nellthorp, J. (2000). Transport project appraisal in the European Union. *Transport Policy*, 7(1), 51-60.
Brown, S. R. (1980). *Political subjectivity: Applications of Q methodology in political science*. Yale University Press.
Bruzelius, N., Flyvbjerg, B., & Rothengatter, W. (2002). Big decisions, big risks. Improving accountability in mega projects. *Transport Policy*, 9, 143-154.
Buyukyoran, F., & Gundes, S. (2018). Optimized real options-based approach for government guarantes in PPP toll road projects. *Construction Management & Economics*, 36(4), 203-216.
Cantarelli, C. C., Flyvbjerg, B., & Buhl, S. L. (2012). Geographical variation in project cost performance: The Netherlands versus worldwide. *Journal of Transport Geography*, 24, 324-331.
Cantarelli, C. C., Flyvbjerg, B., Molin, E. J. E., & van Wee, B. (2010). Cost overruns in large-scale transportation infrastructure projects: Explanations and their theoretical embeddedness. *European Journal of Transport and Infrastructure Research*, 10(1), 5-18.
Cantarelli, C. C., Flyvbjerg, B., van Wee, B., & Molin, E. J. E. (2010). Lock-in and its influence on the project performance of large-scale transportation infrastructure projects: Investigating the way in which lock-in can emerge and affect cost overruns. *Environment and Planning B: Planning and Design*, 37, 792-807.
Cantarelli, C. C., Molin, E. J. E., van Wee, B., & Flyvbjerg, B. (2012). Characteristics of cost overruns for Dutch transport infrastructure projects and the importance of the decision to build and project phases. *Transport Policy*, 22, 49-56.
Cantarelli, C. C., Oglethorpe, D., & van Wee, B. (2021). Perceived risk of lock-in in the front-end phase of major transportation projects. *Transportation*.
Cantarelli, C. C., van Wee, B., Molin, E. J. E., & Flyvbjerg, B. (2012). Different cost performance, different determinants? The case of cost overruns in Dutch transport infrastructure projects. *Transport Policy*, 22, 88-95.
Cardenas, I. C., & Halman, J. I. M. (2016). Coping with uncertainty in environmental impact assessments: Open techniques. *Environmental Impact Assessment Review*, 60, 24-39.
Chakraborty, A., Kaza, N., Knaap, G. J., & Deal, B. (2011). Robust plans and contingent plans scenario planning for an uncertain world. *Journal of the American Planning Association*, 77(3), 251-266.
Chakraborty, A., & McMillan, A. (2015). Scenario planning for urban planners: Toward a practitioner's guide. *Journal of the American Planning Association*, 81(1), 18-29.
Cheah, C. Y. J., & Garvin, M. J. (2009). Application of real options in PPP infrastructure projects: Opportunities and challenges. In A. Akintoye & M. Beck (Eds.), *Policy, Finance & Management for Public-Private Partnerships* (pp. 229-249). Wiley-Blackwell.
Chen, Q., Shen, G., Xue, F., & Xia, B. (2018). Real options model of toll-adjustment mechanism in concession contracts of toll road projects. *Journal of Management in Engineering*, 34(1), 1-11.
Chevalier, J. M., & Buckles, D. J. (2013). *Participatory action research: theory and methods for engaged inquiry*. Routledge.
Chiara, N., Garvin, M. J., & Vecer, J. (2007). Valuing simple multiple-exercise real option in infrastructure projects. *Journal of Infrastructure Systems*, 13, 97-104.
Chiara, N., & Kokkaew, N. (2013). Alternative to government revenue guarantees: Dynamic revenue insurance contracts. *Journal of Infrastructure Systems*, 19, 287-296.

Christensen, K. S. (1985). Coping with uncertainty in planning. *Journal of the American Planning Association*, 51(1), 63-73.
Christiaanse, K., Gasco, A., & Hanakata, N. C. (Eds.). (2019). *The Grand Projet: Understanding the Making and Impact of Urban Megaprojects*. nai010 Publishers.
Chu, X., Wang, S., & Feng, K. (2017). *Evaluating demand guarantee for PPP projects by real-option pricing*. International Conference on Construction and Real Estate Management 2017, Guangzhou, China.
Cohen, M. D., March, J. G., & Olsen, J. P. (1972). A garbage can model of organizational choice. *Administrative Science Quarterly*, 17(1), 1-25.
Colin, F. C., Soliño, A. S., & Galera, A. L. L. (2016). Default and Abandonment Option in Motorway Concessions. *Journal of Infrastructure Systems*, 23(1).
Collan, M., Fuller, R., & Mezei, J. (2009, 24-26 July 2009). *A Fuzzy Pay-Off Method for Real Option Valuation*. (Ed.),^(Eds.). 2009 International Conference on Business Intelligence and Financial Engineering.
Compernolle, T., Coppens, T., Lamberts-Van-Assche, H., & Machiels, T. (2021). *Werkbank financiering Toekomstverbond. Eindrapport verkenningsfase*
Coppens, T., Van Acker, M., Machiels, T., & Compernolle, T. (2021). A real options framework for adaptive urban design. *Journal of Urban Design*, 26(6), 681-698.
Cotton, M., & Devine-Wright, P. (2011). Discourses of energy infrastructure development: A Q-method study of electricity transmission line siting in the UK. *Environment and Planning A: Economy and Space*, 43(4), 942-960.
Couclelis, H. (2005). "Where has the future gone?" Rethinking the role of integrated land-use models in spatial planning. *Environment and Planning A: Economy and Space*, 37(8), 1353-1371.
Couto, G., Nunes, C., & Pimentel, P. (2012). High-speed rail transport valuation and conjecture shocks. *The European Journal of Finance*, 21(10-11), 791-805.
Couto, G., Pimentel, P., & Oliveira, A. (2022). The optimal time to invest in the new Montijo airport in Portugal. *Spatial Economic Analysis*, 17(1), 34-46.
Cui, Q., Bayraktar, M. E., Hastak, M., & Minkarah, I. (2004). Use of warranties on highway projects: A real option perspective. *Journal of Management in Engineering*, 20, 118-125.
Cuppen, E. (2012). Diversity and constructive conflict in stakeholder dialogue: considerations for design and methods. *Policy Sciences*, 45(1), 23-46.
Cuppen, E., Bosch-Rekveldt, M. G., Pikaar, E., & Mehos, D. C. (2016). Stakeholder engagement in large-scale energy infrastructure projects: Revealing perspectives using Q methodology. *International Journal of Project Management*, 34(7), 1347-1359.
Cuppen, E., Breukers, S., Hisschemöller, M., & Bergsma, E. (2010). Q methodology to select participants for a stakeholder dialogue on energy options from biomass in the Netherlands. *Ecological Economics*, 69(3), 579-591.
Curry, R., Barry, J., & McClenaghan, A. (2013). Northern visions? Applying Q methodology to understand stakeholder views on the environmental and resource dimensions of sustainability. *Journal of Environmental Planning and Management*, 56(5), 624-649.
Daniel, P. A., & Daniel, C. (2018). Complexity, uncertainty and mental models: From a paradigm of regulation to a paradigm of emergence in project management. *International Journal of Project Management*, 36(1), 184-197.
Dantata, N. A., Touran, A., & Schneck, D. C. (2006). *Trends in U.S. rail transit project cost overrun*. Transportation Research Board 85th Annual Meeting, Washington, D.C.
Davies, A., Dodgson, M., & Gann, D. M. (2017). Innovation and flexibility in megaprojects. In B. Flybjerg (Ed.), *The Oxford Handbook of Megaproject Management* (pp. 313-339). Oxford University Press.
Davis, J. (2020). Avoiding white elephants? The planning and design of London's 2012 Olympic and Paralympic venues, 2002–2018. *Planning Perspective*s, 35(5), 827-848.
Davoudi, S. (2021). Resilience, uncertainty, and adaptive planning. In E. Peker & A. Ataöv (Eds.), *Governance of Climate Responsive Cities: Exploring Cross-Scale Dynamics* (pp. 9-19). Springer International Publishing.

de Haan, J., Kwakkel, J. H., Walker, W. E., Spirco, J., & Thissen, W. A. H. (2011). Framing flexibility: Theorising and data mining to develop a useful definition of flexibility and related concepts. *Futures*, 43(9), 923-933.

De Jong, M., Annema, J. A., & Van Wee, G. P. (2013). How to build major transport infrastructure projects within budget, in time and with the expected output; a literature review. *Transport Reviews*, 33(2), 195-218.

De Meyer, A., Loch, C. H., & Pich, M. T. (2002). Managing project uncertainty: From variation to chaos. *MIT Sloan Management Review*, 43(2), 60-67.

de Neufville, R. (2003). Real options: Dealing with uncertainty in systems planning and design. *Integrated Assessment*, 4(1), 26-34.

de Neufville, R., & Scholtes, S. (2006). *Maximizing value from large-scale projects: Implementing flexibility in public - private partnerships*. http://ardent.mit.edu/real_options/Real_opts_papers/Scholtes%20IMPLEMENTING%20Flexibility%20Draft.pdf

de Neufville, R., Scholtes, S., & Wang, T. (2006). Real options by spreadsheet: Parking garage case example. *Journal of Infrastructure Systems*, 12(2), 107-111.

de Roo, G. (2010). Planning and complexity: An introduction. In G. de Roo & E. A. Silva (Eds.), *A Planner's Encounter with Complexity* (pp. 1-15). Ashgate.

de Roo, G. (2018). Spatial planning and the complexity of turbulent, open environments: About purposeful interventions in a world of non-linear change. In M. Gunder, A. Madanipour, & V. Watson (Eds.), *The Routledge Handbook of Planning Theory* (pp. 314-325). Routledge.

de Roo, G., Rauws, W., & Zuidema, C. (2020). Adaptive planning and the capacity to perform in moments of change. In G. De Roo, C. Yamu, & C. Zuidema (Eds.), *Handbook on Planning and Complexity* (pp. 85-109). Edward Elgar Publishing.

de Roo, G., & Zuidema, C. (Eds.). (2020). Handbook on Planning and Complexity. Edward Elgar Publishing.

Defossé, J.-C. (1990). *Le petit guide des grands travaux inutiles*. Legrain.

Denicol, J., Davies, A., & Krystallis, I. (2020). What are the causes and cures of poor megaproject performance? A systematic literature review and research agenda. *Project Management Journal*, 51(3), 328-345.

Di Maddaloni, F., & Davis, K. (2017). The influence of local community stakeholders in megaprojects: Rethinking their inclusiveness to improve project performance. *International Journal of Project Management*, 35(8), 1537-1556.

Di Maddaloni, F., Favato, G., & Vecchiato, R. (2022). Whether and when to invest in transportation projects: Combining scenarios and real options to manage the uncertainty of costs and benefits. *IEEE Transactions on Engineering Management*, 1-15.

Díaz, P., Adler, C., & Patt, A. (2017). Do stakeholders' perspectives on renewable energy infrastructure pose a risk to energy policy implementation? A case of a hydropower plant in Switzerland. *Energy Policy*, 108, 21-28.

Dimitriou, H. T., Low, N., Sturup, S., Zembri, G., Campagnac, E., Kaparos, G., Skayannis, P., Muromachi, Y., Iwakura, S., Itaya, K., Giezen, M., Bertolini, L., Salet, W., Khan, J., Petterson, F., Holmberg, B., Ward, E. J., Wright, P. G., Dimitriou, H. T., & Dimitriou, H. T. (2014). What constitutes a "successful" mega transport project?/Leadership, risk and storylines: The case of the Sydney Cross City Tunnel/The case of the LGV Méditerranée high speed railway line/Dealing with context and uncertainty in the development of the Athens Metro Base Project/What constitutes a "successful" mega transport project? Lessons from the Metropolitan Expressway in Tokyo/The RandstadRail project: A case study in decision-making strategies under uncertainty/Constructive conflicts in the case of the Öresund Link/Perspectives on "success" from the UK Channel Tunnel Rail Link Project/Some concluding remarks. *Planning Theory & Practice*, 15(3), 389-430.

Dimitriou, H. T., Ward, J. E., & Wright, P. G. (2017). Megaprojects and mega risks: Lessons for decision-makers of large-scale transport projects: OMEGA Centre lessons derived from European, US and Asia-Pacific case studies. In M. Lehtonen, P.-B. Joly, & L. Aparicio (Eds.), *Socioeconomic Evaluation of Megaprojects: Dealing with uncertainties* (pp. 44-61). Routledge.

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under Uncertainty*. Princeton University Press.
Doan, P., & Menyah, K. (2013). Impact of irreversibility and uncertainty on the timing of infrastructure projects. *Journal of Construction Engineering and Management*, 139, 331-338.
Domingues, S., Zlatkovic, D., & Roumboutsos, A. (2014). *Contractual flexibility in transport infrastructure PPP*. European Transport Conference.
Durose, C., van Hulst, M., Jeffares, S., Escobar, O., Agger, A., & de Graaf, L. (2016). Five ways to make a difference: Perceptions of practitioners working in urban neighborhoods. *Public Administration Review*, 76(4), 576-586.
The Economist. (2008). *Building BRICs of growth*. The Economist https://www.economist.com/finance-and-economics/2008/06/05/building-brics-of-growth
Eden, S., Donaldson, A., & Walker, G. (2005). Structuring subjectivities? Using Q methodology in human geography. *Area*, 37(4), 413-422.
Eliasson, J., & Lundberg, M. (2012). Do cost–benefit analyses influence transport investment decisions? Experiences from the Swedish Transport Investment Plan 2010–21. *Transport Reviews*, 32(1), 29-48.
Ellis, G., Barry, J., & Robinson, C. (2007). Many ways to say ‘no’, different ways to say ‘yes’: Applying Q-methodology to understand public acceptance of wind farm proposals. *Journal of Environmental Planning and Management*, 50(4), 517-551.
Erkul, M., Yitmen, I., & Çelik, T. (2016). Stakeholder engagement in mega transport infrastructure projects. *Procedia Engineering*, 161, 704-710.
Esposito, G., Terlizzi, A., & Crutzen, N. (2022). Policy narratives and megaprojects: The case of the Lyon-Turin high-speed railway. *Public Management Review*, 24(1), 55-79.
European Court of Auditors (2020). *EU transport infrastructures: More speed needed in megaproject implementation to deliver network effects on time*. Special Report. (https://www.eca.europa.eu/en/Pages/DocItem.aspx?did=53699)
Favato, G., & Vecchiato, R. (2017). Embedding real options in scenario planning: A new methodological approach. *Technological Forecasting and Social Change*, 124, 135-149.
Fawcett, W., Urquijo, R., Krieg, H., Hughes, M., Mikalsen, L., & Gutiérrez, O. R. R. (2015). Cost and environmental evaluation of flexible strategies for a highway construction project under traffic growth uncertainty. *Journal of Infrastructure Systems*, 21(3).
Fernandes, B., Cunha, J., & Ferreira, P. (2011). The use of real options approach in energy sector investments. *Renewable and Sustainable Energy Reviews*, 15, 4491-4497.
Fitch, G. J., Odeh, I., Kautz, F., & Ibbs, C. W. (2018). System dynamics models for the valuation of real options in P3 concession project agreements. *Journal of Infrastructure Systems*, 24(1).
Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative inquiry*, 12(2), 219-245.
Flyvbjerg, B. (2007). Cost overruns and demand shortfalls in urban rail and other infrastructure. *Transportation Planning and Technology*, 30(1), 9-30.
Flyvbjerg, B. (2008). Curbing optimism bias and strategic misrepresentation in planning: Reference class forecasting in practice. European Planning Studies, 16(1), 3-21.
Flyvbjerg, B. (2009). Survival of the unfittest: Why the worst infrastructure gets built—and what we can do about it. *Oxford review of economic policy*, 25(3), 344-367.
Flyvbjerg, B. (2013). Quality control and due diligence in project management: Getting decisions right by taking the outside view. *International Journal of Project Management*, 31, 760-774.
Flyvbjerg, B. (2014). What you should know about megaprojects and why: An overview. *Project Management Journal*, 45(2), 6-19.
Flyvbjerg, B. (2017a). The iron law of megaproject management. In B. Flyvbjerg (Ed.), *The oxford handbook of megaproject management* (pp. 1-18). Oxford University Press.
Flyvbjerg, B. (2021). Top ten behavioral biases in project management: An overview. *Project Management Journal*, 52(6), 531-546.
Flyvbjerg, B. (Ed.) (2017b). *The Oxford Handbook of Megaproject Management*. Oxford University Press.
Flyvbjerg, B., Ansar, A., Budzier, A., Buhl, S., Cantarelli, C., Garbuio, M., Glenting, C., Holm, M. S., Lovallo, D., Lunn, D., Molin, E., Rønnest, A., Stewart, A., & van Wee, B. (2018). Five things you

should know about cost overrun. *Transportation Research Part A: Policy and Practice*, 118, 174-190.
Flyvbjerg, B., Bruzelius, N., & Rothengatter, W. (2003). *Megaprojects and risk: An anatomy of ambition*. Cambridge University Press.
Flyvbjerg, B., Garbuio, M., & Lovallo, D. (2009). Delusion and deception in large infrastructure projects: Two models for explaining and preventing executive disaster. *California Management Review*, 51(2), 170-193.
Flyvbjerg, B., Skamris Holm, M. K., & Buhl, S. L. (2002). Underestimating costs in public works projects: Error or lie? *Journal of the American Planning Association*, 68(3), 279-295.
Flyvbjerg, B., Skamris holm, M. K., & Buhl, S. L. (2004). What causes cost overrun in transport infrastructure projects? *Transport Reviews: A Transnational Transdisciplinary Journal*, 24(1), 3-18.
Flyvbjerg, B., Skamris holm, M. K., & Buhl, S. L. (2005). How (in)accurate are demand forecasts in public works projects? The case of transportation. *Journal of the American Planning Association*, 71(2), 131-146.
FMI. (2019). *Megaprojects: Changing the converstation* (https://fmicorp.com/insights/industry-insights/megaprojects-changing-the-conversation)
Ford, D. N., Lander, D. M., & Voyer, J. J. (2002). A real options approach to valuing strategic flexibility in uncertain construction projects. *Construction Management & Economics*, 20(4), 343-351.
Forrester, J., Cook, B., Bracken, L., Cinderby, S., & Donaldson, A. (2015). Combining participatory mapping with Q-methodology to map stakeholder perceptions of complex environmental problems. *Applied Geography*, 56, 199-208.
Friend, J., & Hickling, A. (2005). *Planning under pressure. The strategic choice approach* (Third ed.). Pergamon Press.
Friend, J., & Jessop, N. (1969). *Local government and strategic choice. An operational research approach to the processes of public planning*. Tavistock Publications.
FTA. (2003). *Predicted and actual impacts of New Starts Projects: Capital cost, operating cost and ridership data*
FTA. (2008). *The predicted and actual impacts of New Starts Projects: Capital cost and ridership*
Galera, A. L. L., Soliño, A. S., & Abad, B. G. (2018). Sharing risks in toll motorway concessions: Subsidies as real options on traffic volumes. *Journal of Infrastructure Systems*, 24(4).
Gao, N., & Touran, A. (2020). Cost overruns and formal risk assessment program in US rail transit projects. *Journal of Construction Engineering and Management*, 146(5), 05020004.
Garvin, M. J., & Ford, D. N. (2012). Real options in infrastructure projects: Theory, practice and prospects. *Engineering Project Organization Journal*, 2(1-2), 97-108.
Geltner, D., & De Neufville, R. (2012). Uncertainty, flexibility, valuation and design: How 21st century information and knowledge can improve 21st century urban development – part I of II. *Pacific Rim Property Research Journal*, 18(3), 231-249.
Giezen, M. (2012). Keeping it simple? A case study into the advantages and disadvantages of reducing complexity in mega project planning. *International Journal of Project Management*, 30, 781-790.
Giezen, M. (2013). Adaptive and strategic capacity: Navigating megaprojects through uncertainty and complexity. *Environment and Planning B-Planning & Design*, 40(4), 723-741.
Giezen, M., Bertolini, L., & Salet, W. (2015). Adaptive Capacity Within a Mega Project: A Case Study on Planning and Decision-Making in the Face of Complexity. *European Planning Studies*, 23(5), 999-1018.
Giezen, M., Salet, W., & Bertolini, L. (2015). Adding value to the decision-making process of mega projects: Fostering strategic ambiguity, redundancy, and resilience. *Transport Policy*, 44, 169-178.
Gijzel, D., Bosch-Rekveldt, M., Schraven, D., & Hertogh, M. (2020). Integrating sustainability into major infrastructure projects: Four perspectives on sustainable tunnel development. *Sustainability*, 12(1), 6.
Gil, N. (2009). Project safeguards: Operationalizing option-like strategic thinking in infrastructure development. *IEEE Transactions on Engineering Management*, 56(2), 257-270.
Gil, N. (2017). A collective-action perspective on the planning of megaprojects. In B. Flyvbjerg (Ed.), *The Oxford Handbook of Megaproject Management* (pp. 259-286). Oxford University Press.
Goodspeed, R. (2017). *An evaluation framework for the use of scenarios in urban planning* [Working

Paper WP17RG1]. Lincoln Institute of Land Policy. https://www.lincolninst.edu/sites/default/files/pubfiles/goodspeed_wp17rg1.pdf
Goodspeed, R. (2020). *Scenario planning for cities and regions: Managing and envisioning uncertain futures*. Lincoln Instititute of Land Policy.
Grimes, A. (2011). B*uilding bridges: Treating a new transport link as a real option*. 51st Congress of the European Regional Science Association: "New Challenges for European Regions and Urban Areas in a Globalised World", Barcelona, Spain.
Haezendonck, E. (2008). *Transport project evaluation: Extending the social cost benefit approach*. Springer.
Hall, P. A., & Taylor, R. C. R. (1996). Political science and the three new institutionalisms. *Political Studies*, 44(5), 936-957.
Hanakata, N. C., & Gasco, A. (2018). The Grand Projet politics of an urban age: Urban megaprojects in Asia and Europe. *Palgrave Communications*, 4(1), 86.
Hardcastle, C., & Boothroyd, K. (2003). Risks overview in public-private partnership. In A. Akintoye, M. Beck, & C. Hardcastle (Eds.), *Public-Private Partnerships* (pp. 31-57). Blackwell Science Ltd.
Healey, P. (2006). Transforming governance: Challenges of institutional adaptation and a new politics of space. *European Planning Studies*, 14(3), 299-320.
Healey, P. (2018). Developing a 'sociological institutionalist' approach to analysing institutional change in place governance. In W. Salet (Ed.), *The Routledge Handbook of Institutions and Planning in Action* (pp. 24-42). Routledge.
Herder, P. M., de Joode, J., Ligtvoet, A., Schenk, S., & Taneja, P. (2011). Buying real options - Valuing uncertainty in infrastructure planning. *Futures*, 43, 961-969.
Hijmans, E. (1996). Logic for qualitative media content analysis: A typology. *Communications -Sankt Augustin Then Berlin-*, 21, 93-108.
Hillier, J. (2017). Strategic spatial planning in uncertainty or planning indeterminate futures? In L. Albrechts, A. Balducci, & J. Hillier (Eds.), *Situated practices of strategic planning: An international perspective* (pp. 298-316). Routledge.
Hopkins, L. D. (2001). *Urban development: The logic of making plans*. Island Press.
Hopkins, L. D., & Zapata, M. A. (2007). E*ngaging the future: Forecasts, scenarios, plans, and projects*. Lincoln Institute of Land Policy.
Horne, J. (2007). The four 'knowns' of sports mega-events. *Leisure Studies*, 26(1), 81-96.
Huang, Y.-L., & Pi, C.-C. (2014). Real-option valuation of build-operate-transfer infrastructure projects under performance bonding. *Journal of Construction Engineering and Management*, 140(5).
Irimia-Diéguez, A., Sanchez-Cazorla, A., & Alfalla-Luque, R. (2014). Risk management in megaprojects. *Procedia - Social and Behavioral Sciences*, 119, 407-416.
ISO. (2009). ISO 31000:2009 - *Risk management: Principles and guidelines. International Organization for Standardization ISO*.
Iyer, K. C., & Sagheer, M. (2011). A real options based traffic risk mitigation model for build-operate-transfer highway projects in India. *Construction Management and Economics*, 29(8), 771-779.
Jacobson, G., & Adams, A. E. (2017). Understanding environmental risk perceptions: A case of contested illness in South Florida. *Sociological Inquiry*, 87(4), 659-684.
Jahanshahi, A. A., & Brem, A. (2017). Does Real Options Reasoning Support or Oppose Project Performance? Empirical Evidence from Electronic Commerce Projects. *Project Management Journal*, 48(4), 39-54.
Jaligot, R., & Chenal, J. (2019). Stakeholders' perspectives to support the integration of ecosystem services in spatial planning in Switzerland. *Environments*, 6(8), 88.
Kato, S., & Ahern, J. (2008). 'Learning by doing': Adaptive planning as a strategy to address uncertainty in planning. *Journal of Environmental Planning and Management*, 51(4), 543-559.
Kingdon, J. W. (2003). Agendas, alternatives, and public policies (2 ed.). Longman.
Knaap, G.-J., Engelberg, D., Avin, U., Erdogan, S., Ducca, F., Welch, T. F., Finio, N., Moeckel, R., & Shahumyan, H. (2020). Modeling sustainability scenarios in the Bbaltimore–Washington (DC) region. *Journal of the American Planning Association*, 86(2), 250-263.

Knight, F. H. (1921). Risk, Uncertainty and Profit. Houghton Mifflin.
Koops, L., Bosch-Rekveldt, M., Coman, L., Hertogh, M., & Bakker, H. (2016). Identifying perspectives of public project managers on project success: Comparing viewpoints of managers from five countries in North-West Europe. *International Journal of Project Management*, 34(5), 874-889.
Koops, L., van Loenhout, C., Bosch-Rekveldt, M., Hertogh, M., & Bakker, H. (2017). Different perspectives of public project managers on project success. *Engineering, Construction and Architectural Management*, 24(6), 1294-1318.
Koppenjan, J., Veeneman, W., van der Voort, H., ten Heuvelhof, E., & Leijten, M. (2011). Competing management approaches in large engineering projects: The Dutch RandstadRail project. *International Journal of Project Management*, 29(6), 740-750.
Kozlova, M. (2017). Real option valuation in renewable energy literature: Research focus, trends and design. *Renewable and Sustainable Energy Reviews*, 80, 180-196.
Krane, H. P., Rolstadås, A., & Olsson, N. O. E. (2010). Categorizing risks in seven large projects—Which risks do the projects focus on? *Project Management Journal*, 41(1), 81-86.
Krüger, N. A. (2012). To kill a real option - Incomplete contracts, real options and PPP. *Transportation Research Part A*, 46, 1359-1371.
Krystallis, I., Locatelli, G., & Murtagh, N. (2020). Talking about futureproofing: Real options reasoning in complex infrastructure projects. *IEEE Transactions on Engineering Management*, 1-14.
Kwakkel, J. H., Walker, W. E., & Marchau, V. A. (2010). Classifying and communicating uncertainties in model-based policy analysis. *International journal of technology, policy and management*, 10(4), 299-315.
Law, S. M., Mackay, A. E., & Nolan, J. F. (2004). Rail infrastructure management policy. Applying a real-options methodology. *Public Works Management & Policy*, 9(2), 145-153.
Lee, J.-K. (2008). Cost overrun and cause in Korean social overhead capital projects: Roads, rails, airports, and ports. *Journal of Urban Planning and Development*, 134(2), 59-62.
Lehtiranta, L. (2014). Risk perceptions and approaches in multi-organizations: A research review 2000-2012. *International Journal of Project Management*, 32, 640-653.
Lehtonen, M. (2014). Evaluating megaprojects: From the 'iron triangle' to network mapping. *Evaluation*, 20(3), 278-295.
Lehtonen, M., Joly, P.-B., & Aparicio, L. (2017a). Introduction. In M. Lehtonen, P.-B. Joly, & L. Aparicio (Eds.), *Socioeconomic evaluation of megaprojects. Dealing with uncertainties* (pp. 1-22). Routledge.
Lehtonen, M., Joly, P.-B., & Aparicio, L. (Eds.). (2017b). *Socioeconomic evaluation of megaprojects: Dealing with uncertainties*. Routledge.
Leleur, S., Salling, K. B., Pilkauskiene, I., & Nicolaisen, M. S. (2015). Combining reference class forecasting with overconfidence theory for better risk assessment of transport infrastructure investments. *European Journal of Transport and Infrastructure Research*, 15(3), 362-375.
Lethanh, N., & Adey, B. T. (2016). A real option approach to determine optimal intervention windows for multi-national rail corridors. *Journal of Civil Engineering and Management*, 22(1), 38-46.
Leung, W., Noble, B., Gunn, J., & Jaeger, J. A. G. (2015). A review of uncertainty research in impact assessment. *Environmental Impact Assessment Review*, 50, 116-123.
Leung, W., Noble, B. F., Jaeger, J. A. G., & Gunn, J. A. E. (2016). Disparate perceptions about uncertainty consideration and disclosure practices in environmental assessment and opportunities for improvement. *Environmental Impact Assessment Review*, 57, 89-100.
Lindblom, C. E. (1959). The Science of "muddling through". *Public Administration Review*, 19(2), 79-88.
Little, R. G. (2011). The emerging role of public-private partnerships in megaproject delivery. *Public Works Management & Policy*, 16(3), 240-249.
Love, P. E. D., & Ahiaga-Dagbui, D. D. (2018). Debunking fake news in a post-truth era: The plausible untruths of cost underestimation in transport infrastructure projects. *Transportation Research Part A: Policy and Practice*, 113, 357-368.
Love, P. E. D., Ika, L. A., & Pinto, J. K. (2022). Homo heuristicus: From risk management to managing uncertainty in large-scale infrastructure projects. *IEEE Transactions on Engineering Management*, 1-10.

Love, P. E. D., Zhou, J., Edwards, D. J., Irani, Z., & Sing, C.-P. (2017). Off the rails: The cost performance of infrastructure rail projects. Transportation Research Part A: Policy and Practice, 99, 14-29.
Lui, J., Gao, R., & Cheah, C. Y. J. (2017). Pricing mechanism of early termination of PPP projects based on real option theory. *Journal of Management in Engineering*, 33(6), 1-10.
Lundberg, M., Jenpanitsub, A., & Pyddoke, R. (2011). *Cost overruns in Swedish transport projects* [Working Paper 2011:11]. Centre for Transport Studies Stockholm
Lv, J., Ye, G., Kiu, W., Shen, L., & Wang, H. (2015). Alternative Model for Determining the Optimal Concession Period in Managing BOT Transportation Projects. *Journal of Management in Engineering*.
Lyons, G., & Davidson, C. (2016). Guidance for transport planning and policymaking in the face of an uncertain future. *Transportation Research Part A*, 88, 104-116.
Lyons, G., & Marsden, G. (2021). Opening out and closing down: the treatment of uncertainty in transport planning's forecasting paradigm. *Transportation*, 48(2), 595-616.
Macharis, C., & Nijkamp, P. (2013). Multi-actor and multi-criteria analysis in evaluating mega-projects. In H. Priemus & B. van Wee (Eds.), *International Handbook on Mega-Projects* (pp. 242-266). Edward Elgar Publishing Limited.
Machiels, T., Compernolle, T., & Coppens, T. (2020). Uncertainties in the decision-making process of megaprojects: The Zeebrugge new sea lock. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning*, 173(2), 41-53.
Machiels, T., Compernolle, T., & Coppens, T. (2021a). Explaining uncertainty avoidance in megaprojects: Resource constraints, strategic behaviour, or institutions? *Planning Theory & Practice*, 22(4), 537-555.
Machiels, T., Compernolle, T., & Coppens, T. (2021b). Real option applications in megaproject planning: Trends, relevance and research gaps. A literature review. *European Planning Studies*, 29(3), 446-467.
Mack, R. P. (1971). *Planning on uncertainty: Decision making in business and government administration*. Wiley-Interscience.
Mackie, P. (2010). *Cost-benefit analysis in transport-A UK perspective*. OECD/ITF Joint Transport Research Centre Discussion Paper
Martins, J., Marques, R. C., & Cruz, C. O. (2014). Maximizing the value for money of PPP arrangements through flexibility: An application to airports. *Journal of Air Transport Management*, 39, 72-80.
Martins, J., Marques, R. C., & Cruz, C. O. (2015). Real options in infrastructure: revisiting the literature. *Journal of Infrastructure Systems*, 21(1).
Martins, J., Marques, R. C., Cruz, C. O., & Fonseca, Á. (2017). Flexibility in planning and development of a container terminal: an application of an American-style call option. *Transportation Planning and Technology*, 40(7), 828-840.
Mathews, S., Datar, V., & Johnson, B. (2007). A practical method for valuing real options: The Boeing approach. *Journal of Applied Corporate Financ*e, 19(2), 95-104.
McKeown, B., & Thomas, D. B. (2013). *Q methodology* (2nd ed., Vol. 66). Sage publications.
Miller, K. D., & Waller, H. G. (2003). Scenarios, real options and integrated risk management. *Long Range Planning*, 36(1), 93-107.
Minkman, E., & Molenveld, A. (2020). Q-methodologie als methode om beleid te beschrijven, te ontwikkelen of te evalueren. *Beleidsonderzoek Online*, Januari 2020.
Mirzadeh, I., & Birgisson, B. (2016). Evaluation of highway projects under government support mechanisms based on an option-pricing framework. *Journal of Construction Engineering and Management*, 142(4).
Mok, K. Y., Qiping, S., & Yang, J. (2015). Stakeholder management studies in mega construction projects: A review and future directions. *International Journal of Project Management*, 33, 446-457.
Molenveld, A. (2020). Using Q methodology in comparative policy analysis. In B. G. Peters & G. Fontaine (Eds.), *Handbook of Research Methods and Applications in Comparative Policy Analysis* (pp. 333-347). Edward Elgar Publishing
Moroni, S. (2014). Complexity and the inherent limits of explanation and prediction: Urban codes for self-organising cities. *Planning Theory*, 14(3), 248-267.

Moroni, S., Buitelaar, E., Sorel, N., & Cozzolino, S. (2018). Simple Planning Rules for Complex Urban Problems: Toward Legal Certainty for Spatial Flexibility. *Journal of Planning Education and Research*, 40(3), 320-331.

Moroni, S., & Chiffi, D. (2021). Complexity and uncertainty: implications for urban planning. In J. Portugali (Ed.), *Handbook on cities and complexity*. Edward Elgar Publishing.

Mouter, N., Holleman, M., Calvert, S., & Annema, J. A. (2015). Towards improved handling of uncertainty in cost-benefit analysis: addressing the 'price-quality' and 'communication' dilemmas. *European Journal of Transport and Infrastructure Research*, 15(3).

Myers. (1977). Determinants of corporate borrowing. *Journal of Financial Economics*, 5(2), 147-176.

Nachbagauer, A. G. M., & Schirl-Boeck, I. (2019). Managing the unexpected in megaprojects: Riding the waves of resilience. *International Journal of Managing Projects in Business*, 12(3), 694-715.

Nadin, V., Stead, D., Dąbrowski, M., & Fernandez-Maldonado, A. M. (2021). Integrated, adaptive and participatory spatial planning: Trends across Europe. *Regional Studies*, 55(5), 791-803.

Neuendorf, F., von Haaren, C., & Albert, C. (2018). Assessing and coping with uncertainties in landscape planning: An overview. *Landscape Ecology*, 33(6), 861-878.

Nicolaisen, M. S. (2012). *Forecasts: Fact or Fiction?* [PhD, Department of Develpment and Planning, Aalborg University].

North, D. C. (1990). *Institutions, institutional change and economic performance*. Cambridge university press.

Nost, E., Robertson, M., & Lave, R. (2019). Q-method and the performance of subjectivity: Reflections from a survey of US stream restoration practitioners. *Geoforum*, 105, 23-31.

Odeck, J. (2019). Variation in cost overruns of transportation projects: An econometric meta-regression analysis of studies reported in the literature. *Transportation*, 46(4), 1345-1368.

Oliveira, A., Couto, G., & Pimentel, P. (2021). Uncertainty and flexibility in infrastructure investments: Application of real options analysis to the Ponta Delgada airport expansion. *Research in Transportation Economics*, 90, 100845.

Park, Y.-I., & Papadopoulou, T. C. (2012). Causes of cost overruns in transport infrastructure projects in Asia: Their significance and relationship with project size. *Built Environment Project and Asset Management*, 2(2), 195-216.

Patanakul, P., Hoon Kwak, Y., Zwikael, O., & Liu, M. (2016). What impacts the performance of large-scale government projects? *International Journal of Project Management*, 34, 452-466.

Pellegrino, R., Vajdic, N., & Carbonara, N. (2013). Real option theory for risk mitigation in transport PPPs. *Built Environment Project and Asset Management*, 3(2), 199-213.

Perminova, O., Gustafsson, M., & Wikström, K. (2008). Defining uncertainty in projects – A new perspective. *International Journal of Project Management*, 26(1), 73-79.

Petticrew, M., & Roberts, H. (2008). *Systematic reviews in the social sciences: A practical guide*. John Wiley & Sons.

Pickrell, D. H. (1990). *Urban rail transit projects: Forecast versus actual ridership and costs* (No. UMTA-MA-08-9021-89-1)

Pickrell, D. H. (1992). A desire named streetcar fantasy and fact in rail transit planning. *Journal of the American Planning Association*, 58(2), 158-176.

Pimentel, P., Nunes, C., & Couto, G. (2017). High-speed rail transport valuation with stochastic demand and investment cost. *Transportmetrica A: Transport Science*, 14(4), 275-291.

PMI. (2021). *A guide to the project management body of knowledge* (PMBOK guide) (7th ed.). Project Management Institute.

Priemus, H. (2007). Development and design of large infrastructure projects: Disregarded alternatives and issues of spatial planning. *Environment and Planning B: Planning and Design*, 34(4), 626-644.

Priemus, H. (2010). Mega-projects: Dealing with pitfalls. *European Planning Studies*, 18(7), 1023-1039.

Priemus, H., Bosch-Rekveldt, M., & Giezen, M. (2013). Dealing with the complexity, uncertainties and risks of mega-projects: Redundancy, resilience and adaptivity. In H. Priemus & B. van Wee (Eds.), *International Handbook in Mega-Projects* (pp. 83-110). Edward Elgar Publishing Limited.

Priemus, H., Flyvbjerg, B., & van Wee, B. (2008a). Introduction: Scope of the book. In H. Priemus & B.

van Wee (Eds.), *Decision-Making on Megaprojects* (pp. 1-20). Edward Elgar Publishing Limited.
Priemus, H., Flyvbjerg, B., & van Wee, B. (Eds.). (2008b). Decision-Making on Mega-Projects. Edward Elgar.
Priemus, H., & Van Wee, B. (Eds.). (2013). *International Handbook on Mega-Projects*. Edward Elgar.
Quay, R. (2010). Anticipatory governance. *Journal of the American Planning Association*, 76(4), 496-511.
Raadgever, G., Mostert, E., & Van De Giesen, N. (2008). Identification of stakeholder perspectives on future flood management in the Rhine basin using Q methodology. *Hydrology and earth system sciences*, 12(4), 1097-1109.
Rajé, F. (2007). Using Q methodology to develop more perceptive insights on transport and social inclusion. *Transport Policy*, 14(6), 467-477.
Ramjerdi, F., & Fearnley, N. (2014). Risk and irreversibility of transport interventions. *Transportation Research Part A: Policy and Practice*, 60, 31-39.
Rauws, W. (2017). Embracing uncertainty without abandoning planning. *disP - The Planning Review*, 53(1), 32-45.
Rauws, W., Cook, M., & Van Dijk, T. (2014). How to make development plans suitable for volatile contexts. *Planning Practice & Research*, 29(2), 133-151
Rauws, W., Zuidema, C., & de Roo, G. (2019). *Adaptieve Planning in Perspectief: Over adaptieve sturingsbenaderingen voor het borgen en versterken van de kwaliteit van de leefomgeving in een veranderlijke wereld*. Rijksuniversiteit Groningen.
Rittelmeyer, P. (2020). Socio-cultural perceptions of flood risk and management of a levee system: Applying the Q methodology in the California Delta. *Geoforum*, 111, 11-23.
Robbins, P., & Krueger, R. (2000). Beyond bias? The promise and limits of Q method in human geography. *The Professional Geographer*, 52(4), 636-648.
Rokicki, B. (2022). Cost underruns in major road transport infrastructure projects: The surprising experience of Poland. *Sustainability*, 14(21), 14608.
Salet, W. (Ed.) (2018). *The Routledge handbook of institutions and planning in action*. Routledge.
Salet, W., Bertolini, L., & Giezen, M. (2013). Complexity and uncertainty: Problem or asset in decision making of mega infrastructure projects. *International Journal of Urban and Regional Research*, 37(6), 1984-2000.
Samset, K., & Volden, G. H. (2016). Front-end definition of projects: Ten paradoxes and some reflections regarding project management and project governance. *International Journal of Project Management*, 34(2), 297-313.
Sanchez-Cazorla, A., Alfalla-Luque, R., & Irimia-Dieguez, A. I. (2016). Risk identification in megaprojects as a crucial phase of risk management: A literature review. *Project Management Journal*, 47(6), 75-93.
Sanchez-Soliño, A., Lara-Galera, A., & Colin, F. C. (2018). Valuation of the option of early reversion in road concessions. *European Journal of Transport and Infrastructure Research*, 18(2), 239-249.
Sanderson, J. (2012). Risk, uncertainty and governance in megaprojects: A critical discussion of alternative explanations. *International Journal of Project Management*, 30(4), 432-443.
Savini, F., Majoor, S., & Salet, W. (2015). Dilemmas of planning: Intervention, regulation, and investment. *Planning Theory*, 14(3), 296-315.
Searle, G. (2020). Metropolitan strategic Ppanning after modernism. *Planning Theory & Practice*, 21(2), 325-329.
Siemiatycki, M. (2013a). Public-private partnerships in megaprojects: Successes and tensions. In H. Priemus & B. van Wee (Eds.), *International Handbook on Mega-Projects* (pp. 133-157). Edward Elgar Publishing Limited.
Siemiatycki, M. (2013b). Riding the wave: explaining cycles in urban mega-project development. *Journal of Economic Policy Reform*, 16(2), 160-178.
Simon, H. A. (1997). *Administrative behavior: A study of decision-making processes in administrative organizations* (4 ed.). Free Press.
Singh, R. A. M. (2010). Delays and Cost Overruns in Infrastructure Projects: Extent, Causes and Remedies. *Economic and Political Weekly*, 45(21), 43-54.

Skamris holm, M. K., & Flyvbjerg, B. (1997). Inaccuracy of traffic forecasts and costs estimates on large transport projects. *Transport Policy*, 4(3), 141-146.
Skrimizea, E., Haniotou, H., & Parra, C. (2019). On the 'complexity turn'in planning: An adaptive rationale to navigate spaces and times of uncertainty. *Planning Theory*, 18(1), 122-142.
Smit, H. T. J. (2003). Infrastructure investment as a real options game: The case of European airport expansion. *Financial Management*, 32(4), 27-57.
Sneegas, G., Beckner, S., Brannstrom, C., Jepson, W., Lee, K., & Seghezzo, L. (2021). Using Q-methodology in environmental sustainability research: A bibliometric analysis and systematic review. *Ecological Economics*, 180, 106864.
Snel, K. A. W., Witte, P. A., Hartmann, T., & Geertman, S. C. M. (2019). More than a one-size-fits-all approach – tailoring flood risk communication to plural residents' perspectives. *Water International*, 44(5), 554-570.
Sohi, A. J., Bosch-Rekveldt, M., & Hertogh, M. (2019). Practitioners' perspectives on flexible project management. *IEEE Transactions on Engineering Management*, 1-15.
Sorensen, A. (2015). Taking path dependence seriously: An historical institutionalist research agenda in planning history. *Planning Perspectives*, 30(1), 17-38.
Sorensen, A. (2017). New institutionalism and planning theory. In M. Gunder, A. Madanipour, & V. Watson (Eds.), *The Routledge handbook of planning theory* (pp. 250-263). Routledge.
Sorensen, A. (2018). Institutions and urban space: Land, infrastructure, and governance in the production of urban property. *Planning Theory & Practice*, 19(1), 21-38.
Souza, J. C. F., Silva, M. M., Fernandes, L. M., Nóbrega, G., & Moutinho, F. (2019). A real options model for evaluating investments in the Guarulhos airport concession psrogram. *American Journal of Theoretical and Applied Business*, 5(3), 47-52.
Spencer, M. H. (1962). Uncertainty, expectations, and foundations of the theory of planning. *Academy of Management Journal*, 5(3), 197-206.
Stapleton, J. (2020). *Exploratory scenario planning (XSP). How to navigate an uncertain future*. Lincoln Institute of Land Policy.
Steele, W., & Ruming, K. J. (2012). Flexibility versus certainty: Unsettling the land-use planning shibboleth in Australia. *Planning Practice & Research*, 27(2), 155-176.
Stephenson, W. (1953). *The study of behavior; Q-technique and its methodology*. University of Chicago Press.
Stults, M., & Larsen, L. (2020). Tackling uncertainty in US local climate adaptation planning. *Journal of Planning Education and Research*, 40(4), 416-431.
Taleb, N. N. (2007). The black swan: The impact of the highly improbable. Random house.
Taylor, Z. (2013). Rethinking planning culture: A new institutionalist approach. *The Town Planning Review*, 84(6), 683-702.
Taylor, Z., Fitzgibbons, J., & Mitchell, C. L. (2020). Finding the future in policy discourse: An analysis of city resilience plans. *Regional Studies*, 1-13.
Terryn, E., Boelens, L., & Pisman, A. (2016). Beyond the divide: Evaluation in co-evolutionary spatial planning. *European Planning Studies*, 24(6), 1079-1097.
Thijssen, J. J. J. (2015). A model for irreversible investment with construction and revenue uncertainty. *Journal of Economic Dynamics & Control*, 57, 250-266.
Trigeorgis, L. (1996). *Real options. Managerial flexibility and strategy in recourse allocation*. The MIT Press.
Trigeorgis, L. (2005). Making use of real options simple: An overview and applications in flexible/modular decision making. *The Engineering Economist*, 50(1), 25-53.
Trigeorgis, L., & Reuer, J. J. (2017). Real options theory in strategic management. *Strategic Management Journal*, 38(1), 42-63.
Urquhart, J., Potter, C., Barnett, J., Fellenor, J., Mumford, J., & Quine, C. P. (2017). Expert risk perceptions and the social amplification of risk: A case study in invasive tree pests and diseases. *Environmental Science & Policy*, 77, 172-178.
van den Boomen, M., Spaan, M. T. J., Schoenmaker, R., & Wolfert, A. R. M. (2019). Untangling decision

tree and real options analyses: A public infrastructure case study dealing with political decisions, structural integrity and price uncertainty. *Construction Management and Economics*, 37(1), 24-43.
van der Heijden, K. (1996). *Scenarios: The art of strategic conversation*. Wiley.
Van Exel, J., & De Graaf, G. (2005). *Q methodology: A sneak preview*. https://www.researchgate.net/profile/Gjalt_Graaf/publication/228574836_Q_Methodology_A_Sneak_Preview/links/02bfe50f946fc9978b000000.pdf
van Marrewijk, A., Clegg, S. R., Pitsis, T. S., & Veenswijk, M. (2008). Managing public–private megaprojects: Paradoxes, complexity, and project design. *International Journal of Project Management*, 26(6), 591-600.
van Reedt Dortland, M., Voordijk, H., & Dewulf, G. (2012). Towards a decision support tool for real estate management in the health sector using real options and scenario planning. *Journal of Corporate Real Estate*, 14(3), 140-156.
Van Reedt Dortland, M., Voordijk, H., & Dewulf, G. (2014). Making sense of future uncertainties using real options and scenario planning. *Futures*, 55, 15-31.
van Wee, B., & Rietveld, P. (2013). CBA, ex ante evaluation of mega-projects. In H. Priemus & B. van Wee (Eds.), *International Handbook on Mega-projects* (pp. 269-290). Edward Elgar Publishing Limited.
Verweij, S. (2017). Addressing the evaluation-implementation gap in infrastructure megaproject research with qualitative comparative analysis. In M. Lehtonen, P.-B. Joly, & L. Aparicio (Eds.), *Socioeconomic Evaluation of Megaprojects: Dealing with uncertainties* (pp. 220-239). Routledge.
Volden, G. H., & Welde, M. (2022). Public project success? Measuring the nuances of success through ex post evaluation. *International Journal of Project Management*, 40(6), 703-714.
Vugteveen, P., Lenders, H. J. R., Devilee, J. L. A., Leuven, R. S. E. W., van der Veeren, R. J. H. M., Wiering, M. A., & Hendriks, A. J. (2010). Stakeholder value orientations in water management. *Society & Natural Resources*, 23(9), 805-821.
Wachs, M. (1987). Forecasts in urban transportation planning: Uses, methods, and dilemmas. *Climatic Change*, 11(1-2), 61-80.
Wachs, M. (1989). When planners lie with numbers. American Planning Association. *Journal of the American Planning Association*, 55(4), 476.
Wachs, M. (1990). Ethics and advocacy in forecasting for public policy. *Business & professional ethics journal*, 141-157.
Walker, W. E., Haasnoot, M., & Kwakkel, H. J. (2013). Adapt or perish: A review of planning approaches for adaptation under deep uncertainty. *Sustainability*, 5(3), 955-979.
Walker, W. E., Harremoës, P., Rotmans, J., Van Der Sluijs, J. P., Van Asselt, M. B. A., Janssen, P., & Krayer von Krauss, M. P. (2003). Defining uncertainty: A conceptual basis for uncertainty management in model-based decision support. *Integrated Assessment*, 4(1), 5-17.
Wang, A., & Pitsis, T. S. (2020). Identifying the antecedents of megaproject crises in China. *International Journal of Project Management*, 38(6), 327-339.
Wang, C., Liang, W., & Wang, S. (2014). Real option in urban rapid rail transit PPP project. *Applied Mechanics and Materials*, 505-506, 437-442.
Wang, Y., Shen, C., Zuo, J., & Rameezdeen, R. (2021). Same tune, different songs? Understanding public acceptance of mega construction projects: A comparative case study. *Habitat International*, 118, 102461.
Ward, S., & Chapman, C. (2003). Transforming project risk management into project uncertainty management. *International Journal of Project Management*, 21(2), 97-105.
Wathern, P. (2013). *Environmental impact assessment: Theory and practice*. Routledge.
Watts, S., & Stenner, P. (2012). *Doing Q methodological research: Theory, method & interpretation*. Sage.
Webler, T., Danielson, S., & Tuler, S. (2009). *Using Q method to reveal social perspectives in environmental research*. Greenfield MA: Social and Environmental Research Institute, 54, 1-45.
Welde, M., & Odeck, J. (2011). Do planners get it right? The accuracy of travel demand forecasting in norway. *European Journal of Transport and Infrastructure Research*, 11(1).
Welde, M., & Odeck, J. (2017). Cost escalations in the front-end of projects – empirical evidence from

Norwegian road projects. *Transport Reviews*, 37(5), 612-630.
Welkenhuysen, K., Meyvis, B., Swennen, R., & Piessens, K. (2018). Economic threshold of CO2-EOR and CO2 storage in the North Sea: A case study of the Claymore, Scott and Buzzard oil fields. *International Journal of Greenhouse Gas Control*, 78, 271-285.
Welkenhuysen, K., & Piessens, K. (2017). *The essential role of uncertainty and limited foresight in energy modelling*. https://www.sjscience.org/article?id=598
Welkenhuysen, K., Ramírez, A., Swennen, R., & Piessens, K. (2013). Strategy for ranking potential CO2 storage reservoirs: A case study for Belgium. *International Journal of Greenhouse Gas Control*, 17, 431-449.
Welkenhuysen, K., Rupert, J., Compernolle, T., Ramirez, A., Swennen, R., & Piessens, K. (2017). Considering economic and geological uncertainty in the simulation of realistic investment decisions for CO2-EOR projects in the North Sea. *Applied Energy*, 185, 745-761.
Wiechmann, T. (2008). Errors expected — Aligning urban strategy with demographic uncertainty in shrinking cities. *International Planning studies*, 13(4), 431-446.
Williams, T. (2017). The nature of risk in complex projects. *Project Management Journal*, 48(4), 55-66.
Williams, T., & Samset, K. (2010). Issues in front-end decision making on projects. *Project Management Journal*, 41(2), 38-49.
Williams, T., Vo, H., Samset, K., & Edkins, A. (2019). The front-end of projects: A systematic literature review and structuring. *Production Planning & Control*, 30(14), 1137-1169.
Winch, G. (2017). Megaproject stakeholder management. In B. Flyvbjerg (Ed.), *The Oxford Handbook of Megaproject Management* (pp. 339-361). Oxford University Press.
Winch, G. M., & Maytorena, E. (2012). Managing risk and uncertainty on projects. In P. W. G. Morris, J. Pinto, K., & J. Söderlund (Eds.), *The Oxford handbook of project management* (pp. 345-364). Oxford University Press.
Wooldridge, S. C., Garvin, M. J., Cheah, C. Y. J., & Miller, J. B. (2002). Valuing flexibility in private toll road development: Analysis of the Dulles Greenway. *The Journal of Structured Finance*, 7(4), 25-36.
Xiong, W., & Zhang, X. (2016). The real option value of renegotiation in public-private partnerships. *Journal of Construction Engineering and Management*, 142(8).
Yang, J. (2014). An investigation of stakeholder analysis in urban development projects: Empirical or rationalistic perspectives. *International Journal of Project Management*, 32(5), 838-849.
Yang, J., Shen, G. Q., Bourne, L., Ho, C. M. F., & Xue, X. (2011). A typology of operational approaches for stakeholder analysis and engagement. *Construction Management and Economics*, 29(2), 145-162.
Yin, R. K. (2018). *Case study research and applications: Design and methods* (6 ed.). Sage Publications.
Yu, J., & Leung, M.-y. (2015). Exploring factors of preparing public engagement for large-scale development projects via a focus group study. *International Journal of Project Management*, 33(5), 1124-1135.
Yzer, J. R., Walker, W. E., Marchau, V. A. W. J., & Kwakkel, J. H. (2014). Dynamic adaptive policies: a way to improve the cost-benefit performance of megaprojects? *Environment and Planning B: Planning and Design*, 41, 594-612.
Zandvoort, M., Kooijmans, N., Kirshen, P., & van den Brink, A. (2019). Designing with pathways: A spatial design approach for adaptive and sustainable landscapes. *Sustainability*, 11(3), 565.
Zandvoort, M., van der Brugge, R., van der Vlist, M. J., & van den Brink, A. (2018). Dealing with uncertainty in collaborative planning: Developing adaptive strategies for the IJsselmeer. *Journal of Environmental Planning and Management*, 1-18.
Zandvoort, M., van der Vlist, M. J., Klijn, F., & van den Brink, A. (2018). Navigating amid uncertainty in spatial planning. *Planning Theory*, 17(1), 96-116.
Zandvoort, M., van der Vlist, M. J., & van den Brink, A. (2018). Handling uncertainty through adaptiveness in planning approaches: Comparing adaptive delta management and the water diplomacy framework. *Journal of Environmental Policy & Planning*, 20(2), 183-197.
Zapata, M. A., & Kaza, N. (2015). Radical uncertainty: Scenario planning for futures. *Environment and Planning B-Planning & Design*, 42(4), 754-770.
Zhao, T., Sundararajan, S. K., & Tseng, C.-L. (2004). Highway development decision-making under uncertainty: A real options approach. *Journal of Infrastructure Systems*, 10, 23-32.

Appendices

Appendix 1: Reviewed papers (Chapter 2)

Overview of the reviewed papers (part 1/2)

#	Authors	Year	Country	Research objective (Q1)	Case description (Q2)
1	Alonso-Conde, A. B., Brown, C., & Rojo-Suarez, J.	(2007)	Australia	VF, RM, PR	Melbourne CityLink toll road project
2	Ashuri, B., Kashani, H., Molenaar, K. R., Lee, S., & Lu, J.	(2012)	South-Korea	VF, RM, PR	Incheon International Airport Highway, toll road
3	Bowe and Lee	(2004)	Taiwan	VF, PR	Taiwan high-speed rail project
4	Brandao, L. E. T., Bastian-Pinto, C., Gomes, L. L., & Labes, M.	(2012)	Brazil	VF, RM, PR	São Paulo, Metro Line 4
5	Buyukyoran and Gundes	(2018)	-	VF, RM, PR	Toll road
6	Cheah and Garvin	(2009)	USA	PR	Texas High-Speed Rail
7	Chen, Q., Shen, G., Xue, F., & Xia, B.	(2018)	Hong Kong	VF, RM, PR	West Harbor Crossing toll road Hong Kong
8	Chiara and Kokkaew	(2013)	USA	VF, RM, PR, OT	Build-operate-transfer toll road New York
9	Chiara, N., Garvin, M. J., & Vecer, J.	(2007)	-	VF, RM, PR, OT	Build-operate-transfer toll road project
10	Chu, X., Wang, S., & Feng, K.	(2017)	China	VF, RM, PR	Subway system China
11	Colin, F. C., Soliño, A. S., & Galera, A. L. L.	(2016)	Spain	VF, PR	Airport Axis M-12 highway, Madrid
12	Couto, G., Nunes, C., & Pimentel, P.	(2012)	Portugal	VF, RM, PR, OT	Portuguese High speed rail project
13	Cui, Q., Bayraktar, M. E., Hastak, M., & Minkarah, I.	(2004)	USA	VF, PR	Highway warranties USA
14	de Neufville, R., Scholtes, S., & Wang, T.	(2006)	UK	VF, PR	multilevel car park

15	Doan and Menyah	(2013)	-	VF, OT, PR	Real Toll road project under evaluation
16	Domingues, S., Zlatkovic, D., & Roumboutsos, A.	(2014)	Europe	PR	8 European road infrastructure cases
17	Fawcett, W., Urquijo, R., Krieg, H., Hughes, M., Mikalsen, L., & Gutiérrez, O. R. R.	(2015)	Spain	VF, PR	New highway Catalonia
18	Fitch, G. J., Odeh, I., Kautz, F., & Ibbs, C. W.	(2018)	USA	VF, RM, PR	Third crossing Cape Cod Canal, Massachusetts
19	Ford, D. N., Lander, D. M., & Voyer, J. J.	(2002)	-	VF, PR	Toll road in a developing country
20	Galera, A. L. L., Soliño, A. S., & Abad, B. G.	(2016)	Spain	VF, RM, PR	Section of the Madrid-Alicante highway
21	Galera, A. L. L., Soliño, A. S., & Aires, R. G.	(2018)	Spain	VF, RM, PR	Toll motorway concession
22	Grimes	(2011)	New Zealand	VF, PR	Auckland's bridge/motorway
23	Huang and Pi	(2014)	Taiwan	VF, RM	Taiwan high-speed rail project
24	Iyer and Sagheer	(2011)	India	RM, PR	Kondhali–Talegaon highway toll road
25	Krüger	(2012)	Sweden	VF, PR	Two-lane road
26	Law, S. M., Mackay, A. E., & Nolan, J. F.	(2004)	Canada	PR	Rail track abandonment case near Toronto
27	Lethanh and Adey	(2016)	Europe	VF, OT, PR	European multi-national rail corridors
28	Lv, J., Ye, G., Kiu, W., Shen, L., & Wang, H.	(2015)	China	VF, RM, PR	Toll road Chongqing
29	Lui, J., Gao, R., & Cheah, C. Y. J.	(2017)	Malaysia	VF, RM, PR	Secondary Crossing Malaysia-Singapore
30	Martins, J., Marques, R. C., & Cruz, C. O.	(2014)	Portugal	VF, PR	New Lisbon Airport
31	Martins, J., Marques, R. C., Cruz, C. O., & Fonseca, Á.	(2017)	Spain	VF, PR	Terminal Container expansion, Ferrol
32	Mirzadeh and Birgisson	(2016)	Finland	VF, RM, PR	E18 Highway
33	Pimentel, P., Nunes, C., & Couto, G.	(2017)	Portugal	VF, OT, PR	Portuguese High speed rail project

34	Sanchez-Soliño and Lara-Galera	(2018)	Spain	VF, RM, PR	Toll motorway concession
35	Smit	(2003)	Netherlands	VF	Schiphol Airport
36	Souza, J. C. F., Silva, M. M., Fernandes, L. M., Nóbrega, G., & Moutinho, F	(2019)	Brazil	VF, PR	Guarulhos Airport expansion (Sao Paulo)
37	Thijssen	(2015)	UK	VF, OT, PR	HS2 High-speed rail link London-Birmingham
38	Wang, C., Liang, W., & Wang, S.	(2014)	China	VF, PR	Parking garage, Beijing
39	Wooldridge, S. C., Garvin, M. J., Cheah, C. Y. J., & Miller, J. B.	(2002)	USA	VF, PR	Dull toll road highway Virginia
40	Xiong and Zhang	(2016)	-	VF, RM, PR	Toll road ("Project A")
41	Yzer, J. R., Walker, W. E., Marchau, V. A. W. J., & Kwakkel, J. H.	(2014)	Netherlands	VF, PR	Schiphol Airport
42	Zhao, T., Sundararajan, S. K., & Tseng, C.-L.	(2004)	USA	VF, OT	Highway in USA

Overview of the reviewed papers (part 2/2)

#	Case type (Q3)	Uncertainty sources (Q4)	Real options (Q5)	Valuation method (Q6)
1	Ex post	Demand (MU)	Risk mitigation, delay, abandon	BLM, MCS
2	Ex post	Demand (MU)	Risk sharing (MRG, TRC)	BLM, MCS
3	Ex post	Demand (MU), construction cost (TU)	delay, scale (expand and contract)	BLM
4	Ex post	Demand (MU)	Risk mitigation (government guarantee)	MCS
5	Hypothetical	Demand (MU)	Risk mitigation (MRG, TRC)	MCS
6	Ex post	Demand (MU)	abandon, scale, growth	Descriptive
7	Ex post (H)	Demand (MU)	Toll-adjusted mechanism (risk mitigation)	DTA
8	Hypothetical	demand, O&M cost (MU)	Dynamic revenue insurance contracts	MCS, DP
9	Hypothetical	Demand (MU)	Risk mitigation (government guarantee)	MCS, DP
10	Hypothetical	Demand (MU)	Risk mitigation (government guarantee)	MCS, SA
11	Ex post	Demand (MU)	abandon	MCS
12	Ex post	Demand (MU)	delay	DP

13	Hypothetical	Infrastructure conditions (TU)	delay	BSE
14	Hypothetical	Demand (MU)	scale (expand)	MCS
15	Current project	demand, O&M cost (MU)	delay	BLM, MCS, DP
16	Ex post	-	Managerial flexibilities	Descriptive
17	Ex post	demand, discount rate (MU)	scale ("upgrade")	MCS, SA
18	Current project	Demand (MU)	Abandon, risk mitigation (MRG)	SD model
19	Hypothetical	construction cost (MU)	delay	DTA, BLM
20	Ex post	Demand (MU)	Risk mitigation (participation loan)	MCS
21	Ex post	Demand (MU)	Risk sharing (subsidies)	GBM, MCS, SA
22	Ex post	demand, population growth, land value (MU)	delay	DTA
23	Ex post	project value (MU)	performance bonds	BSM, SA
24	Ex post	Demand (MU)	Traffic band (MRG + TRC)	BLM
25	Hypothetical	Demand (MU)	scale (expand)	DTA, BLM
26	Ex post	Demand (MU)	abandon, switch use	Descriptive
27	Hypothetical	Infrastructure conditions (TU)	delay (optimal intervention window)	BSM, DP, SA
28	Ex post	Demand (MU)	Concession period	GT
29	Ex post	Demand (MU)	abandon (early contract termination)	/
30	Current project	Demand (MU)	stage	BLM, MCS
31	Ex post	Demand (MU)	Scale (expand)	BLM, MCS, SA
32	Hypothetical	energy price (MU)	Risk mitigation (PACs)	BLM
33	Ex post	demand, investment cost (MU)	delay	DP
34	Ex post	Demand (MU)	Option of early reversion	MCS
35	Ex post	Demand (MU)	Growth option	BLM, GT
36	Current project	Demand (MU)	delay	BSM
37	Current project	Revenue (MU), construction time (TU)	delay	DP
38	Hypothetical	Demand (MU)	scale (expand)	MCS
39	Ex post	Demand (MU)	delay	BLM

40	Ex post	Demand (MU)	Contract renegotiations	BLM, MCS, GT, SA
41	Current project	Demand (MU)	Contingency plans	DAP
42	Hypothetical	demand, land price (MU), infrastructure conditions (TU)	Scale (expand)	MCS, DP

Appendix 2: Sources used for the Zeebrugge New Sea Lock document analysis (Chapters 3 & 4)

Original name (Dutch) – translation English – publication date – description

Project documents

1. MKBA Zeesluis Zeebrugge – SCBA Sea Lock Zeebrugge – April 2019 (latest version) – the social cost benefit analysis of the project
2. Strategische milieubeoordeling verbetering nautische toegankelijkheid tot de (achter) haven van Zeebrugge – Strategic environmental impact assessment improvement of the nautical accessibility to the rear port of Zeebrugge ¬– April 2019 (latest version) – the environmental impact assessment of the project
3. Nautische screening – Nautical screening – 2016 – research report on the nautical feasibility of the six alternatives, conducted and written at the same time as the SCBA and EIA.
4. Voorontwerp Voorkeursbesluit – predesign preferred decision – March-April 2018 – the first draft expressing the preferred decision for alternative 2, accompanied by a motivation for this choice
5. Ontwerp voorkeursbesluit – design preferred decision – December 2018 – the second draft of the preferred decision alternative 2, with adjustments to the motivation and action plan after the consultancy rounds among private/public expert institutions and advisory commissions
6. Principiële vaststelling voorkeursbesluit – principal determination preferred decision – May 2019 – the third and final draft of the preferred decision alternative 2, with adjustments to the motivation and action plan after the public inquiry.
7. Voorkeursbesluit – preferred decision – June 2019 – the final document stating the preferred decision, after the advice from the Council of State, with a regulatory status, marking the end of the planning (research) phase and start of the project (design) phase.
8. Alternatievenonderzoeksnota – alternatives research note – March 2017 – document at the early stages of the research phase, containing an extensive description of the six alternatives to be researched in the SCBA, EIA and Nautical Screening.
9. Antwoordennota naar aanleiding van adviesronde voorontwerp voorkeursbesluit – December 2018 – answers following the consultancy rounds for the predesign preferred decision ¬– this document contains an extensive summary of all the questions or comments given for each advisory commission or consulted public/ private (exper) instition, with responses from the project team for each question or comment.
10. Antwoordennota naar aanleiding van het openbaar onderzoek van het ontwerp van voorkeursbesluit ¬– answers following the public inquiry from the design preferred decision – March-April 2019 – this document contains an extensive summary of alle the questions and comments submitted from individuals – anonymous in this

document – during the public inquiry, with responses from the project team for each question or comment.

11. Synthesenota – synthesis – April 2019 (latest version) – a summary of the results from the research phase – SCBA, EIA, nautical screening – for all alternatives, as a first step towards the preferred decision.
12. Procesnota – process note – December 2018 (latest version) – an informative document including (I) general information (objective, actors, timing) about the project and process, (II) an overview of participation moments and the location of available documents, and (III) a description of the communication approach in favor of the process' transparency.

The above listed documents are free to consult and download in PDF-version at the project's website: https://www.nieuwesluiszeebrugge.vlaanderen.be/

Other documents

13. Richtlijnenboek Milieueffectenrapportage – Book of Guidelines for Environmental Impact Assessment ¬– October 2015 – guidelines for making an EIA. These guidelines were written conjointly by the Flemish Department of Environment, Nature and Energy; and 'Technicum', a subdivision of the international consultancy and engineering company 'Tractabel'. The PDF version can be downloaded for free at the Department's website: https://www.lne.be/richtlijnenboeken-en-handleidingen
14. Standaardmethodiek voor MKBA van transportinfrastructuurprojecten – Standard methodology for SCBA of transport infrastructure projects – December 2013 – These guidelines were written by Rebel Group, an international advisory commission, on behalf of the Flemish Department of Mobility and Public Works.

Press articles

15. Press articles were gathered from various Flemish news sources using a combination of the search terms 'Port Zeebrugge' and 'Sea Lock'. Sources from between May 2017 and June 2019 were found on the following news websites: https://www.vrt.be/vrtnws/nl/; https://www.standaard.be/; https://www.nieuwsblad.be/; https://kw.be/.

Appendix 3: Interview and coding protocol of semi-structured interviews of the Zeebrugge case study (Chapter 4)

Semi-structured interviews are a research method for which the researcher prepares a list of questions or topics that he/she wishes to talk about, but interview itself is more of an open conversation. It is the interviewer's responsibility to make sure that all of the topics or questions came up in the end.

To design the protocol – the list of questions – for the semi-structured interviews with stakeholders of the NSZ case study, we followed the guidelines offered in the handbook of qualitative research methods of Mortelmans (2013). According to this handbook, semi-structured interviews are prepared around four types of questions: an opening question as an ice breaker; transition questions to steer the interview in the direction of the topic and to gauge the interviewee's general perspective of the topic; key questions that form the core of the research; and a closing question to summarize the interview or to emphasize the interviewee's most important statement(s) or opinion(s). Each question furthermore can contain follow-up questions or sub-questions. Depending on the knowledge and the background of the stakeholder, certain sub questions will (not) be asked. Generally, an interview is composed of 5-10 questions.

Interview questions of for the Zeebrugge case study data collection (translated from Dutch to English):

Opening question

1. What does uncertainty mean to you?
    - When is something more or less uncertain to you?

Transition questions

2. How would you describe the complexity of the NSZ project?
    - When is this a successful project for you?
    - Are you happy with the chosen location alternative for the new lock
    - What do you think about the arguments that were used to (not) choose an alternative?
3. What do you believe are the importance of the SCBA and EIA in the decision making of this project?
    - Have you been involved in the drafting or communication of SCBA and EIA reports?
    - What are, according to you, the strengths or weaknesses of the SCBA and EIA of this project?

Key questions

4. Which procedures or ways have been used to manage uncertainties in this project?
- How are uncertainties identified for the SCBA and EIA?
- Did discussions take place about uncertainties?
- If uncertainties are identified, how is it determined in which way these are incorporated in the SCBA or EIA?
- What happens if uncertainties are identified after the SCBA and EIA are completed, for example, during a public inquiry?

5. How do you experience the procedures or ways that were used to manage uncertainties?
6. Is there any communication about uncertainties with stakeholders that are not involved in the drafting of project documents?
- Do you believe it is important to communicate about uncertainties with these stakeholders?

7. What do you believe are the main uncertainties that will influence the success of this project?
- How do you believe these uncertainties should be managed?

8. *The interviewee is presented with uncertainties identified in the project documents, and asked to express their opinion about these elements in terms of degree of uncertainty and the impact of that uncertainty on the project's success.*

Closing question

9. Do you believe there are possibilities or opportunities to change the way uncertainties are identified, communicated, or managed in this process?

The interview transcriptions were analysed with the software program NVivo. For the first coding phase (open coding), a codebook was designed a priori as an aid to analyse the transcriptions. The codebook was inductively adjusted through the phases of open coding and axial coding. The final codebook consisted of the following codes and child codes (translated from Dutch to English):

1. Strong quotes
2. Complex project NSZ
    - Complexity
    - Goals and conditions
    - Integrated research (SCBA, EIA, nautical screening)
        - Choices about scope and depth
        - Determining the direction of the research
    - Societal impact during the project
    - Location alternatives
        - Visart
        - Carcoke
        - Vandamme West
        - Vandamme Oost

        - Verbindingsdok
    - Procedure complex projects
    - Project success criteria
    - Project history
3. Identification of uncertainties
4. Communication and documentation of uncertainties
5. Uncertainty types
    - Market uncertainty
    - Technical uncertainty
    - Policy uncertainty
    - Legal uncertainty
    - Societal uncertainty
    - Impact uncertainty
6. Describing and interpreting uncertainties
7. Decision making NSZ
    - Arguments in favour of an alternative
    - Arguments against an alternative
    - Influence of uncertainty on decision making
    - Political decision making
8. Uncertainty avoidance
    - Resource constraints
    - Strategic behaviour
    - Planning institutions
9. Project elements
    - Project financing
    - Impact on companies
    - Impact on yacht club
    - Impact on environment and community
    - Impact on fishing sector
    - Impact during construction
    - Knowledge gap Verbindingsdok
    - Liveability and spatial quality
    - Spatial relations neighbourhoods Zeebrugge
    - Societal support
    - Mitigation measures
    - Nautical accessibility and optimalisation
    - NX tunnel
    - Displacements and relocations
    - Benefits projects
    - Legal procedures council of state
    - Timing and scheduling
    - Traffic forecasts SCBA

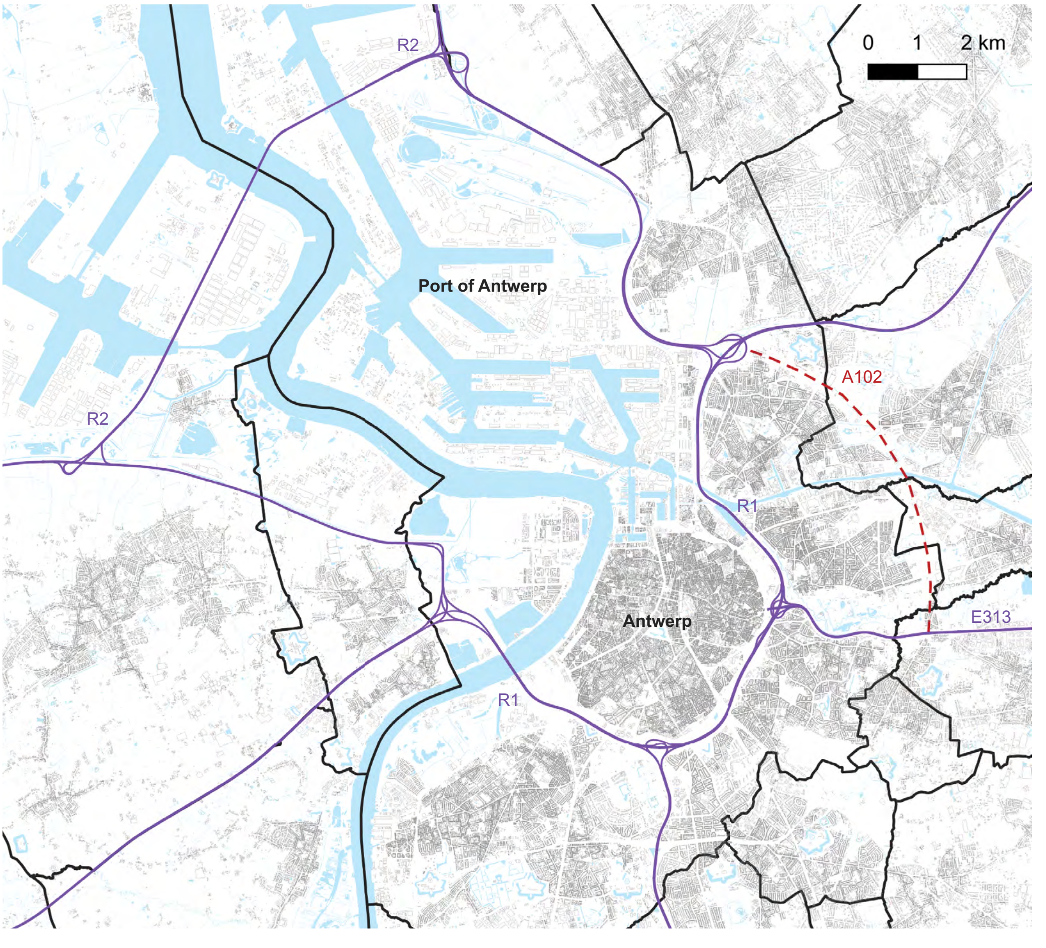
Appendix 4: Details about the Q methodology application (Chapter 5)

This appendix provided additional methodological information about the Q methodology application. We recommend reading the paper first before using the appendix for additional information, as alle steps of our Q methodology application are only explained in the paper.

For readers who are interested in performing their own Q methodology study, we highly recommend the book ‘Doing Q methodological research: Theory, method & interpretation’ by Watts and Stenner (2012). Rich with references and examples, the book guides the reader through every step of Q.

Map of the A102

The map below shows main highways around Antwerp and the planned A102 road tunnel (black lines = municipal borders; purple lines = existing highways; red dotted line = planned A102 road tunnel)



Matrix for structured sampling uncertainty statements (Q step 1)

During the first step, the concourse that consisted of 194 statements was reduced to a more manageable number of statements for participants to sort. To reduce the concourse into the final Q set, a matrix for structured sampling was used. The matrix helped to find similar statements, which are then reformulated into a smaller set of uncertainties that remains representative for the concourse. Columns and rows were inductively created when project elements or an uncertainty type came up from the concourse. Statements listed under the columns 'general' and 'uncertainty' were appointed to one of the uncertainty types after the matrix was completed. The number in each of the cells refers to the number of statements from the concourse about that project element and uncertainty type.

The sum of statements in the matrix is 197. The concourse consists of only 194 statements, which means 3 statements were placed in two cells of the matrix.

	General	uncertainty	Market/ mobility	Technical	Policy and political	Stakeholder and societal	Impact	Total
Related projects	1	1		1	5		2	10
Political decision making		1						1
Construction		1		4			2	7
Policy and project ojbectives	20	2	11		2	2	4	41
Support and opposition		3				6	1	10
Project phasing and timing	10	6	6	2	2			26
Financing and cost	1	6		1	4	1		13
Environmental impact		2	2		1		8	13
Mobility impact		6	6					12
SCBA and EIA	6	5	4			3	1	19
Design choices	8	1	6	4				19
Participation and com- munication	4	8	1			6		19
Cost and benefit distri- bution	1							1
Effect of the A102	1		5					6
Total	52	42	41	12	14	18	18	197

Theoretical explanations about the factor analysis (Q step 4)

Factor analysis with principal component analysis and centroid factor analysis

Two factor analysis techniques can be used to extract factors: principal component analysis (PCA) and centroid factor analysis (CFA). PCA will resolve itself into a single mathematically best solution, while CFA enables the researcher to interfere more with the extraction process and produce factors more manually (Watts & Stenner, 2012). In most studies, PCA and CFA generate fairly similar results (Watts & Stenner, 2012; Webler et al., 2009), which was also the case in our study after applying both techniques. PCA is the most common type of factor analysis (Webler et al., 2009), so we decided to use PCA for extracting factors from the Q sorts.

Why are non-loaders and confounders excluded from factor analysis?

Confounded Q sorts are typically not used in the construction of the factor arrays because they are a reflection of at least two factors, which can increase the correlation between factors and make the resulting factor arrays less distinct. Nevertheless, confounded Q-sorts can still be explained in terms of the resulting factor arrays onto which they significantly load (Armatas et al., 2014).

Conventional Q practice would exclude confounders, while these might be interesting individuals which Q-method can help identify, as confounders indicate some people truly have hybrid views (Nost et al., 2019).

Non-loaders are typically excluded from factor analysis since they do not load significantly on any of the factors. It is up to the researchers to decide, by analyzing each non-loader individually, whether their viewpoint is important to consider. It might be that the story told by a non-loader about his final ranking does not deviate strongly from other perceptions, although the ranking was performed significantly different from those of the extracted factors.

Factor loadings table (Q step 4)

The extent to which a participant correlates with each factor is determined by the factor loading of the Q sort. Factor loadings range from 1 (positive correlation) through 0 (no correlation) to -1 (negative correlation). The table below shows the factor loadings of each Q sort (participant) for each factor in a four-factor solution after performing principal component analysis and varimax rotation. Factor loadings marked with an 'X' are Q sorts that load significantly on that factor at the $p < 0.01$ level. Factor loadings marked with an 'X*' are Q sorts that load significantly on that factor at the $p < 0.05$ level. A significant factor loading is determined by the following formula (where the number of items in the Q set is 32 in this study):

At the p < 0.01 level: 2,58(1/√(no of items in Q set))=0,49*
At the p < 0.05 level: 1,96(1/√(no of items in Q set))=0,37*

Q sorts without a marking are either non-loaders (CG19, RG30) or confounders (RG28, CG11). Non-loaders are Q sorts that do not load significantly on any factor. Confounders are Q sorts that load significantly on more than one factor. Non-loaders and confounders are excluded from factor interpretation.

The abbreviations in the table below refer to the different stakeholder groups that participated in the Q study: IG = interest group; CG = citizen group; MU = municipality; RG = regional government (Flemish and provincial government administrations)

Q-sort (participant)	Factor 1	Factor 2	Factor 3	Factor 4	Significance
IG01	-0,0555	0,029	0,5648 X	-0,1355	p < 0.01
IG02	0,2216	0,1445	0,568 X	0,1915	p < 0.01
IG03	0,3287	0,054	-0,3086	0,688 X	p < 0.01
IG04	0,2341	-0,0613	0,1781	0,385 X*	p < 0.05
CG05	0,44	0,6999 X	0,1348	0,0457	p < 0.01
CG06	0,1338	0,6093 X	0,3242	-0,0912	p < 0.01
CG07	0,5771 X	0,1539	0,1213	0,1516	p < 0.01
CG08	0,0895	0,7495 X	-0,0877	0,07	p < 0.01
CG09	-0,2926	0,6703 X	0,3827	0,1765	p < 0.01
CG10	-0,3672	0,5095 X	0,29	0,4312	p < 0.01
CG11	0,2494	0,1294	0,4498	0,4102	confounder
CG12	0,7284 X	-0,1451	0,3496	0,2621	p < 0.01
CG13	-0,1395	0,0197	0,153	0,7769 X	p < 0.01
CG14	0,3955	-0,0141	-0,1108	0,5706 X	p < 0.01
CG15	0,4384	-0,4913	0,5452 X	0,1337	p < 0.01
MU16	-0,037	0,6669 X	0,0081	0,0586	p < 0.01
MU17	0,1556	0,5961 X	0,4468	-0,203	p < 0.01
MU18	0,5857 X	0,0599	0,1141	0,3029	p < 0.01
MU19	0,2521	0,1685	0,3407	0,0375	non-loader
MU20	0,1798	0,3338	0,6745 X	0,0487	p < 0.01
MU21	-0,0752	-0,1564	0,0888	0,772 X	p < 0.01
MU22	-0,0187	0,0502	0,7934 X	0,3173	p < 0.01
MU23	0,2051	0,8497 X	0,0545	0,0525	p < 0.01
MU24	0,0924	0,2364	0,3428	0,7231 X	p < 0.01
RG25	0,8602 X	-0,0334	0,0129	-0,0503	p < 0.01

RG26	0,3766	-0,0458	-0,16	0,7482 X	p < 0.01
RG27	0,3669	0,1163	0,3386	0,5861 X	p < 0.01
RG28	0,5672	0,2776	-0,221	0,5604	confounder
RG29	-0,3893	0,7352 X	0,0996	0,0917	p < 0.01
RG30	-0,0417	0,2342	0,0741	0,3243	non-loader
RG31	0,6501 X	-0,009	0,4507	0,0517	p < 0.01
RG32	0,186	0,3183	0,3462	0,4008 X*	p < 0.05

Factor arrays used for factor interpretation (Q step 5)

The factor analysis identifies a factor array for each factor, a single composite Q sort or idealized Q sort that represents the viewpoint of a factor. The factor array is calculated as the weighted average of the Q sorts that load significantly on that factor. The factor arrays are used to interpret the perceptions and construct a factor's narrative. Below, the factor arrays are summarized in a table for all factors, followed by a visualization of each factor array

The colors in the visualized factor arrays represent an uncertainty type: blue = market and transport uncertainties; orange = technical uncertainties; purple = political and policy uncertainties; green = societal and stakeholder uncertainties; yellow = environmental impact uncertainties.

Q item. uncertainty about…		**Factor number and ranking on factor array**			
		F1	**F2**	**F3**	**F4**
1	the evolution of the modal split of passenger transport in the Antwerp region	-4	4	0	-1
2	the evolution of the modal split of freight transport in the Antwerp region	-2	3	-1	0
3	the evolution of passenger transport on the Antwerp ring road	-1	1	0	-1
4	the evolution of freight transport on the Antwerp ring road	0	1	-1	-1
5	the societal necessity of the A102	0	0	2	3
6	the societal support for the A102	2	2	2	4
7	the composition of future political administrations	-1	-4	-2	1
8	the political priority of the A102 compared with other policies and projects	0	-2	1	4
9	the effect of Oosterweel on transport in the Antwerp region*	-3	0	-2	-2
10	the effect of the A102 on the modal split in the Antwerp region	-2	2	0	-1
11	the effect of the A102 on passenger transport demand	-4	0	-3	-2

12	the effect of the A102 on freight transport demand	-3	0	0	0
13	the impact of the A102 on its direct spatial, human, and ecological environment	3	4	3	0
14	the effect of the A102 on economic growth	-2	-3	-4	-2
15	the effect of toll roads on transport demand (on the A102)	0	-2	-1	1
16	the effect of the A102 on the underlying road infrastructure network	1	3	2	1
17	the correct completion of legal and administrative procedures	4	-2	-3	0
18	the availability of financial resources for the A102	1	-1	1	3
19	the availability of financial resources for livability projects in the context of the A102	4	2	0	1
20	scope changes because of additional requirements of stakeholders	1	-1	1	2
21	reaching consensus with all stakeholders	3	-1	0	2
22	the sum of the societal costs, benefits, and effects of the entire Port route	2	1	-2	0
23	the construction time of the A102	-1	-4	-4	-4
24	the impact of the A102 on reaching climate goals	0	1	-1	0
25	the environmental impact during the construction of the A102	2	0	1	-4
26	the technical feasibility of a joint construction of the A102 and the second freight rail line.	1	-1	3	-3
27	the cost of an A102 tunnel constructed with a tunnel boring machine	0	-3	4	-3
28	the route choice and connection of the A102 with the existing road infrastructure	-1	0	4	2

Perception 1: uncertainty about livability as a driver for legal action

Which uncertainties (do not) have an important impact on the A102 decision making?								
Most unimportant				Neutral (indifferent or no opintion)				Most important
-4	-3	-2	-1	0	+1	+2	+3	+4
Uncertainty about the evolution of the modal split of passenger transport in the Antwerp region	Uncertainty about the effect of the A102 on freight transport demand	Uncertainty the evolution of the modal split of freight transport in the Antwerp region	Uncertainty about the route choice and connection of the A102 with the existing road infrastructure	Uncertainty about the political priority of the A102 compared with other policies and projects	Uncertainty about the availability of financial resources for the A102	Uncertainty about the societal support for the A102	Uncertainty about the impact of the A102 on its direct spatial, human and ecological environment	Uncertainty about the correct completion of legal and administrative procedures
Uncertainty about the effect of the A102 on passenger transport demand	Uncertainty about the effect of OWV on transport in the Antwerp region	Uncertainty about the effect of the A102 on the modal split in the Antwerp region	Uncertainty about the composition of future political administrations	Uncertainty about the impact of the A102 on reaching climate goals	Uncertainty about the technical feasibility of a joint construction of the A102 and the second freight rail line.	Uncertainty about the environmental impact during the construction of the A102	Uncertainty about reaching consensus with all stakeholders	Uncertainty about the availability of financial resources for livability projects in the context of the A102
		Uncertainty about the effect of the A102 on economic growth	Uncertainty about the construction time of the A102	Uncertainty about the cost of an A102 tunnel constructed with a TBM	Uncertainty about the effect of the A102 on the underlying road infrastructure network	Uncertainty about the sum of the societal costs, benefits, and effects of the entire Port route		
			Uncertainty about the evolution of passenger transport on the Antwerp ring road	Uncertainty about the societal necessity of the A102	Uncertainty about scope changes because of additional requirements of stakeholders			
				Uncertainty about the evolution of freight transport on the Antwerp ring road				
				Uncertainty about the effect of toll on transport demand (on the A102)				

Perception 2: potential project redundancy driven by future model split uncertainty

Which uncertainties (do not) have an important impact on the A102 decision making?								
Most unimportant				Neutral (indifferent or no opintion)				Most important
-4	-3	-2	-1	0	+1	+2	+3	+4
Uncertainty about the construction time of the A102	Uncertainty about the cost of an A102 tunnel constructed with a TBM	Uncertainty about the effect of toll on transport demand (on the A102)	Uncertainty about the availability of financial resources for the A102	Uncertainty about the environmental impact during the construction of the A102	Uncertainty about the impact of the A102 on reaching climate goals	Uncertainty about the availability of financial resources for livability projects in the context of the A102	Uncertainty about the evolution of the modal split of freight transport in the Antwerp region	Uncertainty about the evolution of the modal split of passenger transport in the Antwerp region
Uncertainty about the composition of future political administrations	Uncertainty about the effect of the A102 on economic growth	Uncertainty about the correct completion of legal and administrative procedures	Uncertainty about the technical feasibility of a joint construction of the A102 and the second freight rail line.	Uncertainty about the effect of the A102 on passenger transport demand	Uncertainty about the evolution of passenger transport on the Antwerp ring road	Uncertainty about the societal support for the A102	Uncertainty about the effect of the A102 on the underlying road infrastructure network	Uncertainty about the impact of the A102 on its direct spatial, human and ecological environment
		Uncertainty about the political priority of the A102 compared with other policies and projects	Uncertainty about scope changes because of additional requirements of stakeholders	Uncertainty about the effect of the A102 on freight transport demand	Uncertainty about the sum of the societal costs, benefits, and effects of the entire Port route	Uncertainty about the effect of the A102 on the modal split in the Antwerp region		
			Uncertainty about reaching consensus with all stakeholders	Uncertainty about the societal necessity of the A102	Uncertainty about the evolution of freight transport on the Antwerp ring road			
				Uncertainty about the route choice and connection of the A102 with the existing road infrastructure				
				Uncertainty about the effect of OWV on transport in the Antwerp region				

Perception 3: technical and cost uncertainties influence project impact and design

Which uncertainties (do not) have an important impact on the A102 decision making?								
Most unimportant				Neutral (indifferent or no opintion)				Most important
-4	-3	-2	-1	0	+1	+2	+3	+4
Uncertainty about the construction time of the A102	Uncertainty about the effect of the A102 on passenger transport demand	Uncertainty about the composition of future political administrations	Uncertainty about the impact of the A102 on reaching climate goals	Uncertainty about the availability of financial resources for livability projects in the context of the A102	Uncertainty about scope changes because of additional requirements of stakeholders	Uncertainty about the societal necessity of the A102	Uncertainty about the impact of the A102 on its direct spatial, human and ecological environment	Uncertainty about the route choice and connection of the A102 with the existing road infrastructure
Uncertainty about the effect of the A102 on economic growth	Uncertainty about the correct completion of legal and administrative procedures	Uncertainty about the sum of the societal costs, benefits, and effects of the entire Port route	Uncertainty about the evolution of freight transport on the Antwerp ring road	Uncertainty about reaching consensus with all stakeholders	Uncertainty about the environmental impact during the construction of the A102	Uncertainty about the effect of the A102 on the underlying road infrastructure network	Uncertainty about the technical feasibility of a joint construction of the A102 and the second freight rail line.	Uncertainty about the cost of an A102 tunnel constructed with a TBM
		Uncertainty about the effect of OWV on transport in the Antwerp region	Uncertainty about the evolution of the modal split of freight transport in the Antwerp region	Uncertainty about the effect of the A102 on the modal split in the Antwerp region	Uncertainty about the political priority of the A102 compared with other policies and projects	Uncertainty about the societal support for the A102		
			Uncertainty about the effect of toll on transport demand (on the A102)	Uncertainty about the evolution of passenger transport on the Antwerp ring road	Uncertainty about the availability of financial resources for the A102			
				Uncertainty about the effect of the A102 on freight transport demand				
				Uncertainty about the evolution of the modal split of passenger transport in the Antwerp region				

Perception 4: uncertainty about societal and political support drive the project priorities

Which uncertainties (do not) have an important impact on the A102 decision making?								
Most unimportant				Neutral (indifferent or no opintion)				Most important
-4	-3	-2	-1	0	+1	+2	+3	+4
Uncertainty about the environmental impact during the construction of the A102	Uncertainty about the cost of an A102 tunnel constructed with a TBM	Uncertainty about the effect of the A102 on passenger transport demand	Uncertainty about the evolution of the modal split of passenger transport in the Antwerp region	Uncertainty about the impact of the A102 on its direct spatial, human and ecological environment	Uncertainty about the composition of future political administrations	Uncertainty about the route choice and connection of the A102 with the existing road infrastructure	Uncertainty about the societal necessity of the A102	Uncertainty about the societal support for the A102
Uncertainty about the construction time of the A102	Uncertainty about the technical feasibility of a joint construction of the A102 and the second freight rail line.	Uncertainty about the effect of OWV on transport in the Antwerp region	Uncertainty about the effect of the A102 on the modal split in the Antwerp region	Uncertainty about the impact of the A102 on reaching climate goals	Uncertainty about the effect of toll on transport demand (on the A102)	Uncertainty about reaching consensus with all stakeholders	Uncertainty about the availability of financial resources for the A102	Uncertainty about the political priority of the A102 compared with other policies and projects
		Uncertainty about the effect of the A102 on economic growth	Uncertainty about the evolution of freight transport on the Antwerp ring road	Uncertainty about the correct completion of legal and administrative procedures	Uncertainty about the availability of financial resources for livability projects in the context of the A102	Uncertainty about scope changes because of additional requirements of stakeholders		
			Uncertainty about the evolution of passenger transport on the Antwerp ring road	Uncertainty about the evolution of the modal split of freight transport in the Antwerp region	Uncertainty about the effect of the A102 on the underlying road infrastructure network			
				Uncertainty about The effect of the A102 on freight transport demand				
				Uncertainty about the sum of the societal costs, benefits, and effects of the entire Port route				

Characterizing and distinguishing uncertainties used for factor interpretation (Q step 5)

Perspective 1: uncertainty about livability as a driver for legal action		
Most important uncertainties (characterizing)		
(17) Uncertainty about the correct completion of legal and administrative procedures	+4	Societal and stakeholder
(19) Uncertainty about the availability of financial resources for livability projects in the context of the A102	+4	Political and policy
Important uncertainties ranked higher in Perception 1 factor array than in other factor arrays (distinguishing)		
(21) Uncertainty about reaching consensus with all stakeholders	+3	Societal and stakeholder
(25) Uncertainty about the environmental impact during the construction of the A102	+2	Environmental impact
(22) Uncertainty about the sum of the societal costs, benefits, and effects of the entire Port route	+2	Societal and stakeholder
Unimportant uncertainties ranked lower in Perception 1 factor array than in other factor arrays (distinguishing)		
(5) Uncertainty about the societal necessity of the A102	0	Societal and stakeholder
(28) Uncertainty about the route choice and connection of the A102 with the existing road infrastructure	-1	Technical
(3) Uncertainty about the evolution of passenger transport on the Antwerp ring road	-1	Market and transport
(2) Uncertainty about the evolution of the modal split of freight transport in the Antwerp region	-2	Market and transport
(10) Uncertainty about the effect of the A102 on the modal split in the Ant-werp region	-2	Market and transport
(12) Uncertainty about the effect of the A102 on freight transport demand	-3	Market and transport
(9) Uncertainty about the effect of OWV on transport in the Antwerp region	-3	Market and transport
Most unimportant uncertainties (characterizing)		
(1) Uncertainty about the evolution of the modal split of passenger transport in the Antwerp region	-4	Market and transport
(11) Uncertainty about the effect of the A102 on passenger transport demand	-4	Market and transport

Perspective 2: potential project redundancy driven by future model split uncertainty		
Most important uncertainties (characterizing)		
(1) Uncertainty about the evolution of the modal split of passenger transport in the Antwerp region	+4	Market and transport
(13) Uncertainty about the impact of the A102 on its direct spatial, human, and ecological environment	+4	Environmental impact
Important uncertainties ranked higher in Perception 2 factor array than in other factor arrays (distinguishing)		
(2) Uncertainty about the evolution of the modal split of freight transport in the Antwerp region	+3	Market and transport

(16) Uncertainty about the effect of the A102 on the underlying road infrastructure network	+3	Market and transport
(10) Uncertainty about the effect of the A102 on the modal split in the Antwerp region	+2	Market and transport
(24) Uncertainty about the impact of the A102 on reaching climate goals	+1	Environmental impact
(3) Uncertainty about the evolution of passenger transport on the Antwerp ring road	+1	Market and transport
(4) Uncertainty about the evolution of freight transport on the Antwerp ring road	+1	Market and transport
(11) Uncertainty about the effect of the A102 on passenger transport demand	0	Market and transport
(12) Uncertainty about the effect of the A102 on freight transport demand	0	Market and transport
(9) Uncertainty about the effect of OWV on transport in the Antwerp region	0	Market and transport
Unimportant uncertainties ranked lower in Perception 2 factor array than in other factor arrays (distinguishing)		
(5) Uncertainty about the societal necessity of the A102	0	Societal and stakeholder
(18) Uncertainty about the availability of financial resources for the A102	-1	Political and policy
(20) Uncertainty about scope changes because of additional requirements of stakeholders	-1	Societal and stakeholder
(21) Uncertainty about reaching consensus with all stakeholders	-1	Societal and stakeholder
(15) Uncertainty about the effect of toll roads on transport demand (on the A102)	-2	Market and transport
(8) Uncertainty about the political priority of the A102 compared with other policies and projects	-2	Political and policy
(27) Uncertainty about the cost of an A102 tunnel constructed with a tunnel boring machine	-3	Technical
Most unimportant uncertainties (characterizing)		
(23) Uncertainty about the construction time of the A102	-4	Technical
(7) Uncertainty about the composition of future political administrations	-4	Political and policy

Perspective 3: technical and cost uncertainties influence project impact and design		
Most important uncertainties (characterizing)		
(28) Uncertainty about the route choice and connection of the A102 with the existing road infrastructure	+4	Technical
(27) Uncertainty about the cost of an A102 tunnel constructed with a tunnel boring machine	+4	Technical
Important uncertainties ranked higher in Perception 3 factor array than in other factor arrays (distinguishing)		
(26) Uncertainty about the technical feasibility of a joint construction of the A102 and the second freight rail line.	+3	Technical
(12) Uncertainty about the effect of the A102 on passenger transport demand	0	Market and transport
Unimportant uncertainties ranked lower in Perception 3 factor array than in other factor arrays (distinguishing)		
(19) Uncertainty about the availability of financial resources for livability projects in the context of the A102	0	Political and policy

(24) Uncertainty about the impact of the A102 on reaching climate goals	-1	Environmental impact
(4) Uncertainty about the evolution of freight transport on the Antwerp ring road	-1	Market and transport
(22) Uncertainty about the sum of the societal costs, benefits, and effects of the entire Port route	-2	Societal and stakeholder
(17) Uncertainty about the correct completion of legal and administrative procedures	-3	Societal and stakeholder
Most unimportant uncertainties (characterizing)		
(23) Uncertainty about the construction time of the A102	-4	Technical
(14) Uncertainty about the effect of the A102 on economic growth	-4	Market and transport

Perspective 4: uncertainty about societal and political support drive the project priorities		
Most important uncertainties (characterizing)		
(6) Uncertainty about the societal support for the A102	+4	Societal and stakeholder
(8) Uncertainty about the political priority of the A102 compared with other policies and projects	+4	Political and policy
Important uncertainties ranked higher in Perception 4 factor array than in other factor arrays (distinguishing)		
(5) Uncertainty about the societal necessity of the A102	+3	Societal and stakeholder
(18) Uncertainty about the availability of financial resources for the A102	+3	Political and policy
(20) Uncertainty about scope changes because of additional requirements of stakeholders	+2	Societal and stakeholder
(7) Uncertainty about the composition of future political administrations	+1	Political and policy
(15) Uncertainty about the effect of toll roads on transport demand (on the A102)	+1	Market and transport
(12) Uncertainty about the effect of the A102 on freight transport demand	0	Market and transport
Unimportant uncertainties ranked lower in Perception 4 factor array than in other factor arrays (distinguishing)		
(13) Uncertainty about the impact of the A102 on its direct spatial, human, and ecological environment	0	Environmental impact
(4) Uncertainty about the evolution of freight transport on the Antwerp ring road	-1	Market and transport
(3) Uncertainty about the evolution of passenger transport on the Antwerp ring road	-1	Market and transport
(27) Uncertainty about the cost of an A102 tunnel constructed with a TBM	-3	Technical
(26) Uncertainty about the technical feasibility of a joint construction of the A102 and the second freight rail line.	-3	Technical
Most unimportant uncertainties (characterizing)		
(25) Uncertainty about the environmental impact during the construction of the A102	-4	Environmental impact
(23) Uncertainty about the construction time of the A102	-4	Technical

Appendix 5: TIPROE model code VBA (Chapter 7)

BLACK = code
GREEN = commentary

```
Option Explicit

Sub TIPROE_Model()

'-Declare all parameters-==================================================================

'Parameters for the NPV calculation of the Primary Monte Carlo (PMC) process (option dependent)------------------------
Dim Annual_benefits_EV() As Double
Dim Min_annual_benefits() As Double
Dim Max_annual_benefits() As Double
Dim rndAnnual_benefits_EV As Double 'parameter to calculate the stochastic value of Annual_benefits_EV
Dim Annual_capital_cost_EV() As Double
Dim Annual_capital_cost_CO() As Double
Dim rndAnnual_capital_cost_EV As Double 'parameter to calculate the stochastic value of Annual_capital_cost_EV
Dim Annual_OandM() As Double
Dim rehabreplacecost() As Double 'Rehabilitation and replacement cost
Dim Residual_value() As Double
Dim Annual_Growoption_cost() As Double
Dim SD_Annual_capital_cost_EV As Double 'standard deviation to determine the stochastic value of Annual_capital_cost_EV

'Parameters for the NPV calculation of the Secondary Monte Carlo (SMC) Process (option dependent)-------------------
Dim Annual_benefits_LF_SMC As Double
Dim rndAnnual_benefits_LF_SMC As Double 'parameter to determine the stochastic value of Annual_benefits_LF_SMC
Dim annualcapitalcost_SMC As Double 'Value = Annual_capital_cost_EV from PMC
Dim annualOandM_SMC As Double 'Value = Annual_OandM from PMC
Dim rehabreplacecost_SMC As Double 'Value = rehabreplacecost from PMC
Dim residualvalue_SMC As Double 'Value = Residual_value from PMC
Dim growoption_SMC As Double 'Value = Annual_Growoption_cost from PMC
Dim SD_Annual_benefits_LF_SMC As Double 'standard deviation to determine the stochastic value of Annual_benefits_LF

'-Parameters for the NPV calculation (same for all options in PMC and SMC)----------------------------------------------------
Dim Discountrate As Double
Dim Growthrate As Double
Dim Constructiontime As Integer
Dim Operationaltime As Integer
Dim lifetime As Integer 'sum of the construction time and operational time = total project alternative lifetime
Dim Cost_overrun As Double

'-Output parameters NPVs------------------------------------------------------------------------------------------------------------------
Dim discannualbenefit() As Double 'the discounted annual benefits
Dim discannualcapitalcost() As Double 'the discounted capital costs
Dim discannualOandM() As Double 'the discounted annual O&M
Dim disctotalbenefits As Double 'the discounted total benefits (sum of the discounted annual benefits)
Dim disctotalcapitalcosts As Double 'the discounted total capital costs (sum of the discounted annual capital costs)
Dim disctotalOandM As Double 'the discounted total O&M (sum of the discounted annual O&M)
Dim decomtotal As Double 'sum of the discounted rehab and replace cost and the residual value
Dim disctotalcost As Double 'the sum of the discounted  total costs, decomtotal, disctotalOandM and disctotalcapitalcosts
Dim NPV_EV() As Double 'NPV expected value = NPV of a single primary Monte Carlo iteration
Dim NPV_LF() As Double 'NPV limited foresight = NPV of a single secondary Monte Carlo iteration

'-Decision tree parameters------------------------------------------------------------------------------------------------------------------
Dim OptionID As Integer 'Id of the options in the decision tree (1=NI, 2=RR, 3=BART, 4=RR+,
Dim DecisionTree() As Double 'Decistion tree table (branches as rows, decision-making years as columns)
```

```
'-Parameters decision tree--------------------------------------------------------------------------------------------------------------------
Dim BestOptionID() As Integer 'The best option that is selected for a single SMC iteration
Dim BestNPV() As Double 'The best NPV (corresponding to the best option) that is selected for a single SMC iteration
Dim DecisionOptionID() As Integer 'The decision for an option made for a single decision-making year
Dim AvgNPV() As Double 'Average of the NPVs of an option group (TIPROE model step 7)
Dim VarNPV() As Double 'Variance of the NPVs of an option group (TIPROE model Step 7)
Dim Riskreturn() As Double 'Avg/Var of the NPVs of an option group (TIPROE model step 7)
Dim Cnt() As Integer 'Counter to count the number of NPVs in an option group (TIPROE model step 7)

'-Monte Carlo parameters--------------------------------------------------------------------------------------------------------------------
Dim PMCID As Integer 'PMC iteration
Dim PMCMax As Integer 'Total number of PMC iterations
Dim SMCID As Integer 'SMC iteration
Dim SMCMax As Integer 'Total number of SMC iterations
Dim BranchID As Integer 'Branch number of the decision tree
Dim BranchIDMax As Integer 'Total number of branches
Dim I As Integer 'Counter
Dim J As Integer 'Counter
Dim K As Integer 'Counter for the decision-making year
Dim L As Integer 'Counter
Dim Y As Integer 'Counter for the project horizon year (either a year of construction or operation)
Dim SkipBranchID() As Integer 'variabele to determine which branches to exclude during the analysis for the next decision-making year
Dim Switch01 As Integer

'-Decision tree simulation time------------------------------------------------------------------------------------------------------------
Dim StartTime As Double
Dim RunTime As String

'-Assigning fixed parameter values for all options------------------------------------------------------------------------------------------
SMCMax = 25 'total number of SMC iterations
PMCMax = 1000 'total number of PMC iterations
BranchIDMax = 251 'total number of branches
lifetime = Sheets("NPV NC").Cells(34, 3).Value
Constructiontime = Sheets("NPV NC").Cells(35, 3).Value
Operationaltime = Sheets("NPV NC").Cells(36, 3).Value
Discountrate = Sheets("NPV NC").Cells(37, 3).Value
Growthrate = Sheets("NPV NC_Growth rate").Cells(27, 3).Value
Cost_overrun = 1.485 'Avg cost overrun for major rail projects in the US (Gao and Touran, 2020)
SD_Annual_capital_cost_EV = 0.15
SD_Annual_benefits_LF_SMC = 0.05

'-Determine dimensions of parameters with arrays-------------------------------------------------------------------------------------------
'1 to 8 refers to the number of options in the tree; parameter values are option dependent
ReDim Annual_benefits_EV(1 To 8) As Double
ReDim Min_annual_benefits(1 To 8) As Double
ReDim Max_annual_benefits(1 To 8) As Double
ReDim Annual_capital_cost_EV(1 To 8) As Double
ReDim Annual_capital_cost_CO(1 To 8) As Double
ReDim Annual_OandM(1 To 8) As Double
ReDim rehabreplacecost(1 To 8) As Double
ReDim Residual_value(1 To 8) As Double
ReDim Annual_Growoption_cost(1 To 8) As Double

ReDim discannualbenefit(1 To 110) 'total number of years in the tree (until the last possible year of operation)
ReDim discannualcapitalcost(1 To 110)
ReDim discannualcapitalcost(1 To 110)
ReDim discannualOandM(1 To 110)
```

```
ReDim DecisionTree(1 To BranchIDMax, 1 To 110) 'total size of the decision tree (251 branches, 110 columns)
ReDim BestOptionID(1 To SMCMax)
ReDim BestNPV(1 To SMCMax)
ReDim DecisionOptionID(1 To 55) 'total length of the period from the first to the last decision-making year (2025-2079)

'-Declaring parameters completed-==================================================================

'PRIMARY MONTE CARLO---------------------------------------------------------------------------------------------------------------
StartTime = Timer

Application.ScreenUpdating = False

 For OptionID = 1 To 8
   'Assign option dependent parameter values for the primary MC process that will not change
   Min_annual_benefits(OptionID) = Sheets("DT NC_Input").Cells(33 + OptionID, 3).Value
   Max_annual_benefits(OptionID) = Sheets("DT NC_Input").Cells(33 + OptionID, 4).Value
   Annual_capital_cost_CO(OptionID) = (Sheets("DT NC_Input").Cells(33 + OptionID, 6).Value) * Cost_overrun
   Annual_O& M(OptionID) = Sheets("DT NC_Input").Cells(33 + OptionID, 7).Value
   rehabreplacecost(OptionID) = Sheets("DT NC_Input").Cells(33 + OptionID, 8).Value
   Residual_value(OptionID) = Sheets("DT NC_Input").Cells(33 + OptionID, 9).Value
   Annual_Growoption_cost(OptionID) = Sheets("DT NC_Input").Cells(33 + OptionID, 10).Value
 Next OptionID

'STEP 1-10 START
'STEP 1 START: initiate a single Monte Carlo iteration
For PMCID = 1 To PMCMax

 ReDim NPV_EV(1 To PMCMax) 'Reset the NPV after every PMCID to avoid NPVs to be summed accross multiple iterations

 rndAnnual_benefits_EV = Rnd 'Determine a random between 0 and 1
 rndAnnual_capital_cost_EV = Rnd 'Determine a random between 0 and 1

 For OptionID = 1 To 8
   If OptionID = 1 Then 'option ID 1 = NI; there are not benefits or costs if NI
     Annual_benefits_EV(OptionID) = 0
     Annual_capital_cost_EV(OptionID) = 0
   Else
     'If the option is a project alternative (2 to 8), then a random stochastic parameter value is assigned)
            Annual_benefits_EV(OptionID) = (Max_annual_benefits(OptionID) - Min_annual_benefits(OptionID)) * rndAnnu
            al_benefits_EV + Min_annual_benefits(OptionID) ‘random between the range of min and max annual benefits
            Annual_capital_cost_EV(OptionID) = Application.WorksheetFunction.Norm_Inv(rndAnnual_capital_cost_EV,
            Annual_capital_cost_CO(OptionID), Annual_capital_cost_CO(OptionID) * SD_Annual_capital_cost_EV) ‘random as
            a normal distribution around the value Annual_capital_cost_CO
   End If
   Sheets("DT NC_Output").Cells(PMCID + 2, 58 + OptionID) = Annual_benefits_EV(OptionID)
   Sheets("DT NC_Output").Cells(PMCID + 2, 66 + OptionID).Value = Annual_capital_cost_EV(OptionID)
 Next OptionID

'---TIME HORIZON (total length of the decision-making period)------------------------------------------------------------------------

'STEPS 2-8 start: determining which decision to make in each decision-making year

'A decision has to be made for every year between (2025-2034 and 2070-2079), creating a total period of 55 years (2025-2079).
'Years 2035-2069 cannot be skipped to avoid problems with discounting values, but no new NPVs will calculated for this period
 For K = 1 To 55

   'Insert the decision tree------------
   For BranchID = 1 To BranchIDMax 'All the branches
     For Y = K To K + 54 'All the remaining columns starting from the current K
```

```
            DecisionTree(BranchID, Y) = Sheets("DT NC_Input").Cells(BranchID + 4, Y + 16).Value 'Start with the first decision tree
            cell
        Next Y
    Next BranchID

'-------INNER MC--------------------------------------------------------------------------------------------------------------------------
'STEPS 2-5 START: determining a best option and corresponding NPV for the current decision-making year
'STEP 2 START: initiating a single SMC iteration and determine the stochastic parameter value for the LF param-
eter
    For SMCID = 1 To SMCMax

        ReDim NPV_LF(1 To BranchIDMax) 'Reset the NPV after every SMCID to avoid NPVs to be summed accross multiple
        iterations
        ReDim SkipBranchID(1 To BranchIDMax)

        rndAnnual_benefits_LF_SMC = Rnd
        rndannualcapitalcost_SMC = Rnd

        For BranchID = 1 To BranchIDMax 'Cover all the branches

          'Reset NPV output parameters after every branch to avoid NPVs to be summed accross multiple branches
          disctotalbenefits = 0
          disctotalcapitalcosts = 0
          disctotalOandM = 0
          decomtotal = 0

'STEP 2 END

          'Condition that excludes branches for the current decision-making year based on the decision made in the previous year
          SkipBranchID(BranchID) = 1
          If K = 1 Then
            SkipBranchID(BranchID) = 0
          Else
            If DecisionTree(BranchID, K - 1) = DecisionOptionID(K - 1) Then
              SkipBranchID(BranchID) = 0
            End If
          End If

          If SkipBranchID(BranchID) = 0 Then 'for the branches that are not skipped, proceed

            For Y = K To 55 'Every year between 2025 and 2079, departing from the current year K

              OptionID = DecisionTree(BranchID, Y) 'Find the correct option ID based in its position in the decision tree

    'Condition to only assign parameter values if the optionID is different from the one in the previous Y (year)
    'If the optionID is the same, that investment has already been made and the value are set to 0 to not calculate the
    NPV another time
              If OptionID = 1 Then
                Annual_benefits_LF_SMC = 0
                annualcapitalcost_SMC = 0
                annualOandM_SMC = 0
                rehabreplacecost_SMC = 0
                residualvalue_SMC = 0
                growoption_SMC = 0
              Else
                If Y = 1
                  Annual_benefits_LF_SMC = Application.WorksheetFunction.Norm_Inv(rndAnnual_benefits_LF_SMC,
                  Annual_benefits_EV(OptionID), Annual_benefits_EV(OptionID) * SD_Annual_benefits_LF_SMC) 'random value
                  around a normal distribution with Annual_benefits_EV as mean value
```

```
      annualcapitalcost_SMC = Annual_capital_cost_EV(OptionID)
      annualOandM_SMC = Annual_OandM(OptionID)
      rehabreplacecost_SMC = rehabreplacecost(OptionID)
      residualvalue_SMC = Residual_value(OptionID)
      growoption_SMC = Annual_Growoption_cost(OptionID)
    Else
      If DecisionTree(BranchID, Y) <> DecisionTree(BranchID, Y - 1) Then
        Annual_benefits_LF_SMC = Application.WorksheetFunction.Norm_Inv(rndAnnual_benefits_LF_SMC,
        Annual_benefits_EV(OptionID), Annual_benefits_EV(OptionID) * SD_Annual_benefits_LF_SMC)
        annualcapitalcost_SMC = Annual_capital_cost_EV(OptionID)
        annualOandM_SMC = Annual_OandM(OptionID)
        rehabreplacecost_SMC = rehabreplacecost(OptionID)
        residualvalue_SMC = Residual_value(OptionID)
        growoption_SMC = Annual_Growoption_cost(OptionID)
      Else
        Annual_benefits_LF_SMC = 0
        annualcapitalcost_SMC = 0
        annualOandM_SMC = 0
        rehabreplacecost_SMC = 0
        residualvalue_SMC = 0
        growoption_SMC = 0
      End If
    End If
  End If

'STEP 3&4 START: calculate discounted cash flows and NPV for every branch for the current decision-making year K

  'Annual_benefits_LF_SMC cannot be a negative value. If so, it is set to 0
  If Annual_benefits_LF_SMC < 0 Then
    Annual_benefits_LF_SMC = 0
  End If

  For L = Y To Y + Constructiontime - 1
    discannualcapitalcost(L) = (annualcapitalcost_SMC + growoption_SMC) / (1 + Discountrate) ^ (L + 5)
    disctotalcapitalcosts = disctotalcapitalcosts + discannualcapitalcost(L)
  Next L

  For L = Y + Constructiontime To Y + Constructiontime + Operationaltime - 1
    discannualbenefit(L) = Annual_benefits_LF_SMC / (1 + Discountrate - Growthrate) ^ (L + 5)
    disctotalbenefits = disctotalbenefits + discannualbenefit(L)

    discannualOandM(L) = annualOandM_SMC / (1 + Discountrate) ^ (L + 5)
    disctotalOandM = disctotalOandM + discannualOandM(L)
  Next L

  decomtotal = decomtotal + ((-rehabreplacecost_SMC + residualvalue_SMC) / (1 + Discountrate) ^ (Y - 1))

 Next Y

 NPV_LF(BranchID) = disctotalbenefits - disctotalcapitalcosts - disctotalOandM + decomtotal

End If

Next BranchID

'STEP 3-4 END
'STEP 5 START: determine the best option ID and corresponding NPV for a single SMC iteration
```

```
    'Code to look over all the branches' options and NPVs and remember the BestNPV
    Switch01 = 0
    For BranchID = 1 To BranchIDMax
      If SkipBranchID(BranchID) = 0 Then
        If Switch01 = 0 Then
          BestOptionID(SMCID) = DecisionTree(BranchID, K)
          BestNPV(SMCID) = NPV_LF(BranchID)
          Switch01 = 1

        If NPV_LF(BranchID) > BestNPV(SMCID) Then
          BestOptionID(SMCID) = DecisionTree(BranchID, K)
          BestNPV(SMCID) = NPV_LF(BranchID)
        End If

      End If
    Next BranchID

'STEP 5 END

  Next SMCID 'proceed to the next SMC iterationa nd repeat steps 2-5

'STEP 2-5 END: 25 best options and NPVs, one for every SMC iteration

  'reset values
  ReDim AvgNPV(1 To 8)
  ReDim VarNPV(1 To 8)
  ReDim Riskreturn(1 To 8)
  ReDim Cnt(1 To 8)

'STEP 6: group the best NPVs in option groups
  For I = 1 To 8 'Look for NPVs for all of the option IDs
    For SMCID = 1 To SMCMax 'Check to which option group the best NPV of each SMC iteration belongs
      For J = 1 To BranchIDMax
        If BestOptionID(SMCID) = I Then
          AvgNPV(I) = AvgNPV(I) + BestNPV(SMCID)
          Cnt(I) = Cnt(I) + 1 'Count the number of best NPVs in every option group

         End If
      Next J
    Next SMCID

'STEP 6 END

'STEP 7 START: calculate the risk and return of every option group

    If Cnt(I) = 0 Then
      Riskreturn(I) = 0
    Else
      AvgNPV(I) = AvgNPV(I) / Cnt(I)

      For SMCID = 1 To SMCMax
        For J = 1 To BranchIDMax
          If BestOptionID(SMCID) = I Then
            VarNPV(I) = VarNPV(I) + ((BestNPV(SMCID) - AvgNPV(I)) ^ 2)
          End If
        Next J
      Next SMCID

      VarNPV(I) = VarNPV(I) / Cnt(I)
```

```
        If VarNPV(I) = 0 Then VarNPV(I) = 0.0000000001


        Riskreturn(I) = AvgNPV(I) / VarNPV(I)
      End If

    Next I

'STEP 7 END

'STEP 8 START: select the option group with the highest risk and return. That option is the decision made for year
K

      DecisionOptionID(K) = BestOptionID(1)
      For I = 1 To 8
        If Riskreturn(I) > Riskreturn(DecisionOptionID(K)) Then
          DecisionOptionID(K) = I
        End If
      Next I
      Sheets("DT NC_Output").Cells(2 + PMCID, 2 + K).Value = DecisionOptionID(K)

  Next K 'Proceed to the next decision-making year and repeat steps 2-8

'STEPS 2-8 END: a decision made for every year K

'STEPS 9-10: calculate the discounted cash flows and NPVs for a decision-making pathway for a single PMC itera-
tion

  'Reset NPV output parameters after every branch to avoid NPVs to be summed accross multiple branches
  disctotalbenefits = 0
  disctotalcapitalcosts = 0
  disctotalOandM = 0
  decomtotal = 0

  For K = 1 To 55
    If K = 1 Then
      For L = K To K + Constructiontime - 1
        discannualcapitalcost(L) = (Annual_capital_cost_EV(DecisionOptionID(K)) + Annual_Growoption_cost(DecisionOp
        tionID(K))) / (1 + Discountrate) ^ (L + 5)
        disctotalcapitalcosts = disctotalcapitalcosts + discannualcapitalcost(L)
      Next L

      For L = K + Constructiontime To K + Constructiontime + Operationaltime - 1
        discannualbenefit(L) = Annual_benefits_EV(DecisionOptionID(K)) / (1 + Discountrate - Growthrate) ^ (L + 5)
        disctotalbenefits = disctotalbenefits + discannualbenefit(L)

        discannualOandM(L) = Annual_OandM(DecisionOptionID(K)) / (1 + Discountrate) ^ (L + 5)
        disctotalOandM = disctotalOandM + discannualOandM(L)
      Next L

        decomtotal = decomtotal + ((-rehabreplacecost(DecisionOptionID(K)) + Residual_value(DecisionOptionID(K))) / (1 + Discoun-
        trate) ^ (K - 1))

      Else
        If DecisionOptionID(K) <> DecisionOptionID(K - 1) Then
          For L = K To K + Constructiontime - 1
discannualcapitalcost(L) = (Annual_capital_cost_EV(DecisionOptionID(K)) + Annual_Growoption_cost(DecisionOptionID(K))) / (1
+ Discountrate) ^ (L + 5)
```

```
            disctotalcapitalcosts = disctotalcapitalcosts + discannualcapitalcost(L)
          Next L

          For L = K + Constructiontime To K + Constructiontime + Operationaltime - 1
            discannualbenefit(L) = Annual_benefits_EV(DecisionOptionID(K)) / (1 + Discountrate - Growthrate) ^ (L + 5)
            disctotalbenefits = disctotalbenefits + discannualbenefit(L)

            discannualOandM(L) = Annual_OandM(DecisionOptionID(K)) / (1 + Discountrate) ^ (L + 5)
            disctotalOandM = disctotalOandM + discannualOandM(L)
          Next L

decomtotal = decomtotal + ((-rehabreplacecost(DecisionOptionID(K)) + Residual_value(DecisionOptionID(K))) / (1 + Discountrate) ^
(K - 1))

        End If
    End If
  Next K

  NPV_EV(PMCID) = disctotalbenefits - disctotalcapitalcosts - disctotalOandM + decomtotal
  Sheets("DT NC_Output").Cells(2 + PMCID, 2).Value = NPV_EV(PMCID)

'STEP 9-10 END

Next PMCID 'Proceed to the next PMC iteration

'STEP 1-10 END: result is a decision-making pathway and NPV for every PMC iteration

Application.ScreenUpdating = True

RunTime = Format((Timer - StartTime) / 86400, "hh:mm:ss")
MsgBox "Decision tree run time " & RunTime & ""

End Sub
```

Appendix 6: TIPROE model cost and benefit parameters (Chapter 7)

Benefit-cost ratio	Total benefits divided by the total costs. Benefit-cost ratio is calculated using benefit and cost streams over a 60 year analysis period, for three different futures
BENEFITS - Accessibility Benefits	"Represents change in accessibility benefits to all Bay Area residents as a result of the project. Accessibility is a measure of how easily people are able to get to the destinations of their choice. Acessibility benefits include travel time - in vehicle; travel time - out of vehicle; vehicle operating costs; travel costs; mode choice availability. These have the largest share in the total benefits and imply an increase in potential demand, since accessibility increases for more/all Bay Area residents. Logsum is a metric that measures utility or consumer surplus, and captures mobility benefits (i.e., travel time savings, in-vehicle or out-of-vehicle), travel costs (i.e., tolls, fares, parking, vehicle operating) and the ease of consumers to reach destinations of their choice. These benefits collectively will be termed as “atccessibility benefits” this c ycle, consistent with the estimation methodology"
BENEFITS - Environmental Benefits	Captures monetary value of change in GHG emissions or impact on natural lands (wetlands, pastureland, farmland) due to the project.
BENEFITS - Freeway Reliability and Vehicle Ownership Benefits	Reflects change in non-recurring vehicle delay on freeways, and the costs of change in vehicle ownership as a result of the project
BENEFITS - Health benefits	Represents benefits from increased physical activity due to more walking/biking and reduction in air pollutants and noise.
BENEFITS - Safety benefits	Captures decrease in injuries and collisions due to reduced VMT as well as operational and safety improvements such as freewayramp redesign or grade separations.
BENEFITS - Transit crowding benefits	Captures the (dis)benefits associated with increase/decrease in crowding, since people may change their travel choices or be denied boarding, or experience discomfort in a crowded vehicle
COSTS - Initial capital cost	Capital cost of constructing/implementing the project.
COSTS - Initial capital cost (BART)	initial capital costs for a BART tunnel include SF landside improvements (41%), East Bay landside improvements (24%), Crossing infrastructure (16%), Vehicles (14%), Foundational projects (5%)
COSTS - Initial capital cost (regional rail)	initial capital costs for a regional rail tunnel include foundational projects (73%), SF landside improvements (5%), East Bay landside improvements (8%), crossing infrastructure (12%), vehicles (2%)
COSTS - Initial capital cost (BART + regional rail)	initial capital costs for a BART + regional rail tunnel include foundational projects (41%), SF landside improvements (22%), East Bay landside improvements (15%), crossing infrastructure (14%), vehicles (8%)
COSTS - Lifecycle costs	This includes initial capital cost, annual O&M costs, rehabilitation and replacements costs, and a residual value of the investment at the end of the analysis period, calculated using discounted present value methodology. Note: Societal transfers such as fare/toll revenue (or loss) are excluded from both benefits and costs, following standard practice for societal benefit-cost analyses.

COSTS - Operating and maintenance	Annual operating and maintenance costs of the project over the full analysis period.
COSTS - Project costs (as reviewed by sponsor)	Reflects sponsor submitted costs of projects. These were revised in some cases when a high-level cost review of all projects using an independent cost consultant and a uniform methodology flagged sponsor costs that may have been underestimated (such cases were discussed with the sponsors individually).
COSTS - Rehab + Replacement	Rehabiliation costs of pavement and roadway structures; replacement costs of roadway and transit assets after their useful lives. (e.g. bus replacement every 14 years, roadway technology every 20 years)
COSTS - Residual value	Represents useful value of assets/infrastucture at the end of the analysis period (based on straight line depreciation).

Appendix 7: PSS IV simulation procedure (Chapter 7)

The figure below comes from Welkenhuysen et al. (2017), and shows a flowchart of the PSS IV simulation procedure as how it was applied in their study. This flowchart was used as an inspiration to visualise the TIPROE procedure (Figure 7.3 in Chapter 7).

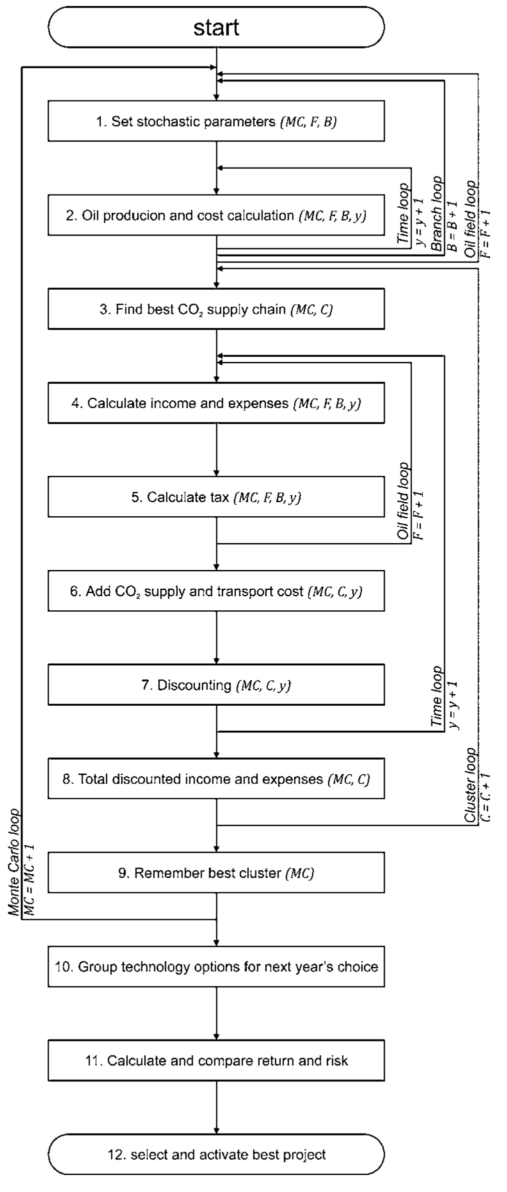


Fig. 11. Flow chart of the CO_2-EOR project evaluation in PSS IV. A Monte Carlo calculation is first performed for all clusters. Every Monte Carlo iterations results in a best cluster, which are grouped for their next year's technology choice (see Fig. 9). The investments' return and risk are compared, and the best investment is chosen to be activated. Parameter dimensions are indicated (MC: Monte Carlo; F: field; y: time; C: cluster; B: technology branch for field).