Negotiated Collaboration: a study in Flexible Infrastructure Design

by

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Abstract

This thesis frames design in infrastructure public-private partnerships (P3s) as an exercise in negotiated collaboration. I investigate whether the collaborative design process in P3s can systematically deliver the benefits of innovation in design. The focus is on two aspects of the design process: project co-design, and collaboration mechanism. I find that both aspects enable innovation by driving project actors to learn about the design space and develop a shared understanding of the design problem. Learning through shared understanding not only improves quantifiable payoffs (Objective Value) but also enhances the actors' psycho-social outcomes (Subjective Value).

Co-design is a process in which project actors simultaneously design technical and contractual features of a project. I developed a tradespace model to visualize and explore value trade-offs from co-design, using a desalination P3 as a project case. Co-design is a fundamental improvement over the traditional sequential design process because it reveals the zone of negotiated agreement, a frontier set of designs available to project actors, that can help them meet their own objectives while balancing value trade-offs. The combination of flexible modular designs and risk sharing revenue guarantee mechanisms emerged as a frontier design choice in the co-design analysis.

Communication and common knowledge are two different collaboration mechanisms that affect the design choices of project actors. A controlled design experiment with 112 experienced designers tested the relative effects of these two mechanisms. The role-playing designers negotiated design decisions for a desalination P3 using the co-design tradespace model. Only the communication mechanism systematically shifted outcomes. To increase the reliability of meeting uncertain water demand, the firm traded away an expected net present value profit share of 24% ($p<0.001$) on average, subject to the parameter assumptions. The water authority increased contractual payments by an expected net present value share of 6.6% ($p<0.001$) on average. Final designs in the exercise were on average 97.5% reliable in meeting uncertain water demand. Communication dominated common knowledge as a collaboration mechanism because it enabled participants to learn about the effects of modularity and revenue guarantees on counter-party outcomes and use these design features to negotiate value trade-offs.

Objective Value represents the technical (reliability) and economic (profits, payments) payoffs to project participants. Subjective Value on the other hand captures social psychological outcomes such as the degree of trust and rapport between collaborators and perceived fairness and legitimacy of the process, which are important for the partnering relationship. Participants in the

collaboration experiment overwhelmingly reported high Subjective Value scores, which are positively correlated with both their improved understanding of the project's design objectives (r = 0.37, ρ = 0.41, $p<0.001$) and their ability to communicate with collaborators to agree on design choices (r = 0.36, ρ = 0.36, p = 0.001).

This work directly addresses the literature on infrastructure public-private partnerships and shows how negotiated collaboration can create objective as well as psychosocial benefits for a stronger partnering relationship. The co-design approach speaks to the literature on systems design to emphasize how a systems view can help designers balance trade-offs. The experimental study is a methodological contribution to both the design and negotiations literature, applying the Subjective Value framework in an integrated design setting.

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Between 2012 and 2015, members of the Center both in Cambridge and Riyadh were deeply engaged in the discussion of "how to design and deploy strategic infrastructure investments?" While the initial scope broadly addressed water and energy systems, in 2013 there was a marked shift in the research team's thinking. In the annual stakeholder meeting in Riyadh in March 2013, the MIT team was honored to spend almost a whole day with Dr. Turki bin Saud bin Mohammad Al Saud, now President of KACST. In the many hours of deep discussions, we realized the importance of and a need for a specific investigation on 'Strategic Sustainable Desalination Network (SSDN)'. KACST-CCES co-directors Professor Olivier de Weck (MIT) and Professor Anas Alfaris (KACST and JCEP) successfully proposed and secured the support for a new project on this topic. One of the main questions on the table was the role of partnering between the public and private sectors for the design and delivery of strategic infrastructure investments. This forms the kernel for the thesis.

Since that initial stakeholder meeting in 2013, this dissertation project has benefited from engagement and feedback from both the Saline Water Conversion Corporation (SWCC) and the Ministry of Water and Electricity (MoWE) in the Kingdom. A number of senior SWCC officials, engineers and managers shared perspectives that helped me better frame the issues. Both of these organizations spent many hours during stakeholder meetings to digest the results of the project as a whole, and for "ground truth"ing our findings and insights.

At CCES Riyadh, Dr. Anas Alfaris (co-director) and Dr. Adnan Alsaati (deputy director) have both been instrumental in helping me establish relationships with Saudi stakeholders. They shared from their wealth of experience to help me understand the functional and cultural views on infrastructure delivery in the Kingdom. I will always have fond memories of the countless hours spent with KACST researchers Ahmad Alabdulkareem, Mohammad Hadhrawi, Waleed Gowharji, and Abdulelah Habib both in the lab and in the neighborhoods of Cambridge and Riyadh.

On the MIT side, Professor Olivier de Weck (CCES co-director) has from the outset encouraged the close look at the role of partnering, especially the idea of technical and contractual co-design. Oli and I first discussed the possibility of exploring this topic at an Engineering Systems Student Society poster session in early 2012, and since then he has helped set a high bar for the depth of this work. I am very grateful that he agreed to join my doctoral committee and supervise key areas of this dissertation under the auspices of the CCES-SSDN program. Oli is one of the most open minded and adept scholars - it has been a privilege to learn how to conduct broad research without sacrificing depth by working with him.

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Professor Richard de Neufville, my thesis advisor and committee chair, has always "ardent"ly supported my research interests in infrastructure delivery issues and flexibility in design. His immense research experience and global leadership has enriched my own throughout my time at MIT. He generously supported an ambitious dissertation project, and helped me navigate the opportunities and the challenges. Richard encouraged me to round out my work at MIT with stints at the World Bank and as a visiting scholar in the UK, Netherlands, and Singapore. It is because of him that I have a global compass today, and a healthy dose of perspective. It has been an honor to learn the academic trade at his knee. I will have fond memories of our thesis discussions at his kitchen table in Cambridge, suppers of *rojak* and *soursop* juice at the hawker centers in Singapore, late night *dhaba* fare somewhere on the road between Mohali and Gurgaon, and trappist ales in Delft.

Professor Donald Lessard not only helped me theoretically ground my research but also mentored me through the process of thinking integratively and weaving management perspectives into my engineering and design disciplines. He has been ever patient and encouraging, even when progress meant taking a step or two back to take one forward. I am grateful to Don for his apt and firm advice on many occasions. I will remember the twinkle in his eye during our discussions of megaprojects as well as motorcycles.

Don also introduced me to Professor Roger Miller through the House of Project Complexity piece, in which we took on an intricate topic that helped us evolve our thinking on the delivery of large engineering projects. Roger's deep insights and support helped us bring that work to light. It has been a delight to watch these two creative masters at work, and to shape ideas in a number of projects with them.

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Chapter 1

Introduction: Negotiated Collaboration

"Private firms cannot manage a common good like water in the public interest"
- Célia Blauel, President of Paris' water utility, Eau de Paris (de Clerq, 2014)

This thesis is about negotiated collaboration in design. The specific design context is the concept stage of an infrastructure public-private partnership (P3). In this stage, project participants partner to co-create the concept that will ultimately turn into the infrastructure project. This study investigates how these project actors collaborate with each other to shape the design of a project for their mutual benefit.

The concept stage of design is very important because it sows the seeds for the future of the project. The design choices the partners make will shape the outcomes of the project over its lifetime. The many design possibilities are not all on an equal footing. Some types of designs will help actors accomplish their objectives, whereas others will lead to a sentiment of regret later in the life of the project. Collaborative design in this stage can create a foundation for success over the project's life.

Collaboration between public and private participants is not the norm in infrastructure delivery because of a fundamental tension between the two types of actors. The tension is one of reconciling public interest and private motives in the delivery of public goods. The opening quote of the chapter illustrates this tension. Blauel, the president of Paris' public water company, states that private firms will be unable to manage the delivery of water in the *public interest*. In this example the public interest is reliable and cost-effective water supply. The perceived conflict is that any private firm responsible for water supply will compromise on reliability and pursue profit, its *private interest*.

Coase (1974) identifies some practical issues that private firms may face while delivering public infrastructure. He used the example of a lighthouse. Ships passing in the night all benefit from a lighthouse, although building and running it comes at a cost. Some entity must see to the lighthouse's installment before the benefits are available to passing ships, and also its continuing upkeep over time. Whose role then is it to provide the broadly beneficial service of a lighthouse? How does that provider recover the costs of delivery from the many different types of vessels that may enjoy safety because of the lighthouse? Can a private firm be legitimately given the authority to profit by charging fees to docking vessels, and how much? Or should this responsibility default to the government? Although technologies, needs, and services have evolved over the centuries, the "lighthouse question" still underlies the delivery of infrastructure that serves the public interest.

To manage competing private and public interests in infrastructure, we have as a society developed a number of institutions over the centuries that set up clear boundaries between public authorities and private firms involved in projects. The main actors usually keep each other at arms length. In a competitive environment, both types of organizations follow strict rules to ensure that they are playing the procurement game by the book. The rules of the game are written with social objectives such as transparency and legitimacy in mind to address the fundamental tension in the opening quote.[1] In traditional procurement, public and private actors in infrastructure engage through very structured processes that preclude a high degree of iterative engagement and communication in the design process.

What promise does a collaborative approach hold? One argument is that a collaborative partnership between public and private actors in a project will lead to innovation in design, which can then benefit both. Innovation takes the form of new technologies, improved engineering or management processes, or novel contractual and financial arrangements. Innovation is desirable in some projects, for example when a project must be able to adapt over time to changing technical and economic conditions and still provide efficient or reliable services. Collaboration is a means for innovation because the two types of actors have different roles, responsibilities, and expertise. The public actor brings the legitimate authority to deliver infrastructure and can remain accountable to society, whereas the private actor contributes deep sector expertise and experience. This rationale for collaboration through partnering is based on the complementary abilities of these two types of actors.

Consider that the Kingdom of Saudi Arabia, a world leader in water desalination, is partnering with Hyflux, a small private firm based in Singapore to develop a collaborative partnership (Grant, 2014). Saudi Arabia has had a long history of developing both small and large desalination projects (see Appendix A), in fact it is the nation with the largest installed production capacity. Since most of the Kingdom's capacity is based on emissions-intensive thermal technologies (a legacy choice because of its large oil resource endowment), it is actively considering new energy efficient and environmentally benign technologies (Ball, 2015). However, the Saline Water Conversion Corporation (SWCC), the Saudi state authority responsible for building and operating desalination facilities, has primarily focused on thermal technologies for the last half-century. By partnering with a firm that is a leading player in more efficient membrane-based technologies, SWCC is making an effort to innovate in its technology choices (energy efficient), typical choice of scale and scope in projects (smaller, phased units that can be scaled quickly).

[1] The irony in the opening quote is not just that it highlights the ever-present tension between public and private infrastructure delivery, but also that it comes from a jurisdiction that has relied on the private sector for water services for the better part of a century and only recently reverted to public provision.

SWCC's sovereign mandate to deliver reliable water supply with associated trade-offs in energy use and environmental impact have led it to partner with aggressive small private firms that bring complementary expertise and credibility of performance.

Collaboration in this setting is negotiated because of the two actors' competing interests. Even if public authorities such as government agencies and private firms create a framework to collaborate through design, they must still address the challenge of possibly competing objectives. For instance, the public agency must secure reliability whereas the private firm seeks to remain profitable. The terms of the arrangement between the two project participants may require them both to make trade-offs.

This thesis assumes that gains from innovation are available and asks whether negotiated collaboration systematically leads project actors to identify and secure those benefits? What collaboration mechanisms enable them to capture the available benefits? Does deliberate engagement through design clarify the trade-offs for the actors involved? Is the benefit of improved understanding through the engagement compelling enough to advocate for systematic collaboration? This is the central topic of the thesis.

In this work, I investigate the effects of negotiated collaboration albeit in the specific design context of infrastructure P3s. I acknowledge that the fundamental ideological debate of public versus private provision of infrastructure continues to evolve and that modern society has developed many ways of securing the delivery of infrastructure services. My research hones in on one particular arrangement - infrastructure P3s - to investigate possibilities in the area of design process. The particular features of infrastructure P3s such as the use of long-term concession contracts between public and private actors and the delegation of design to some of these actors actors create an opportunity to understand and improve the process of collaboration. This opportunity could also exist in other modes of infrastructure delivery, and in other social endeavors.

The rest of this thesis is structured as follows. This introductory chapter has two sections. Section 1.1 synthesizes the literature on infrastructure P3s through a number of design perspectives. It makes a case for co-design: integrated technical and contractual design. The same section also argues that co-design is intertwined with cognitive and pyscho-social dynamics between project actors. A more complete understanding of the design process must consider these aspects. Section 1.2 then formalizes the research question about negotiated collaboration, outlines the research design followed, and summarizes the main contributions of the work. The next chapter (Chapter 2) on co-design in infrastructure P3s links design choices to multi-dimensional value trade-offs through the use of a tradespace model. Then, two chapters (Chapters 3 and 4) cover the design and main results of an experimental collaboration exercise to test the relative effects of different collaboration mechanisms. Finally, Chapter 5 concludes and offers policy recommendations for the early stage design process in infrastructure P3s.

1.1 Infrastructure P3s: Design Perspectives

The schematic in Figure 1.1 shows how a number of different streams of literature converge in the topic of 'negotiated collaboration'. The convergence is at the level of the project, under the umbrella of 'Project Architecture'. Technical and contractual design are both relevant and inform the co-design hypothesis. These draw on broader areas such as infrastructure systems design and institutions which address phenomena in the 'Project Environment', shown at the top. Approaching from the other direction are bodies of work that involve human decision-makers, i.e. the 'Project Actors'. The two fields of design cognition (or design thinking) and the psychology of negotiations also thus feed into the construct of negotiated collaboration. Section 1.1 briefly summarizes some institutional issues before discussing design perspectives in detail and their convergence.

The private sector has long participated in civil infrastructure (Wettenhall, 2003; Wettenhall, 2005), even though governments bear the ultimate responsibility for infrastructure services as part of their social contract. In the lighthouse example introduced earlier, London's Trinity House created an institution for private sector involvement (Coase, 1974). France has had lease contracts or *affermage* in the water sector since the late 19th century. Private firms also owned and operated railways in many countries at that time (Jintamanaskoon and Chan, 2014).

Partnering with the private sector is one of the modes by which governments can procure and deliver infrastructure-related services (Bryce, 2001). Some have called this the "third way" with pure public enterprise and complete privatization as the other two ways. P3s are thus a broad category of mixed or hybrid approaches, occupying an intermediate position along a spectrum between pure public or private provision. Figure 1.2 shows the spectrum of alternatives.

Formally, an infrastructure P3 is an institutional arrangement in which public and private sector actors agree to cooperate (Hodge and Greve, 2007). The object of the partners' cooperation is an infrastructure project and its related services. The cooperative arrangement can take the form of a new organizational unit, commonly labeled as a Special Purpose Vehicle (SPV). This thesis uses the more general term of "project organization" because it extends to the variants of concessions as well as major projects outside of the infrastructure domain.

The mainstay of an infrastructure P3 as a project organization is a long-term concession contract. The concession model is one of many alternatives for writing contracts between the providers and users of infrastructure services. Concessions are a solution to the public goods monopoly contracting problem (Gómez-Ibáñez, 2003) and are more "market" based than "political" (see Figure 1.3). Most infrastructure P3s involve highly relationship-specific greenfield or new projects (Hart, 1995), although there are some cases in which the private sector enters into brownfield or existing projects.

Appendix B documents an analysis of available data on P3 projects globally. The analysis draws on two sources of data. (1) the World Bank's Private Participation in Infrastructure (PPI) (2015) database (http://ppi.worldbank.org) which contains data on over 7,000 projects, and (2) an analysis of survey data from the OECD's Government at a Glance (2013) report and related

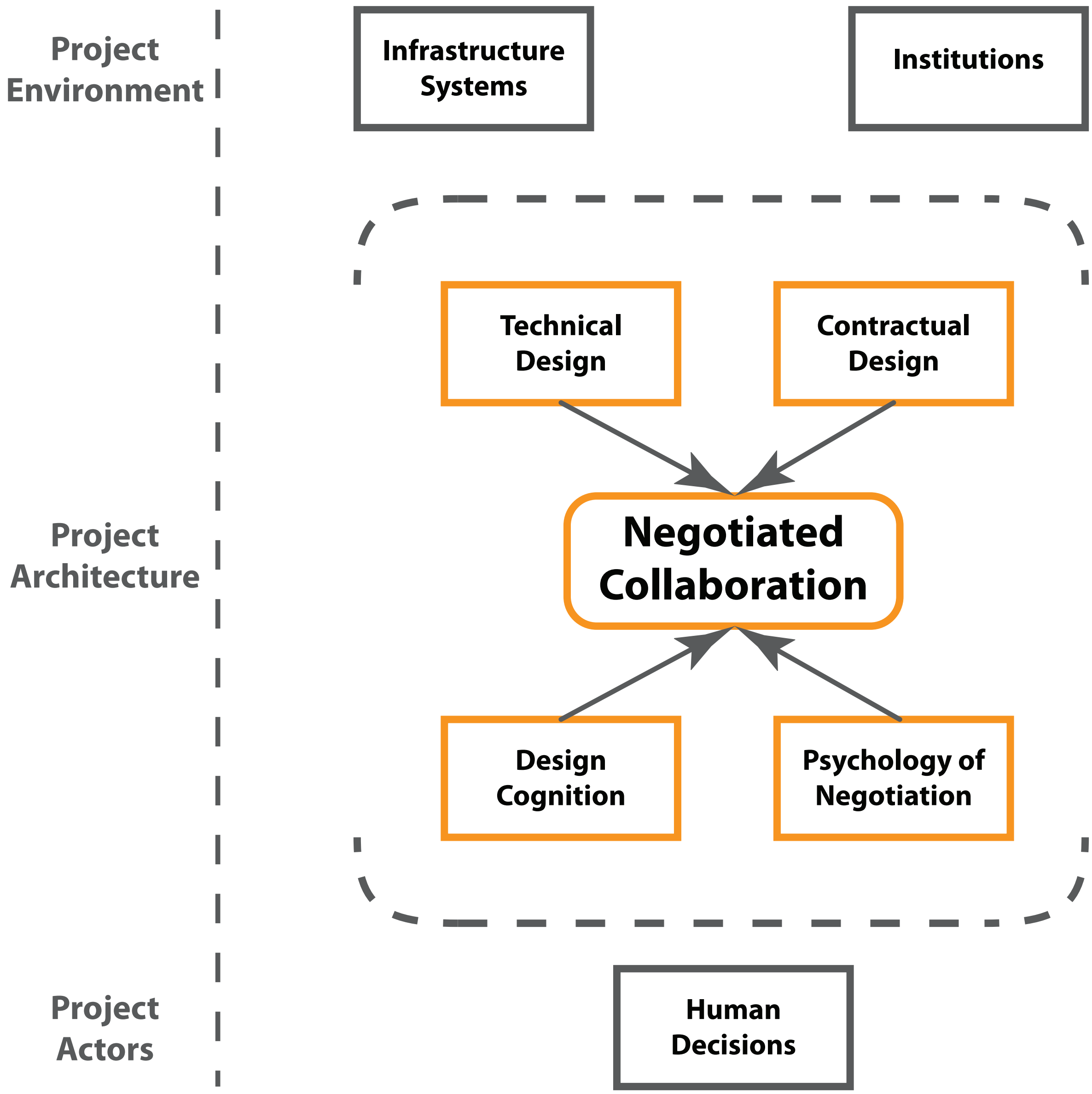

Figure 1.1: Situating this research at a convergence of different perspectives in design applied to infrastructure P3s.

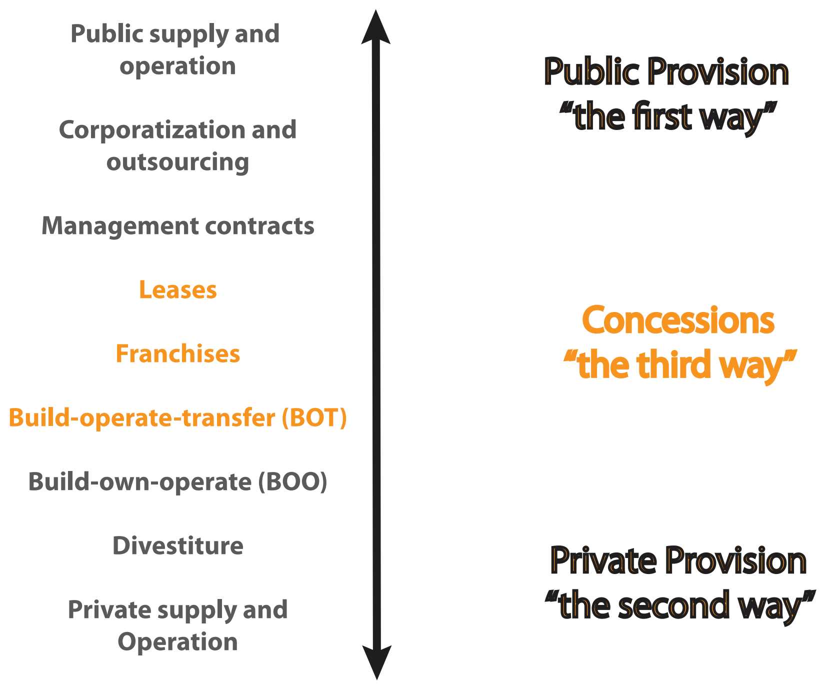

Figure 1.2: A spectrum of infrastructure provision arrangements. Partnerships or concessions are "the third way". Schematic adapted from Guasch (2004)

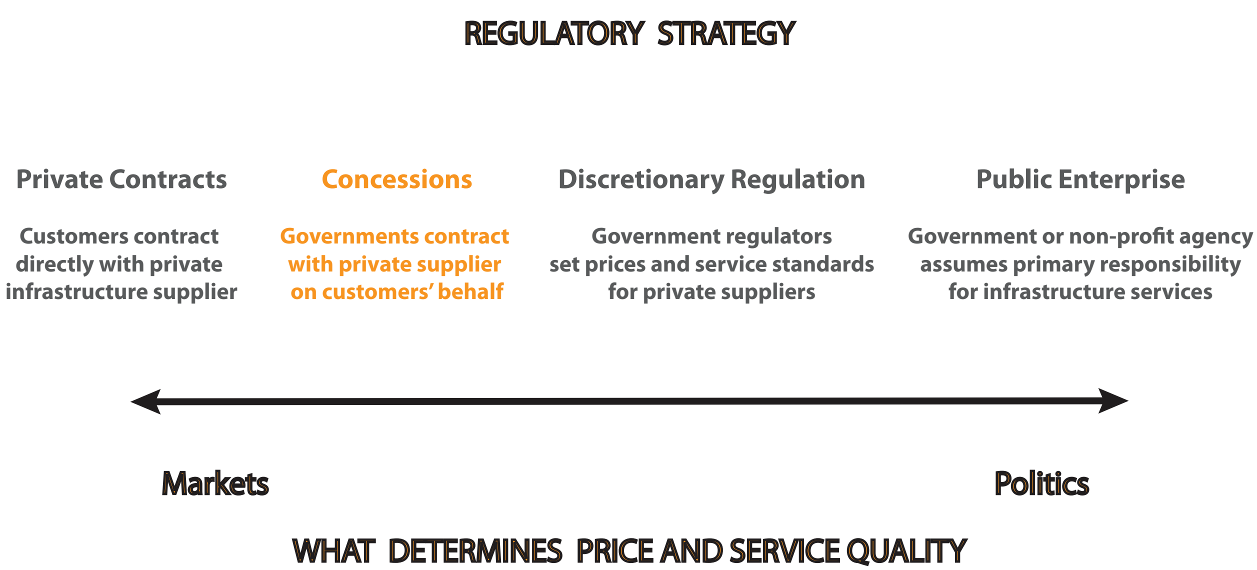

Figure 1.3: A range of solutions to infrastructure monopoly, from Gómez-Ibáñez (2003). The process for determining price and service quality in concessions is closer to market than political in nature.

references. While the World Bank dataset covers projects in markets / countries with less developed infrastructure institutions that receive aid from donor and multi-lateral groups, OECD statistics cover about 30 countries that do not tend to receive development funding because of the advanced state of their infrastructure.

Privatization of infrastructure has occurred in waves (Gómez-Ibáñez, 2003). As political and ideological tides shift, countries tend to oscillate between privatization and renationalization or remunicipalization. In 2008, the city of Paris remunicipalized its water utility Eau de Paris after two decades of contracts with private firms (de Clerq, 2014). The cities of Berlin, Buenos Aires and Atlanta also recently ended their private programs in water.

One possible explanation for the oscillating preference for P3s is that many projects delivered using this approach do not perform as well as expected. The analysis in Appendix B reveals that a sizeable fraction of projects experience "distress", i.e. their performance is sub-par either in terms of their ability to deliver services reliably, or their economic profitability. Table 1.1 shows the percentage shares of distressed investments across sectors and regions, where the shares are the ratio of the investment value of distressed projects to the total investment value n that category. East Asia and Pacific has the largest percentage share of distressed projects. Over 12% of its projects are distressed, with 40% of its water sector falling into this performance category. 50% of its telecom projects are also distressed. Only 7% of projects in Latin America and Caribbean are distressed, however 30% of its water projects are distressed. Overall, only 7.6% of P3 projects across these regions are distressed although most of this is driven by water (30%) and telecom (22%). The water sector has thus proved to be problematic in many parts of the world.

Table 1.1: Percentage share of investments in P3 greenfield and concessions that are distressed.

	Energy	Telecom	Transport	Water and sewerage	Region Total
East Asia and Pacific	4.27	50.66	11.34	38.75	12.60
Europe and Central Asia	2.37	12.18	0.57	0.35	2.18
Latin America and the Caribbean	7.26	4.04	5.16	29.24	7.60
Middle East and North Africa	0.00	0.47	7.91	0.00	1.36
South Asia	3.03	4.45	9.83	0.00	5.73
Sub-Saharan Africa	5.34	7.03	6.61	0.00	5.91
Sector Total	4.83	22.32	7.10	30.28	7.60

Another possible explanation for the wavering intent of governments to pursue P3s is the "obsolescing bargain" between authorities and private providers. Their bargain to exchange value through partnership is obsolete when the government no longer needs the complementary strengths of the private sector to accomplish its infrastructure needs (Woodhouse, 2005). The government then seizes one or both of ownership and control of infrastructure assets. Expropriation is sometimes less drastic and eventually "creep" in once projects are in stable operation.

What are the complementary strengths of the private sector that first motivates governments to use P3s and also revisit this model? Advocates of P3s have put forth two popular arguments for adopting this approach. The first argument is about public budgets and financing and called the "additionality" benefit. The second is about private sector expertise and "innovation" through collaboration.

- **Additionality**: When a private firm expends capital for an infrastructure project, the expenditure does not impact the constrained public sector budget. The project is off the public balance sheet. Public sector payments for the project's services then fall under the category of operating expenses, relieving the public coffers of the need to make large one-off investments.[2] In principle, private financing should thus secure projects additional to those the government would have otherwise funded with its limited budget. The additionality benefit may appear to be an accounting issue at first, although the question of which party should invest is the subject of much discussion since private financing comes at a higher cost of capital (Grimsey and Lewis, 2004). Research also shows that in many countries private financing only goes so far as to deliver the same projects that the public sector would have otherwise delivered (Winch, Onishi, and Schmidt, 2012). Private financing in the UK replaced public funding for projects; it did not spur an increase in infrastructure (Hall, 1998). Hodge and Greve (2007) believe that the budgeting benefit claim is "largely unrealized" (p. 549).

- **Expertise**: Governments can harness deep private sector know-how and experience in the design, construction, and management of infrastructure through partnering. The legitimacy of this argument depends on the identity of the private partners in the project. Many countries have elaborate mechanisms and bidding processes for screening candidate firms and awarding projects only to experienced private sector partners. Innovation in the design of a project is one type of claim that falls under the umbrella of benefits from expertise. It also presupposes that the public sector will be able to absorb this innovation over time (Trebilcock and Rosenstock, 2015).

The literature review that follows and the arguments of this thesis delve into the details of the second argument regarding the effects of collaboration. Questions related to the private financing of infrastructure are out of the scope of this study.

1.1.1 Project Architecture: Technical Design in P3 Organizations

The academic literature on technical design innovation in P3 projects is sparse. Yuan et al. (2009) describe how research on P3s is preoccupied more with broad organizational and institutional issues, and rarely looks at "inter-organizational relationships and process control". The intellectual blind spot includes design processes. Where research does not illuminate, empirical observations from practitioner reviews shed additional light. The discussion below therefore weaves in and out of both academic research and pragmatic reviews.

[2] Tollroads are an exception since the concessionaire directly collects revenues from users. In this case, the agency does not incur even the operating expenses unless payments are a feature of the contract structure.

Few have attempted the difficult test of the claim that P3s deliver design innovation. One practitioner review notes that design outcomes in P3s often fall short of the mark in meeting project objectives (Winch, Onishi, and Schmidt, 2012). With respect to the UK's infrastructure P3 program, the nation's Commission for Architecture and the Built Environment (CABE, 2005) says:

"...there has been endless controversy about whether or not using [P3s] makes it more difficult to achieve good design." (p. 1)

The small number of academic studies targeting design in P3s have also often led with the question of whether P3s induce technical design innovation. A few studies have approached this question by focusing on project actors and the aspects of design they deem important. Others have looked at the connection between process and desirable outcomes such as flexibility and adaptability. These studies build on a rich literature in systems design applied to capital projects (de Weck, de Neufville, and Chaize, 2004; de Neufville, Hodota, et al., 2008; Lin et al., 2009; de Neufville and Scholtes, 2011; Baker et al., 2013), projects and their institutions (Miller and Lessard, 2000; Scott, 2012; Bijker et al., 2012; Lessard and Miller, 2013), and innovation in technical systems and organizations (Cohen and Levinthal, 1990; Gann and Salter, 2000; Geyer and Davies, 2000; Gil and Beckman, 2009). Independent of whether P3-related studies deemed outcomes to be innovative, the studies converge on the idea that the design process itself needs more attention to enhance the potential for innovation. In this respect, researchers and practitioners are of the same view.

Raisbeck and his colleagues are among the few to examine how project actors approach technical and architectural design in PPPs (Raisbeck and Tang, 2013). The authors observed the public outcry about ballooning costs in a number of highly visible Australian P3s. The media claimed that these projects exceeded schedules and budget because of gold plating and excessive aesthetic emphasis. The authors wanted to understand if designers and planners placed undue importance on design without regard to cost (Raisbeck, 2009). They elicited from experts and proposed a framework of critical design factors using the the Analytic Hierarchy Process (AHP) method (Saaty, 2008). Expert respondents emphasized different design factors that balanced both exploration and exploitation (Benner and Tushman, 2003) to manage trade-offs between design quality and cost. With respect to the design process, experienced project actors saw communicating and integrating design knowledge across the project organization as critical. They desired intentional design management processes for collaborative problem-solving. This set of studies reinforced the need for design of the processes themselves.

One study tackled the important question of whether P3 designs are more innovative or adaptible in the face of uncertainty (Barlow and Köberle-Gaiser, 2008; Barlow and Köberle-Gaiser, 2009). The debate on P3 projects in healthcare clearly pointed to ossified planning methods and the desire for hospital designs that could adapt with minimal disruption to changing patterns of demand and healthcare delivery technologies. Barlow and Köberle-Gaiser (2009) identified a focus on risk-sharing, supply chain integration and long-term performance management as important design dimensions for hospital P3s in the UK. Their detailed surveys of decision-makers and case studies of a number of early projects revealed that although innovation was a stated objective, risk-averse project actors quickly shelved new design ideas in favor of older templates.

Winning bidders often claimed innovative technical designs as a primary factor for securing the win, although this emerged a "sales" factor. Raisbeck and Tang (2013) and others have also suggested that bidding processes often collapse to financial criteria alone. Technical design often tends to be an afterthought. CABE (2005) say the following about design selection:

Only when a market settles in a relatively narrow band in terms of financial and competency issues can the design emerge as a differentiator...designs promising better whole-life value have only rarely outweighed cost differentials. (p. 4)

The bidding briefs did not provide sufficient guidance on how to translate adaptability to performance, so early designs did not push the frontier on adaptible designs. Bidders therefore default to standard templates that have proved successful in the past, in the absence of iterative and collaborative design.

Rigid boundaries between the public sector client and designers often precluded true integration and collaboration. Client organizations exhibited a characteristic "public sector mentality". Barlow and Köberle-Gaiser (2009) concluded that:

"...there was very little innovative thinking with regards to new design solutions...it was not evident that [P3s] had promoted more collaborative ways of working, nor that the [Special Purpose Vehicle] was acting as a form of systems integrator..."(p. 139)

The observation that the more complex P3 procurement process did not automatically assure innovative thinking or designs was consistent with earlier insights (Cicmil and Marshall, 2005). These studies further suggested that design innovation needed to occur early in the procurement process; the doors would shut on the opportunity for innovation by the time of financial closure. A key lesson is that project actors should collaborate across boundaries early in the process.

The CABE study also recommended a more diligent project preparation process with a systematic integrated evaluation of both design and economic impact. There is not much to suggest that projects are now prepared in an integrated manner, either in the UK or elsewhere (Jacob et al., 2014). A chief barrier is lack of experience and preparation on the part of the public sector client. The public sector buyer is often unable to systematically evaluate proposed designs before awarding the project (CABE, 2005):

"Many public sector clients are inexperienced and have never procured ... before. As a result they are unprepared for the complexities of [P3s]..."(p. 3)

The ability of the private consortium to understand project needs and propose compatible solutions accordingly is also limited because of time and organizational constraints:

"...bidding consortia's design teams have only limited opportunities to work closely with the client during the bid stages of the [P3] process and to explore different solutions to the clients' service requirements. This happens despite the rhetoric of consultation that appears in bid documentation."(p. 3)

Another study substantiates the need for communication between and learning among project participants to develop innovation potential. Gil, Miozzo, and Massini (2012) observe airport procurement process for a new airport terminal using a grounded-theoretic case study approach. Many private and public actors were involved in this project. The authors identified how some of these actors were limited in their capacity to absorb innovation. Strict timelines, organizational boundaries and internal culture often created disincentives for learning. More adept or aware actors often engaged to educate each other and learn through collaboration. For example, the airport authority used a number of communication mechanisms to interact with an airline as well as construction contractors to pave the way for laying concrete slabs designed to a new standard. The airport was able to educate contractors on the airline's needs after three years of its own internal research and testing. Other ideas for innovation were similarly refined through successive rounds of exploration and discussion. This study demonstrates how collaboration and negotiated decisions between actors resulted in a "collective absorptive capacity" for the project as a whole to innovate in design.

In their evaluation of the UK's 30-year experience with P3s, Winch, Onishi, and Schmidt (2012) reach a conclusion that is promising for this research:

"...private finance is not any more successful in stimulating innovation than public finance of infrastructure assets. This is an important conclusion, because innovation is one of the principal ways by which efficiency savings can be made that will offset the higher cost of capital to privately financed projects."

Their conclusion is promising because it points to the opportunity for innovation over and above that available from financial structure of projects, leaving open the possibilities that future innovations can come from co-design or integrated design. Further, it does not diminish the possibilities of innovation through integrated design evaluation, even if projects were publicly financed.

1.1.2 Project Architecture: Contract Design in P3 Organizations

The literature on contracts in P3s builds on theoretical issues and modeling methods because empirical details of contract structures and negotiations are often legitimately unavailable due to commercial confidentiality. Some authors have nonetheless been able to conduct empirical studies on large datasets (Guasch, 2004; Blanc-Brude, Goldsmith, and Välilä, 2009), which are not otherwise publicly available and otherwise difficult to compile.

The discussion below highlights two thrusts to which this dissertation contributes: computational models of the concession agreement that integrate technical design for use in negotiated decision-making, and the initial formation of relationships early the contracting process.

Most concession design studies address how principals should write contracts to share or allocate risk with agents, assuming a fixed technical design. Concession design has looked at the structure of the concession in terms of optimal concession length (Ng et al., 2007; Carbonara, Costantino, and Pellegrino, 2014a), revenue sharing arrangements (Shan, Garvin, and Kumar, 2010; Engel, Fischer, and Galetovic, 2013; Carbonara, Costantino, and Pellegrino, 2014b), embedded real options (Liu and Cheah, 2009; Cruz and Marques, 2013), policy requirements such as non-compete clauses (Ortiz, Buxbaum, and Little, 2008), and tradeoffs of risk-sharing arrangements (Dewatripont and Legros, 2005; Bennett and Iossa, 2006; Siemiatycki and Friedman, 2012; Gross and Garvin, 2011).

Models in these studies price risk (Shan, Garvin, and Kumar, 2010) or quantify the value of decision flexibility (Ford, Lander, and Voyer, 2002). These authors acknowledge that contracts will be incomplete (Hart, 1995; Hart, 2003). They stylize the decision-making problem by selecting one or two central risk factors such as demand or revenue uncertainty as modeling variables. Both Ford, Lander, and Voyer (2002) and Garvin and Cheah (2004) use binomial lattice models as discrete time approximations to model uncertainty. In contrast, Shan, Garvin, and Kumar (2010) and Liu and Cheah (2009) perform valuations by spreadsheet using Monte Carlo simulations.

A subset of this work positions itself as models for negotiated decision support in concession design. Liu and Cheah (2009) identify a negotiation band within which the principal and agent could conceivably reach agreement. Their model superposes a Minimum Revenue Guarantee (MRG) and Revenue Cap (RC) structure on an underlying cash flow model. This type of combined put-and-call option structure is called a revenue collar (Shan, Garvin, and Kumar, 2010) because it limits both the downside and upside exposure for the concessionaire. Decision-makers would explore different combinations of the tariff-level (price) and the threshold values for the MRG floor and the RC ceiling to determine an acceptable negotiation band. Shan, Garvin, and Kumar (2010) previously showed how to explicitly price the collar option, although decision-makers face the same choices regarding prices and threshold values as in the negotiation band study. These studies move the discussion from pure concession design to negotiated decision-making in projects.

The research that investigates real options 'in' projects (de Neufville, Hodota, et al., 2008) acknowledges that the risk profile of a project also depends on technical and engineering decisions in a project's operating phase. Garvin and Ford (2012) posit that decision-makers find it difficult to to understand the interdependence. This could partially explain their reluctance in designing 'in' options that can enable system reconfiguration. Further, these design alternatives must be explored systematically to understand their impact on the project's distribution of performance. As we have already seen in Section 1.1.1, moving technical design upstream in the procurement process is more likely to create the potential for innovation (Roumboutsos and Saussier, 2014). Models that jointly explore technical design alternatives as well as structural features of the concession can thus improve negotiated decisions by demonstrating the interdependence between the two types of design. Co-design of this type is an important point of departure for this research.

Where decisions under uncertainty are negotiated in this manner, there is also the very realistic chance of future renegotiation as project conditions change. Guasch (2004) was the first to elaborate on the details of renegotiations, based on a set of related studies. Out of 1,000 infrastructure concessions granted between 1985 - 2000 in Latin America and the Caribbean, 30% of all contracts were renegotiated. The number is much higher (42%) if telecommunications projects are excluded. Most renegotiations occurred in the water sector (74%), followed by transportation (55%), and electricity (10%). About 85% of renegotiations occurred within 4 years of award, for contracts with a 15 - 30 year duration. P3 authorities in the UK and elsewhere have also renegotiated a large number of contracts in the last decade (NAO, 2007; Winch, Onishi, and Schmidt, 2012).

The same study also identifies that renegotiations were much less frequent when the principal and the concessionaire negotiated bilaterally, than when the principal used competitive bidding process to award the concession. Only 8% of contracts from bilateral negotiations were renegotiated, compared to 46% of competitive awards. Guasch (2004) attributes the difference to the possibility that bilateral renegotiations allow the concessionaire to extract more favorable terms in the first place, and the more flexible approach lessens the incentives for renegotiation. However, this approach can be much more intransparent.

Renegotiation is a positive instrument when the counterparties use it to address the incomplete nature of contracts. The high incidence in sectors such as water and transportation however indicates the possibility of opportunistic renegotiation (Guasch, Laffont, and Straub, 2008). Both the public and private sectors have demonstrated opportunistic behavior. In some cases the concessionaire may seek to obtain more favorable terms after initial strategic misrepresentation, and in others the awarding authorities may want to claw some of the efficiency gains back. Valero (2015) and Guasch, Laffont, and Straub (2007) show that governments are also very likely to engage in opportunistic behavior. Cases of opportunism aside, the observations discussed here suggest that renegotiations are more likely than not, and tend to occur early in the life of the concession. It therefore becomes more important to think of concessions in terms of life-cycle governance, which involves repeated negotiations and collaborative decisions between the principal and the agent concessionaire.

Life-cycle governance includes both formal contracting (concession design as above) and relational or informal contracting through partnership, collaboration and establishing trust (Cicmil and Marshall, 2005; Dewulf and Kadefors, 2012; Henisz, Levitt, and Scott, 2012). Procurement models such as Integrated Project Delivery rely on a higher degree of relational contracting to enhance flexibility and service quality (Bygballe, Dewulf, and Levitt, 2015). While this dissertation research does not address relational mechanisms, it posits that social psychological dynamics in the early stages of negotiation set the stage for deeper relationships. Section 1.1.4 discusses why the psycho-social aspects of negotiated decision-making can be of inherent value, and how they may affect future interactions between the same negotiators. Before that however, we look at design cognition in conceptual design.

1.1.3 Project Actors: Design Cognition

Problem-solving by human actors is central to the conceptual design of systems like infrastructure projects. Hernandez, Shah, and Smith (2007) suggest that in product design, 70 - 80% of product cost is committed during the conceptual stage as a consequence of design choices. While a similar statistic is unavailable for infrastructure projects, it is clear that the conceptual stage of design has cascading implications for the rest of the project design process, and indeed over the project's life. This section discusses research on cognitive aspects in conceptual design.

Design cognition as a field of research applies cognitive science to design. It takes on questions of how human designers think about a problem, how they find and reason through relevant information, and how they create solutions (Linsey et al., 2010; Dinar et al., 2015). Under the umbrella of design cognition, the topics of shared understanding through collective mental models, information exchange, and communication are germane to negotiated collaboration.

Theories and models of information processing describe how humans perform the complex intellectual function of solving problems (Newell and Simon, 1972). Cognitive science has demonstrated that Working Memory (WM) or Short Term Memory (STM) limits the cognitive abilities of human designers. The 7 +/- 2 rule of chunking is a heuristic for deciding how much human beings can be expected to reasonably retain in WM while solving complex problems (Miller, 1956). Lowering the demands on WM can reduce cognitive cost, for example with the help of devices such as calculators to aid in standard routines, or external memory (EM) aids to store information. The process of learning transfers information or memories from STM to Long-term Memory (LTM). The transfer process is cumulative problem solving, and also requires reasoning to embed relevant schemas in LTM (Lawson, 2004). Both learning and the use of EM aids free up WM to focus on other intellectual functions such as sense-making and communication.

For designers to co-design and negotiate design outcomes they must develop a shared understanding of the design problem (Lawson, 2006). Prior research on team cognition has looked at how interaction and collaboration can lead team members to converge on a single problem solving outcome (Fiore et al., 2010; Reiter-Palmon, Wigert, and de Vreede, 2012). In these situations, designers transform a single or small number of ideas into a creative solution to a technical problem by developing a similar view. Mental models are one way to capture designers' shared understanding (Badke-Schaub et al., 2007).

Wood et al. (2014) study the effect of team interaction structure, i.e. independent versus collaborative design, on the designers' mental models. Representations of mental models are produced with Latent Semantic Analysis (LSA), essentially an analysis of bodies of text (Dong, 2005). They found that collaborating designers had mental models that were more similar than those of independent designers. Collaboration also decreased fixation, the tendency to focus on a subset of features or ideas, and led designers to think openly about possible solutions. Collaboration can thus increase shared understanding between designers.

Information exchange and communication (dialogue, more specifically) are two distinct mechanisms of collaboration. Dialogue between designers embeds relevant information, although dialogue is neither necessary nor sufficient as a means of exchanging relevant information. Written documents such as proposals, graphs and charts, presentations, and other such objects all deliver information without requiring dialogue. Designers may however need to engage in further dialogue over these objects and seek clarity to truly understand their meaning and importance. Too much information can also be burdensome and fail to improve outcomes (Clevenger, Haymaker, and Ehrich, 2013). Conversely, designers may intentionally withhold or bias information in some competitive situations when revealing objects are not available.

When designers possess asymmetric information about the design problem, the mechanism of information exchange becomes critical (Honda et al., 2015). Designers' style or approach towards information exchange can shift system-level design outcomes. Austin-Breneman, Yu, and Yang (2014) show that design practitioners behave strategically while negotiating design trade-offs. They hedge their future needs by representing their view of the problem conservatively and through "worst cases". This biases the collaborators' mental models.

The complexity of the problem can also affect whether designers are able to develop productive mental models and how they exchange information. Hirschi and Frey (2002) find a geometric relationship between problem solving time and the degree of coupling, i.e. interdependence between design parameters. Flager, Gerber, and Kallman (2014) also look at the effects of coupling for a building design problem although they find that coupling becomes less important as the scale of the problem (number of design variables) increases. Instead, solution quality decreases sharply as scale increases. The design process must account for these effects as designers explore complex problem spaces.

Communication (dialogue) can thus assist designers in developing a useful mental model of a complex problem when information is limited, biased or asymmetric. Studies have demonstrated the importance of face-to-face communication for distributed design problems, where designers often work separately and meet infrequently. Others have also studied the effects of collocation. When face-to-face meetings and colocation is infeasible, designers may use computer-based collaboration spaces or methods to support one or both of information exchange and communication (Ostergaard et al., 2005).

As designers negotiate choices in the collaborative design process, they rely on information exchange and communication. Klein et al. (2003) suggest that interdependent designers exhibit tendencies such as "hill climbing" (securing a local maximum) or "annealing" (temporarily accepting lower payoffs to continue the search process). The engineering literature has emphasized the mathematical formulation of strategies and game design to secure desired system-level outcomes (Honda et al., 2015). When human designers engage with each other in real time however, emotional and social psychological effects affect negotiation dynamics (Simon, 1987). The next section discusses these aspects.

1.1.4 Project Actors: Social Psychology in Negotiations

Negotiation is inherent in the collaborative design process, as the design cognition literature shows. After exploring candidate design solutions, designers engage in joint decision-making to ensure that the chosen design will meet their competing objectives. Irrespective of the domain of decision-making (design, managerial decisions, etc), negotiation interactions have a psychological effect on human negotiators. These effects in turn may impact outcomes either in the same or future interactions. The negotiation environment, i.e. the structural conditions of the negotiation, personality, and cognitive biases can all have implications. This section briefly covers these aspects of negotiation as *predictors* of negotiation outcomes before addressing pyscho-social effects as *outcomes* themselves.

Early work in the social psychology of negotiation demonstrated that structural features affected outcomes. These structural or situational features include the number of people on each side, their incentives and payoffs, deadlines, and other environmental conditions. Studies of the 1960s and 1970s focused mainly on (i) the individual differences of negotiators and (ii) situational effects (Bazerman, Curhan, et al., 2000). Rubin and Brown (1975) documented the extensive empirical literature showing that individual differences do not explain much of the variance in negotiators' behavior. Others showed that situational features that define the context of a negotiation easily swamp any effects of individual differences (Thompson, 1998). Recent work with updated methods and variables has also however re-established the importance of individual differences (Elfenbein et al., 2008; Sharma, Bottom, and Elfenbein, 2013). This does not take away from the importance of situational features however.

With a move towards cognitive issues in the 1980s and 1990s, behavioral decision research (BDR) then began to focus on the interaction of structure and behavior. This body of work focused (descriptively) on how negotiators actually make decisions to prescribe strategies for the focal negotiators (Raiffa, 1982; Bazerman and Neale, 1992; Bazerman and Moore, 2012). It tackled questions left unaddressed by the mathematical game theory perspective of decision science.

Behavioral decision research pinpointed the many biases that can lead negotiators to deviate from normative prescriptions and rational behavior. Of the many systematic biases in two-party negotiations (Bazerman, Curhan, et al., 2000; Tsay and Bazerman, 2009), three in particular are very relevant to design-related negotiations:

1. Bounded Awareness: Negotiators are inappropriately affected by readily available information even if it is unimportant or unable to make use of less noticeable but available salient information (Pinkley, Griffith, and Northcraft, 1995). They may fail to focus (Bazerman and Chugh, 2005; Chugh and Bazerman, 2007).

2. Egocentrism: Negotiators may ignore the perspective of other parties (Valley, Moag, and Bazerman, 1998) and overlook valuable available information by failing to consider the opponent's cognitive perspective (Bazerman and Carroll, 1987). Often the egocentric view arises because a negotiator believes that the other party is overstating its case (Tsay and Bazerman, 2009).

3. The "Fixed Pie" effect: Negotiators may falsely assume that the available payoffs from negotiation are constant sum - the size of the so-called "pie" is fixed (Bazerman, Magliozzi, and Neale, 1985; Gimpel, 2008). They miss opportunities for mutually beneficial trade-offs that increase the size of the pie (Fukuno and Ohbuchi, 1997).

These cognitive biases often surface in design interactions. They are important to consider because they affect the negotiating designers mental models and understanding. The literature on mental models in negotiation is parallel to that in design cognition, and rarely do the two acknowledge each other.

Studies of negotiation define a mental model as a cognitive representation of the expected negotiation (Bazerman, Curhan, et al., 2000). This research shows that cognition and the negotiation structure are reciprocally intertwined - structure influences mental models and cognitive perception shapes structure and behavior.

Mental models of the negotiation situation, the other parties in the negotiation, and the self affect negotiator behavior and outcomes. Thompson and Hastie (1990) suggested that negotiators who modified their 'fixed pie' perception, did so early in the negotiation; the bias persisted throughout for negotiators who didn't. Studies on attribution and interpersonal perception (Gilbert, 1994) have demonstrated how negotiators often overestimate the ideological difference or incompatibility of interests of others (Keltner and Robinson, 1997).

Role theory addresses mental models of the self (Montgomery, 1998), showing that in negotiation situations with the same economic structure, individuals behave differently depending on the meta-rules of their roles. The same individual may also modify behavior depending on how they perceive their role changing in different situations. How negotiators understand and define the game for themselves can thus be a critical determinant of how they engage.

Even though individual negotiators may start out with different or contradictory perceptions, asymmetric mental models do not persist over the course of the negotiation interaction. Negotiators eventually create a shared understanding of the situation, their perception of other negotiators, and the rules of engagement (Messick, 1999). This phenomenon is precisely what we are looking to leverage in developing shared understandings of design problems in collaborative processes.

Negotiations have two types of outcomes: economic and psycho-social. The first type, economic outcomes, are the terms of the agreement struck by the negotiating parties. The bulk of the organizational and behavioral science literature over the last quarter century has focused on economic outcomes, treating them as objective or tangible terms of exchange (Raiffa, 1982; Bazerman and Lewicki, 1983; Raiffa, Richardson, and Metcalfe, 2002). For example, Neale and Bazerman (1985) studied the effect of framing and overconfidence in simulated negotiations. Their factorial design framed outcomes in terms of gains and losses between managers and unions, however these outcomes were economic.

The second type of negotiated outcomes, social psychological outcomes, are the attitudes, perceptions and emotions of the negotiators (Thompson and Hastie, 1990; Thompson, 1998). These subjective outcomes are squarely within the psychological and emotional realm. They receive little to no attention as the performance dimensions of negotiation studies because they are transient and fleeting, and perceived as hard to assess. Only in the last decade have researchers formalized the study of social psychological factors as outcome measures, instead of predictors of economic outcomes (Walsh, Weber, and Margolis, 2003; Curhan, Elfenbein, and Xu, 2006; Bendersky and McGinn, 2010).

Recent work suggests that the *Subjective Value (SV)* of social psychological outcomes of negotiation are just as, if not more important than the *Objective Value (OV)* of economic outcomes. Curhan, Elfenbein, and Xu (2006) developed the construct of *SV*, which they define as the "social, perceptual, and emotional consequences of a negotiation."

Subjective Value in negotiated agreements for design is important for at least four reasons. First, negotiators often place high value on the degree of respect or favorable relationships, sometimes even more than the value they attribute to economic payoffs. Social psychological outcomes thus have intrinsic value. For example, when given the choice, negotiators often describe the negotiation objective with frames that signify fairness and respect even if they may secure lower monetary outcomes (Blount and Larrick, 2000). This imbalance may be conscious or unconscious. Second, individuals or entities may be sought out as good counterparts based on the strength of the relationship and credible reputation (Curhan, Elfenbein, and Xu, 2006; Curhan, Elfenbein, and Eisenkraft, 2010). The desire to deal with partners who have established rapport may serve to further enhance SV (Tinsley, O'Connor, and Sullivan, 2002). Third, securing high SV in the first round of a negotiation may lead to both higher SV and OV in subsequent rounds (Drolet and Morris, 2000; Curhan, Elfenbein, and Eisenkraft, 2010). This reinforces the intuition of the two reasons above. Finally, enhanced Subjective Value can serve as a means of commitment to honor the terms of the agreement, when outcomes are not self-enforcing or easily monitored

(Curhan, Elfenbein, and Kilduff, 2009; Ferguson, Moye, and Friedman, 2008). Curhan and Brown (2011) call this the "insurance policy" function of SV. For the reasons described here, the relational view of negotiation (Gelfand et al., 2006) may sometimes take precedence over the rational view (Bazerman and Neale, 1992).

Subjective Value of negotiation thus has implications for the collaborative design processes addressed in this study. The relational phenomenon is observed in contract settings between government agencies and private firms, where a perceived lack of respect or perceived opportunism may contribute to the adversarial nature of the relationship (Edkins and Smyth, 2006). Many authors point to trust as a key element of negotiated decisions in this space (Smyth and Edkins, 2007; Smyth and Pryke, 2009). Relational approaches to contracting therefore emphasize a longer term view of bargaining with an emphasis on collaborative mechanisms for securing outcomes (Rahman and Kumaraswamy, 2004; Osipova, 2014; Suprapto et al., 2014).

The dual nature of value in negotiated decisions implies that neither should be considered in isolation. Curhan and Brown (2011) make the case that the very prescriptions and methods that negotiators apply to enhance OV may undermine SV, a detraction from the overall organizational objective. For this reason, the research described here tracks both the Objective Value and Subjective Value of negotiation outcomes.

1.2 Research framework and summary

The discussion so far has shown how the construct of negotiated collaboration draws on a number of threads in design and human behavioral decisions. This section interweaves the four design perspectives further. It firsts combines these into a theoretical framework and introduces the main research question.

1.2.1 Theoretical framework

In short, this thesis asks the question: "Does collaboration affect design choices?" The question is important because as a society we look to collaboration as a means for innovation in design and its benefits. We often spend an incredible amount of time, effort, and resources to create structures for collaboration in different settings. However, we also create barriers to collaboration, through "arms length" interactions for example, when we believe that it collaboration is unwarranted or interferes with our conception of the greater good. Does collaboration in design create benefits from innovation and what mechanisms can we use to capture these benefits?

I investigate this question in the very specific design context of infrastructure P3s. The objective is to design the early stage concept of a large infrastructure facility under conditions of long-term uncertainty. There are two key design roles, a principal and an agent. The two parties are linked to each other through a concession contract. The contracting parties have different and often competing objectives that can result in trade-offs. The design problem consists of simultaneously making technical as well as contractual choices.

To refocus how the literature relates to this research, a formal definition of 'negotiated collaboration' is necessary. I define negotiated collaboration as a process:

Definition: Negotiated Collaboration

Negotiated collaboration is a process in which project actors with competing objectives and asymmetric information co-create a solution to balance trade-offs through communication and knowledge exchange.

Figure 1.4 presents a framework for connecting the different aspects of this type of design problem. It links the mechanisms of negotiated collaboration and the construct of co-design to multi-dimensional design outcomes.

Design outcomes are at the top of the schematic, since they emerge from the design process. Outcomes are conceptually represented along two dimensions. The 2 x 2 shows the project actors' roles along the horizontal axis and type of outcome value along the vertical.

- **Outcomes by Role Type**: Along the horizontal, 'Public' and 'Private' indicates the project actors playing two key design roles, the principal and the agent respectively. In a real project, the principal is a public authority that must ensure the delivery of an infrastructure service. The agent is a private firm (or consortium) that contracts with the authority to deliver this service. Figure 1.3 covered a number of contracting options; this stylized design problem assumes a concession approach between public and private actors.

- **Outcomes by Value Type**: Along the vertical, outcome values are of two types. The first type, Objective Value (OV), represents the economic and technical payoffs to the principal and agent in the project. Profits and contract payments are examples of economic payoffs for the firm and the authority. System reliability is a technical payoff, and it is experienced by both actors. The bulk of the design and negotiation literature has focused on outcomes in terms of Objective Value. On the other hand, Subjective Value (SV) has received less attention. Subjective Value (SV) denotes the project actors' psycho-social outcomes. These are of an emotional and relational variety. The SV type captures phenomena such as sense of self, rapport, trust, and satisfaction from the engagement process.

The design process composed of co-design as well as collaboration mechanisms is in the middle of Figure 1.4. Project actors design both the concession as well as some high-level technical features of the project. Contract terms such as price (or tariff level - $/unit) and payment levels are important parameters for concession design. Technical design features could include technology type, output production capacity of the project, number of production phases, etc. Technical choices and contractual terms interact to deliver Objective Value outcomes for the actors. The dynamics of negotiation influence Subjective Value outcomes.

For project actors to reach agreement in the collaboration process, they must develop a shared understanding of the design problem. This requires them to reconcile their own interests with those of the negotiation counterparty. In other words, designers' mental models must become

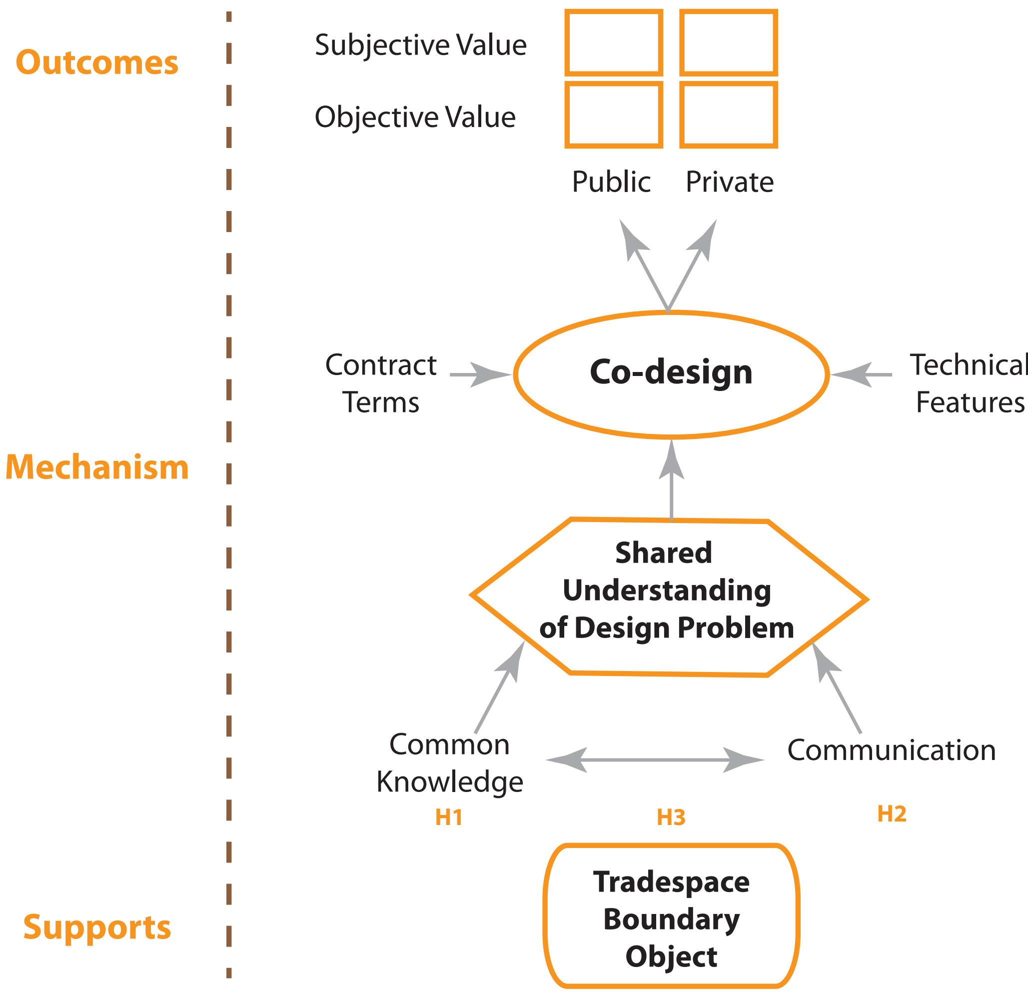

Figure 1.4: A theoretical framework linking the cognitive sub-mechanisms of negotiated collaboration to multi-dimensional design outcomes that emerge from co-design.

similar over time. A designer's individual understanding develops through searching for relevant information, and learning by observing the effect of choices on outcomes. Additional cognitive mechanisms are necessary for shared understanding to develop. After this, collaborators make a number of moves and counter-moves to propose design choices until they approach agreement.

The framework posits three mechanisms of collaboration that can contribute to shared understanding.

H1 – Common Knowledge:
Common knowledge enables collaborators to achieve a shared understanding of the design problem by making explicit the relationship between negotiated choices and the co-designer's expected outcomes.

Common knowledge is the converse of information asymmetry. The more knowledge the designers have about each others interests, objectives and expected outcomes, the lower the degree of information asymmetry. When common knowledge is low, designers must find a way to exchange information with each other to develop a shared understanding. Documents, graphics, and other visual artifacts can all support information exchange. In this sense, these boundary objects are factual. The story is in the data, and collaborators must connect the dots to tell the story.

H2 – Communication:
Communication enables collaborators to achieve a shared understanding of the design problem through a process of discussion and reasoning in which they selectively pass information to alter co-designer's mental models.

Communication is an interactive and iterative process in which designers use language laden with facts to convey meaning through dialogue. Dialogue can be written or verbal. It is characterized by high frequency exchanges composed of individual messages. In other words, communication occurs in real time or over short time spans. Designers propose and evaluate offers and choices iteratively. Communication biases information in that it always represents one party's version of the design story. The bias can be unconscious, or it can be intentional strategic misrepresentation.

H3 – Knowledge - Communication Interaction:
Common knowledge and communication interactively enable collaborators to achieve a shared understanding of the design problem by enhancing the sense-making process.

Common knowledge provides broader factual representations of the collaborator's selective narrative that the recipient can use to question, verify and validate the altering mental model. Common knowledge may reinforce the effect of communication, whereas communication can amplify the effect of common knowledge by by identifying salient information.

Supports for information exchange are at the bottom of the framework schematic in Figure 1.4. While collaborators can rely on their language and training for sense-making and problem-solving, formal artifacts such for information exchange can serve as External Memory (EM) aids to reduce cognitive burden. Computer models that relate design choices to expected performance outcomes for each collaborator are an important form of EM that enable information exchange. Later in the thesis we see how the co-design model (in Chapter 2) also serves as a support for collaboration (in Chapter 3).

The theoretical framework for this research thus captures a process in which collaborators make design choices through co-design. To negotiate choices effectively, they must develop a shared understanding of the design problem by arriving at similar mental models. Computer models of the co-design problem can support the mechanisms of information exchange and communication in collaboration. The dynamics of negotiation and design choices result in multi-dimensional value outcomes both in terms of the roles of project actors as well as the nature of the payoffs, whether economic or pyscho-social.

1.2.2 Research Design and Findings

The first part of the research makes a case for co-design - the simultaneous integrated design of the concession and the technical concept of an infrastructure project. To study co-design, I developed a tradespace model that relates performance trade-offs among different performance dimensions with changes in design. The tradespace model simulates a large-scale desalination project as a tangible example for integrated contractual and technical design. Chapter 2 covers the model development process and key results from co-design. The study continues the same case example of desalination throughout.

In the stylized design problem of a P3 desalination facility, a water authority contracts with an engineering firm. The firm is the agent in this problem; it designs, manages and supplies water to the water authority. The authority is the principal. It wants reliable water supply and makes contract payments to the firm in return for this service.

Desalination is a helpful case for illustrating co-design because most desalination projects are stand-alone dedicated facilities. Desalination projects are not networked, in the manner that power plants are networked into a grid. This allows designers to focus on the concept of the facility and how their choices relate to expected performance over the life of the project. In other words, it is easy to draw a system boundary around the desalination facility for the purpose of this research.

A further reason to select desalination is that even though the suite of technologies in most projects is quite mature, the opportunity for innovation is presented by the considerations of co-design, the *joint* choices of technical and organizational / institutional design. The Kingdom of Saudi Arabia is a case in point. Although it has been a world leader in the design and operations of large desalination facilities for many decades, only recently have the National Water Company and the Saline Water Conversion Corporation embarked on a systematic effort to partner with private sector firms that are at the frontier of technology development as well as project integration and delivery techniques (see **??**). This recent trend suggests that gains from innovation through collaboration continue to remain available, and bolster the motivations for this research in part.

One part of co-design involves developing the structure of the concession contract. Important features of the contract include the contract length, water price, take-or-pay provisions such as revenue guarantees, and other incentive terms. The structural variables relationships are based on the P3 contract design literature reviewed earlier (Section 1.1.2).

The economic performance dimensions are expected profits and expected lifetime payments. Expected profits are an "observed" variable from the firm's point of view. The water authority observes its contract payments to the firm.

The other part of co-design deals with the technical attributes of the facility. In desalination projects, the important high level design variables are technology, plant output capacity, and number of operating phases (modules). These interact with other variables in the project's environment such as input water quality. The study looks at a dataset of about 7,000 projects globally to identify trends and structural relationships among the technical variables.[3] These relationships are used to generate parameter value ranges. For example, the capital cost of facilities is derived as a function of a number of technical variables.

The main technical performance variable is the reliability of meeting demand. The tradespace model measures reliability as the lack of water shortages in contracted supply under conditions of demand uncertainty. In other words, the lower the level of realized water shortages, the more reliable the system.

Chapter 2 presents the analysis and results in detail. The main finding is summarized here.

Findings from Co-Design

Co-design demonstrates the trade-offs in expected value outcomes as a result of interdependent technical and contractual choices. From the agent firm's point of view, the model shows a number of technical designs that can result in the same level of expected profit. While the firm may be indifferent between these choices, some designs reduce water shortages and increase the reliability of meeting demand. The water authority principal prefers the designs that provide high reliability. At some combinations of water prices and revenue guarantees, the authority is able to secure reliability as well as reduce demand risk for the firm. The firm exploits flexibility in design (modular phased units) to meet this level of reliability. The main intuition arising from the co-design analysis is that a subset of feasible designs creates a zone of negotiated agreement. Getting to this "sweet spot" or target area requires both the principal water authority and the agent firm to make trade-offs.

[3]This data set is the IDA Desalination Inventory available by subscription from Global Water Intelligence (2014).

The second part of the research is a controlled design experiment with human participants as designers. These designers play the roles of a principal and agent who are in a collaborative process for the conceptual design of a large desalination facility. As above, the water authority wants to contract for the delivery of water to meet its demand and reliability obligations. The engineering firm is an expert in designing and managing a desalination plant. It supplies water in return for contract payments.

Participants are paired up using stratified sampling and assigned to roles. Pairs are then randomly assigned to treatment and control groups. These designers collaborate with each other using an interactive version of the tradespace model. They co-design, i.e. explore designs as a function of contractual and technical variables. Design choices translate into expected performance outcomes for each role (viz. profits and contract payments). These indicators are Objective Value - type outcomes.

The experiment studies the effects of collaboration mechanisms on understanding and negotiated agreement in design choices. As explained above in the theoretical framework, the three general hypotheses involve: (H1) common knowledge mechanism, (H2) communication mechanism, and (H3) the interaction of the two mechanisms. The general hypotheses are broken down into more specific testable hypotheses in Chapter 3. The same chapter also describes in detail the experiment protocol and main results.

The collaboration experiment also captures participants' factual and perceived understanding of the design problem, and their mood prior to the collaboration process. Participants report on these dimensions after viewing a brief tutorial. After the design exercise, participants report on how their understanding of the problem changed over the course of the exercise. They also answered questions about their satisfaction with the negotiated outcomes, the efficiency and fairness of the process, and the the quality of the relationship they established with their collaborator during the exercise. These responses are scored and collapsed into Subjective Value - type outcomes.

Findings from the experimental Negotiated Collaboration exercise

Collaboration systematically shifts design choices. Communication as a collaboration mechanism dominates information sharing as a mechanism for approaching negotiated agreement. Both the firm and the water authority traded-off profits and contract payments to select designs that enhanced reliability when the communication treatment was active. In contrast, common knowledge had a partial effect when it was the only treatment in that it only caused one role, the water authority, to significantly alter design choices.

Communication is a primary mechanism in collaboration. Communication made a significant difference without *and* with common knowledge, when the two mechanisms were allowed to interact. Information in the common knowledge condition either reinforced or amplified the effect of communication. The use of information exchange to achieve shared understanding is thus a supporting mechanism in collaboration.

The order in which treatments are applied affects the productivity of the design process without changing the final outcomes. Although design outcomes were similar at the end, communication first between designers reduced the number of iterations the collaborators needed to either explore new designs or revisits previously attempted configurations. They were able to approach the zone of reasonable agreement faster and with fewer iterations.

Participants reported that their understanding changed significantly over the course of the exercise. Designers who felt their understanding was enhanced attributed much of the enhancement to the communication process. Many reported that information exchange (the common knowledge condition) confused them and detracted from their understanding.

Participants overwhelmingly reported high Subjective Value outcomes as a consequence of the design exercise across the treatment conditions. Women experienced more of their SV from the relational aspects of collaboration. Subjective Value outcomes are correlated with both their improved understanding of the project's design objectives and their ability to communicate with collaborators to agree on design choices.

This work began with the question of "does collaboration affect design choices?" in reference to the issues of innovation in infrastructure P3s. The research investigated the potential benefits of collaborative design as in partnering arrangements through an experimental study. It concludes that partnering benefits project actors because they develop a shared understanding of the project as a design problem. Partners establish a foundation for managing trade-offs by each walking a mile in the others shoes. Initial interactions in early stages of design can thus pave the way for a more productive partnering relationship over time.

1.2.3 Contributions

This research contributes to three bodies of knowledge. First, it directly addresses the literature on infrastructure public-private partnerships by showing how partnering can create objective as well as psycho-social benefits for a stronger partnering relationship. In the debate on whether P3s have the potential to result in innovation, this contribution suggests that P3s do in fact present this potential. To realize it, partners must develop a mutual understanding of the project's objectives in early stages of design. The design process in P3s must become more flexible and allow for iterative technical and contractual design to take place further upstream in the project delivery process.

Second, the co-design approach speaks to the literature on systems design, via technical and contractual design. This contribution emphasizes how an integrated systems view can help designers balance trade-offs. Infrastructure projects generate value for their participants in multiple dimensions. Designers can avoid prematurely locking out benefits and use co-design to shape and secure value trade-offs. They can preserve system-level objectives such as reliability, a shared interest across actors.

Third, the experimental study on negotiated collaboration demonstrates a useful application of the Subjective Value framework in an integrated design setting. Design studies focus almost exclusively on Objective Value outcomes while very few negotiation studies assess social psychological performance effects as Subjective Value outcomes. This research suggests that both are important in collaborative design interactions, which are an example of integrative bargaining. An experimental test of the collaboration mechanisms of communication and information exchange shows the primacy of communication in helping negotiating collaborators approach agreements. The experimental setup is thus a methodological contribution to both design and negotiation literature.

References

Austin-Breneman, Jesse, Bo Yang Yu, and Maria C Yang (2014). "Biased Information Passing Between Subsystems Over Time in Complex System Design". In: *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, V007T07A023–V007T07A023.

Badke-Schaub, Petra, Andre Neumann, Kristina Lauche, and Susan Mohammed (2007). "Mental models in design teams: a valid approach to performance in design collaboration?" In: *CoDesign* 3.1, pp. 5–20.

Baker, Jonathan, Paul Block, Kenneth Strzepek, and Richard de Neufville (2013). "Power of Screening Models for Developing Flexible Design Strategies in Hydropower Projects: Case Study of Ethiopia". In: *Journal of Water Resources Planning and Management* 140.12.

Ball, Jeffrey (2015). "Why the Saudis are going Solar". In: *The Atlantic*.

Barlow, James and Martina Köberle-Gaiser (2008). "The private finance initiative, project form and design innovation: The UK's hospitals programme". In: *Research Policy* 37.8, pp. 1392–1402.

— (2009). "Delivering innovation in hospital construction: Contracts and collaboration in the UK's Private Finance Initiative hospitals program". In: *California Management Review* 51.2, pp. 126–143.

Bazerman, Max H and John S Carroll (1987). "Negotiator cognition". In: *Research in organizational behavior*.

Bazerman, Max H and Dolly Chugh (2005). "Bounded awareness: Focusing failures in negotiation". In: *Frontiers of social psychology: Negotiation*, pp. 7–26.

Bazerman, Max H, Jared R Curhan, Don A Moore, and Kathleen L Valley (2000). "Negotiation". In: *Annual review of psychology* 51.1, pp. 279–314.

Bazerman, Max H and Roy J Lewicki (1983). *Negotiating in organizations*. Sage Beverley Hills, CA.

Bazerman, Max H, Thomas Magliozzi, and Margaret A Neale (1985). "Integrative bargaining in a competitive market". In: *Organizational behavior and human Decision Processes* 35.3, pp. 294–313.

Bazerman, Max H and Don A Moore (2012). *Judgment in Managerial Decision Making*. 8th edition. Wiley & Sons.

Bazerman, Max H and Margaret A. Neale (1992). *Negotiating rationally*. New York: Free Press.

Bendersky, Corinne and Kathleen L. McGinn (2010). "Perspective—Open to Negotiation: Phenomenological Assumptions and Knowledge Dissemination". In: *Organization Science* 21.3, pp. 781–797.

Benner, Mary J and Michael L Tushman (2003). "Exploitation, exploration, and process management: The productivity dilemma revisited". In: *Academy of management review* 28.2, pp. 238–256.

Bennett, John and Elisabetta Iossa (2006). "Delegation of Contracting in the Private Provision of Public Services". In: *Review of Industrial Organization* 29.1-2, pp. 75–92.

Bijker, Wiebe E, Thomas P Hughes, Trevor Pinch, and Deborah G Douglas (2012). *The social construction of technological systems: New directions in the sociology and history of technology*. Cambridge, USA: MIT press.

Blanc-Brude, Frédéric, Hugh Goldsmith, and Timo Välilä (2009). "A comparison of construction contract prices for traditionally procured roads and public–private partnerships". In: *Review of Industrial Organization* 35.1-2, pp. 19–40.

Blount, Sally and Richard P. Larrick (2000). "Framing the Game: Examining Frame Choice in Bargaining". In: *Organizational Behavior and Human Decision Processes* 81.1, pp. 43–71.

Bryce, Herrington J (2001). "The Authority as a Mechanism for Public Enterprise: United States Experience". In: *International Review of Public Administration* 6.1, pp. 11–19.

Bygballe, Lena E., Geert Dewulf, and Ray E. Levitt (2015). "The interplay between formal and informal contracting in integrated project delivery". In: *Engineering Project Organization Journal* 5.1, pp. 22–35.

CABE (2005). *Design quality and the private finance initiative*. Tech. rep. Commission for Architecture and the Built Environment (CABE).

Carbonara, Nunzia, Nicola Costantino, and Roberta Pellegrino (2014a). "Concession period for PPPs: A win–win model for a fair risk sharing". In: *International Journal of Project Management* 32.7, pp. 1223–1232.

— (2014b). "Revenue guarantee in public-private partnerships: a fair risk allocation model". In: *Construction Management and Economics* 32.4, pp. 403–415.

Chugh, Dolly and Max H Bazerman (2007). "Bounded awareness: What you fail to see can hurt you". In: *Mind & Society* 6.1, pp. 1–18.

Cicmil, Svetlana and David Marshall (2005). "Insights into collaboration at the project level: complexity, social interaction and procurement mechanisms". In: *Building Research & Information* 33.6, pp. 523–535.

Clevenger, Caroline Murrie, John Riker Haymaker, and Andrew Ehrich (2013). "Design exploration assessment methodology: testing the guidance of design processes". In: *Journal of Engineering Design* 24.3, pp. 165–184.

Coase, Ronald H (1974). "The Lighthouse in Economics". In: *Journal of Law and Economics* 17.2, pp. 357–376.

Cohen, Wesley M and Daniel A Levinthal (1990). "Absorptive capacity: a new perspective on learning and innovation". In: *Administrative science quarterly* 35.1, pp. 128–152.

Cruz, Carlos Oliveira and Rui Cunha Marques (2013). "Flexible contracts to cope with uncertainty in public–private partnerships". In: *International Journal of Project Management* 31.3, pp. 473–483.

Curhan, Jared R and Ashley D Brown (2011). "The Oxford handbook of positive organizational scholarship". In: ed. by Kim S Cameron and Gretchen M Spreitzer. Oxford University Press. Chap. Parallel and divergent predictors of objective and subjective value in negotiation.

Curhan, Jared R., Hillary Anger Elfenbein, and Noah Eisenkraft (2010). "The Objective Value of Subjective Value: A Multi-Round Negotiation Study". In: *Journal of Applied Social Psychology* 40.3, pp. 690–709.

Curhan, Jared R, Hillary Anger Elfenbein, and Gavin J Kilduff (2009). "Getting off on the right foot: subjective value versus economic value in predicting longitudinal job outcomes from job offer negotiations." In: *Journal of Applied Psychology* 94.2, p. 524.

Curhan, Jared R, Hillary Anger Elfenbein, and Heng Xu (2006). "What do people value when they negotiate? Mapping the domain of subjective value in negotiation." In: *Journal of personality and social psychology* 91.3, p. 493.

de Clerq, Geert (2014). "Paris's return to public water supplies makes waves beyond France". In: *Reuters*.

de Neufville, Richard, Kenichi Hodota, Joseph Sussman, and Stefan Scholtes (2008). "Real options to increase the value of intelligent transportation systems". In: *Transportation Research Record: Journal of the Transportation Research Board* 2086.1, pp. 40–47.

de Neufville, Richard and Stefan Scholtes (2011). *Flexibility in engineering design*. Cambridge, USA: MIT Press.

de Weck, Olivier L, Richard de Neufville, and Mathieu Chaize (2004). "Staged deployment of communications satellite constellations in low earth orbit". In: *Journal of Aerospace Computing, Information, and Communication* 1.3, pp. 119–136.

Dewatripont, Mathias and Patrick Legros (2005). "Public-private partnerships: contract design and risk transfer". In: *EIB papers* 10.1, pp. 120–145.

Dewulf, Geert and Anna Kadefors (2012). "Collaboration in public construction—contractual incentives, partnering schemes and trust". In: *Engineering project organization journal* 2.4, pp. 240–250.

Dinar, Mahmoud, Jami J Shah, Jonathan Cagan, Larry Leifer, Julie Linsey, Steven M Smith, and Noe Vargas Hernandez (2015). "Empirical Studies of Designer Thinking: Past, Present, and Future". In: *Journal of Mechanical Design* 137.2, p. 021101.

Dong, Andy (2005). "The latent semantic approach to studying design team communication". In: *Design Studies* 26.5, pp. 445–461.

Drolet, Aimee L and Michael W Morris (2000). "Rapport in conflict resolution: Accounting for how face-to-face contact fosters mutual cooperation in mixed-motive conflicts". In: *Journal of Experimental Social Psychology* 36.1, pp. 26–50.

Edkins, A. and H. Smyth (2006). "Contractual Management in PPP Projects: Evaluation of Legal versus Relational Contracting for Service Delivery". In: *Journal of Professional Issues in Engineering Education and Practice* 132.1, pp. 82–93.

Elfenbein, Hillary Anger, Jared R Curhan, Noah Eisenkraft, Aiwa Shirako, and Lucio Baccaro (2008). "Are some negotiators better than others? Individual differences in bargaining outcomes". In: *Journal of Research in Personality* 42.6, pp. 1463–1475.

Engel, Eduardo, Ronald Fischer, and Alexander Galetovic (2013). "The basic public finance of public–private partnerships". In: *Journal of the European Economic Association* 11.1, pp. 83–111.

Ferguson, Merideth, Neta Moye, and Ray Friedman (2008). "The Lingering Effects of the Recruitment Experience on the Long-Term Employment Relationship". In: *Negotiation and Conflict Management Research* 1.3, pp. 246–262.

Fiore, Stephen M., Kimberly A. Smith-Jentsch, Eduardo Salas, Norman Warner, and Michael Letsky (2010). "Towards an understanding of macrocognition in teams: developing and defining complex collaborative processes and products". In: *Theoretical Issues in Ergonomics Science* 11.4, pp. 250–271.

Flager, Forest, David Jason Gerber, and Ben Kallman (2014). "Measuring the impact of scale and coupling on solution quality for building design problems". In: *Design Studies* 35.2, pp. 180–199.

Ford, David N, Diane M Lander, and John J Voyer (2002). "A real options approach to valuing strategic flexibility in uncertain construction projects". In: *Construction Management and Economics* 20.4, pp. 343–351.

Fukuno, Mitsuteru and K-i Ohbuchi (1997). "Cognitive biases in negotiation: the determinants of fixed-pie assumption and fairness bias". In: *Japanese Journal of Social Psychology* 13.1, pp. 43–52.

Gann, David M and Ammon J Salter (2000). "Innovation in project-based, service-enhanced firms: the construction of complex products and systems". In: *Research policy* 29.7, pp. 955–972.

Garvin, Michael J and Charles YJ Cheah (2004). "Valuation techniques for infrastructure investment decisions". In: *Construction Management and Economics* 22.4, pp. 373–383.

Garvin, Michael J and David N Ford (2012). "Real options in infrastructure projects: theory, practice and prospects". In: *Engineering project organization journal* 2.1-2, pp. 97–108.

Gelfand, Michele J., Virginia Smith Major, Jana L. Raver, Lisa H. Nishii, and Karen O'Brien (2006). "Negotiating Relationally: The Dynamics of the Relational Self in Negotiations". In: *Academy of Management Review* 31.2, pp. 427–451.

Geyer, Anton and Andrew Davies (2000). "Managing project–system interfaces: case studies of railway projects in restructured UK and German markets". In: *Research Policy* 29.7, pp. 991–1013.

Gil, Nuno and Sara Beckman (2009). "Infrastructure meets business: building new bridges, mending old ones". In: *California Management Review* 51.2, pp. 6–29.

Gil, Nuno, Marcela Miozzo, and Silvia Massini (2012). "The innovation potential of new infrastructure development: An empirical study of Heathrow airport's T5 project". In: *Research Policy* 41.2, pp. 452–466.

Gilbert, D. (1994). "Advanced Social Psychology". In: ed. by A Tesser. McGraw-Hill. Chap. Attribution and interpersonal perception, pp. 99–147.

Gimpel, Henner (2008). "Cognitive Biases in Negotiation Processes". English. In: *Negotiation, Auctions, and Market Engineering*. Ed. by Henner Gimpel, Nicholas R. Jennings, Gregory E. Kersten, Axel Ockenfels, and Christof Weinhardt. Vol. 2. Lecture Notes in Business Information Processing. Springer Berlin Heidelberg, pp. 213–226.

Gómez-Ibáñez, José A (2003). *Regulating infrastructure: monopoly, contracts, and discretion*. Harvard University Press.

Grant, Jeremy (2014). "Saudi Arabia taps Singapore for desalination technology". In: *Financial Times*.

Grimsey, Darrin and Mervyn K Lewis (2004). "Discount debates: Rates, risk, uncertainty and value for money in PPPs". In: *Public Infrastructure Bulletin* 1.3, pp. 4–7.

Gross, Martha and Michael Garvin (2011). "Structuring PPP toll-road contracts to achieve public pricing objectives". In: *The Engineering Project Organization Journal* 1.2, pp. 143–156.

Guasch, J Luis (2004). *Granting and renegotiating infrastructure concessions: doing it right*. Washington, D.C.: World Bank / World Bank Institute.

Guasch, J Luis, Jean-Jacques Laffont, and Stephane Straub (2008). "Renegotiation of concession contracts in Latin America: Evidence from the water and transport sectors". In: *International Journal of Industrial Organization* 26.2, pp. 421–442.

Guasch, J Luis, Jean-Jacques Laffont, and Stéphane Straub (2007). "Concessions of infrastructure in Latin America: Government-led renegotiation". In: *Journal of Applied Econometrics* 22.7, pp. 1267–1294.

Hall, John (1998). "Private opportunity, public benefit?" In: *Fiscal Studies* 19.2, pp. 121–140.

Hart, Oliver (1995). *Firms, contracts, and financial structure*. Oxford, UK: Oxford university press.

— (2003). "Incomplete contracts and public ownership: Remarks, and an application to public-private partnerships*". In: *The Economic Journal* 113.486, pp. C69–C76.

Henisz, Witold J, Raymond E Levitt, and W Richard Scott (2012). "Toward a unified theory of project governance: economic, sociological and psychological supports for relational contracting". In: *Engineering Project Organization Journal* 2.1-2, pp. 37–55.

Hernandez, Noe Vargas, Jami J Shah, and Steven M Smith (2007). “Cognitive Models of Design Ideation”. In: *ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, pp. 135–144.

Hirschi, N and D Frey (2002). “Cognition and complexity: An experiment on the effect of coupling in parameter design”. In: *Research in Engineering Design* 13.3, pp. 123–131.

Hodge, Graeme A and Carsten Greve (2007). “Public-private partnerships: an international performance review”. In: *Public administration review* 67.3, pp. 545–558.

Honda, Tomonori, Francesco Ciucci, Kemper E. Lewis, and Maria C. Yang (2015). “Comparison of Information Passing Strategies in System-Level Modeling”. In: *AIAA Journal* 53.5, pp. 1121–1133.

Jacob, Dieter, Bernd Kochendörfer, Marcus von Drygalski, and Corinna Hilbig (2014). “Ten years of PPP in Germany: experiences and perspectives”. In: *Proceedings of the ICE-Management, Procurement and Law* 167.4, pp. 180–188.

Jintamanaskoon, Santi and Paul W Chan (2014). “Boundary-making in public-private partnerships: a historical account of the British railway industry”. In: *Proceedings 30th Annual ARCOM Conference*. Ed. by A B Raiden and E Aboagye-Nimo. Association of Researchers in Construction Management, pp. 1295–1304.

Keltner, Dacher and Robert J Robinson (1997). “Defending the status quo: Power and bias in social conflict”. In: *Personality and Social Psychology Bulletin* 23.10, pp. 1066–1077.

Klein, Mark, Hiroki Sayama, Peyman Faratin, and Yaneer Bar-Yam (2003). “The dynamics of collaborative design: insights from complex systems and negotiation research”. In: *Concurrent Engineering* 11.3, pp. 201–209.

Lawson, Bryan (2004). “Schemata, gambits and precedent: some factors in design expertise”. In: *Design studies* 25.5, pp. 443–457.

— (2006). *How designers think: the design process demystified*. 4th. Oxford, UK: Architectural Press.

Lessard, Donald R and Roger Miller (2013). “International Handbook of Mega-Projects”. In: ed. by Hugo Priemus and Bert van Wee. Cheltenham, UK: Edward Elgar. Chap. The shaping of large engineering projects.

Lin, Jijun, Olivier de Weck, Richard de Neufville, Bob Robinson, and David MacGowan (2009). “Designing capital-intensive systems with architectural and operational flexibility using a screening model”. In: *Complex sciences*. Ed. by Jie Zhou. Springer, pp. 1935–1946.

Linsey, JS, I Tseng, K Fu, J Cagan, KL Wood, and C Schunn (2010). “A study of design fixation, its mitigation and perception in engineering design faculty”. In: *Journal of Mechanical Design* 132.4, pages.

Liu, Jicai and Charles YJ Cheah (2009). “Real option application in PPP/PFI project negotiation”. In: *Construction Management and Economics* 27.4, pp. 331–342.

Messick, David M (1999). “Alternative logics for decision making in social settings”. In: *Journal of Economic Behavior and Organization* 39.1, pp. 11–28.

Miller, George A (1956). “The magical number seven, plus or minus two: some limits on our capacity for processing information.” In: *Psychological review* 63.2, p. 81.

Miller, Roger and Donald R Lessard (2000). *The strategic management of large engineering projects: Shaping institutions, risks, and governance*. MIT press.

Montgomery, James D (1998). “Toward a Role-Theoretic Conception of Embeddedness”. In: *American Journal of Sociology* 104.1, pp. 92–125.

NAO (2007). *Improving the PFI tendering process*. Tech. rep. London, UK: National Audit Office, United Kingdom.

Neale, Margaret A. and Max H. Bazerman (1985). “The effects of framing and negotiator overconfidence on bargaining behaviors and outcomes”. In: *Academy of Management Journal* 28.1, pp. 34–49.

Newell, A and H. A. Simon (1972). *Human problem solving*. Prentice-Hall.

Ng, S Thomas, Jingzhu Xie, Yau Kai Cheung, and Marcus Jefferies (2007). “A simulation model for optimizing the concession period of public–private partnerships schemes”. In: *International Journal of Project Management* 25.8, pp. 791–798.

Ortiz, Iris N, Jeffrey N Buxbaum, and Richard Little (2008). “Protecting the public interest: role of long-term concession agreements for providing transportation infrastructure”. In: *Transportation Research Record: Journal of the Transportation Research Board* 2079.1, pp. 88–95.

Osipova, E. (2014). “Establishing Cooperative Relationships and Joint Risk Management in Construction Projects: Agency Theory Perspective”. In: *Journal of Management in Engineering*, p. 05014026.

Ostergaard, Karen J., William R. Wetmore III, Ameya Divekar, Henry Vitali, and Joshua D. Summers (2005). “An experimental methodology for investigating communication in collaborative design review meetings”. In: *CoDesign* 1.3, pp. 169–185.

Pinkley, Robin L, Terri L Griffith, and Gregory B Northcraft (1995). “’Fixed Pie’ a la Mode: Information Availability, Information Processing, and the Negotiation of Suboptimal Agreements”. In: *Organizational Behavior and Human Decision Processes* 62.1, pp. 101–112.

Rahman, M. and M. Kumaraswamy (2004). “Potential for Implementing Relational Contracting and Joint Risk Management”. In: *Journal of Management in Engineering* 20.4, pp. 178–189.

Raiffa, Howard (1982). *The art and science of negotiation*. Cambridge, USA: Belknap Press of Harvard University Press.

Raiffa, Howard, John Richardson, and David Metcalfe (2002). *Negotiation analysis : the science and art of collaborative decision making*. Cambridge, USA: Belknap Press of Harvard University Press.

Raisbeck, Peter (2009). “Considering design and PPP innovation: a review of design factors in PPP research”. In: *Proceedings 25th Annual ARCOM Conference*. Ed. by A Dainty. Nottingham, UK: Association of Researcher Association of Researchers in Construction Management, pp. 239–247.

Raisbeck, Peter and Llewellyn CM Tang (2013). “Identifying design development factors in Australian PPP projects using an AHP framework”. In: *Construction Management and Economics* 31.1, pp. 20–39.

Reiter-Palmon, R, Ben Wigert, and T de de Vreede (2012). "Handbook of organizational creativity". In: ed. by M. D. Mumford. New York: Academic Press. Chap. Team creativity and innovation: The effect of group composition, social processes, and cognition, pp. 295–326.

Roumboutsos, Athena and Stéphane Saussier (2014). "Public-private partnerships and investments in innovation: the influence of the contractual arrangement". In: *Construction Management and Economics* 32.4, pp. 349–361.

Rubin, J.Z. and B.R. Brown (1975). *The social psychology of bargaining and negotiation*. New York: Academic.

Saaty, Thomas L (2008). "Decision making with the analytic hierarchy process". In: *International journal of services sciences* 1.1, pp. 83–98.

Scott, W Richard (2012). "The institutional environment of global project organizations". In: *Engineering Project Organization Journal* 2.1-2, pp. 27–35.

Shan, Liang, Michael J Garvin, and Raman Kumar (2010). "Collar options to manage revenue risks in real toll public-private partnership transportation projects". In: *Construction Management and Economics* 28.10, pp. 1057–1069.

Sharma, Sudeep, William P. Bottom, and Hillary Anger Elfenbein (2013). "On the role of personality, cognitive ability, and emotional intelligence in predicting negotiation outcomes: A meta-analysis". In: *Organizational Psychology Review* 3.4, pp. 293–336.

Siemiatycki, Matti and Jonathan Friedman (2012). "The trade-offs of transferring demand risk on urban transit public–private partnerships". In: *Public Works Management & Policy* 17.3, pp. 283–302.

Simon, Herbert A. (1987). "Making Management Decisions: The Role of Intuition and Emotion". In: *The Academy of Management Executive (1987-1989)* 1.1, pages.

Smyth, H. and S. Pryke (2009). *Collaborative Relationships in Construction: Developing Frameworks and Networks*. cited By 4, pp. 1–253.

Smyth, Hedley and Andrew Edkins (2007). "Relationship management in the management of PFI/PPP projects in the UK". In: *International Journal of Project Management* 25.3, pp. 232–240.

Suprapto, Mohammad, Hans L. M. Bakker, Herman G. Mooi, and Wim Moree (2014). "Sorting out the essence of owner–contractor collaboration in capital project delivery". In: *International Journal of Project Management*.

Thompson, Leigh (1998). *The mind and heart of the negotiator*. Upper Sadddle River, NJ: Prentice Hall.

Thompson, Leigh and Reid Hastie (1990). "Social perception in negotiation". In: *Organizational Behavior and Human Decision Processes* 47.1, pp. 98–123.

Tinsley, Catherine H, Kathleen M O'Connor, and Brandon A Sullivan (2002). "Tough guys finish last: The perils of a distributive reputation". In: *Organizational Behavior and Human Decision Processes* 88.2, pp. 621–642.

Trebilcock, Michael and Michael Rosenstock (2015). "Infrastructure Public–Private Partnerships in the Developing World: Lessons from Recent Experience". In: *The Journal of Development Studies*, pp. 1–20.

Tsay, Chia-Jung and Max H. Bazerman (2009). "A Decision-Making Perspective to Negotiation: A Review of the Past and a Look to the Future". In: *Negotiation Journal* 25.4, pp. 467–480.

Valero, Vanessa (2015). "Government Opportunism in Public-Private Partnerships". In: *Journal of Public Economic Theory* 17.1, pp. 111–135.

Valley, Kathleen L, Joseph Moag, and Max H Bazerman (1998). "'A matter of trust': Effects of communication on the efficiency and distribution of outcomes". In: *Journal of Economic Behavior & Organization* 34.2, pp. 211–238.

Walsh, James P, Klaus Weber, and Joshua D Margolis (2003). "Social issues and management: Our lost cause found". In: *Journal of Management* 29.6, pp. 859–881.

Wettenhall, Roger (2003). "The rhetoric and reality of public-private partnerships". In: *Public Organization Review* 3.1, pp. 77–107.

— (2005). "The challenge of public-private partnerships: Learning from international experience". In: ed. by Graeme A Hodge and Carsten Greve. Cheltenham, UK: Edward Elgar. Chap. The public-private interface: surveying the history, pp. 22–43.

Winch, GM, M Onishi, and S Schmidt (2012). *Taking stock of PPP and PFI around the world*. Tech. rep. London: The Association of Chartered Certified Accountants (ACCA).

Wood, Matthew, Pinzhi Chen, Katherine Fu, Jonathan Cagan, and Kenneth Kotovsky (2014). "Design Computing and Cognition". In: ed. by John S. Gero. Dordrecht: Springer. Chap. The Role of Design Team Interaction Structure on Individual and Shared Mental Models, pp. 209–226.

Woodhouse, Erik J (2005). "The Obsolescing Bargain Redux: Foreign Investment in the Electric Power Sector in Developing Countries". In: *NYU Journal of International Law and Politics* 38, p. 121.

Yuan, Jingfeng, Alex Yajun Zeng, Miroslaw J Skibniewski, and Qiming Li (2009). "Selection of performance objectives and key performance indicators in public–private partnership projects to achieve value for money". In: *Construction Management and Economics* 27.3, pp. 253–270.

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Chapter 2

Co-Design for P3 Projects

This chapter discusses the potential of co-design, the simultaneous technical and contractual design for an infrastructure P3. Technical design dimensions include technology, production capacity, modularity (number of phases), fuel switching options, and other features of the project artifact itself. Contractual design dimensions are aspects of the governance arrangement between the partners such as concession length, payment frequency, unit price terms, lump sum transfers, risk guarantees, contingency arrangements such as take-or-pay transfers. The large number of design dimensions and their interacting combinations make it likely that constraining one or more of these factors early on in the design process may lock-out design possibilities of interest. The discussion therefore makes the case that co-design is important in an uncertain world because it enables project actors to avoid screening out designs that balance value trade-offs. Through co-design, these project concepts stay on the table for further exploration. Connecting the project design to value trade-offs sets up project actors for a later negotiation of design decisions.

The chapter begins (Section 2.1) with a simple general example to show that performance of an infrastructure P3 has different dimensions of value, and that both technical and contractual variables of the P3 project interact to affect performance. Section 2.2 then summarizes the formulation of a computational model to investigate the co-design hypothesis. A large-scale desalination project P3 is the case subject for the model. The specific co-design dimensions tested for desalination are the project capacity and degree of modularity in the technical domain, as well as the unit water price and minimum revenue guarantee in the contractual domain. Section 2.3 ends the chapter with a summary of the model's results that demonstrate performance trade-offs revealed through co-design.

2.1 Why co-design?

This section explains how co-design can have the potential to reveal important value trade-offs for project participants. A simple hypothetical example of a project design problem supports the arguments. The discussion covers the interaction between technical design configurations and contract choices. It then expands the notion of performance into more than one dimension, based on the project actors involved. Relating designs to value along different dimensions sets up the possibility for negotiated design decisions.

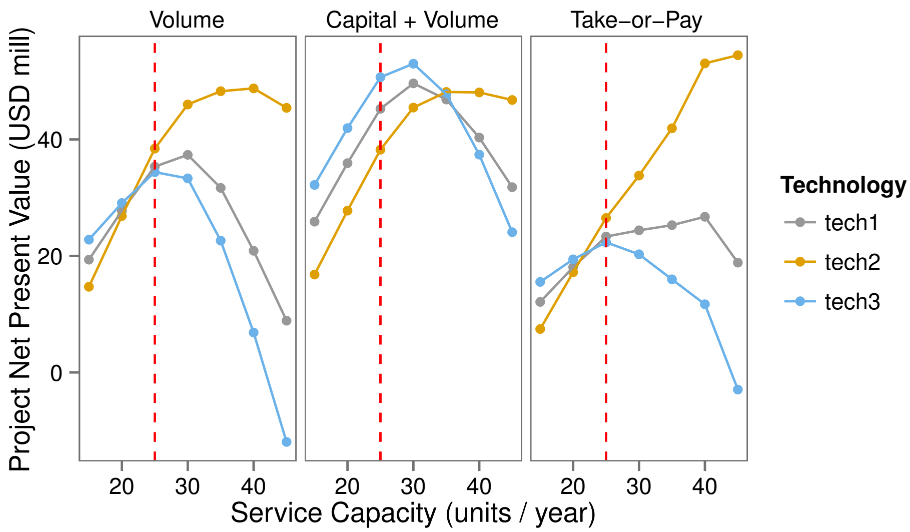
Consider a simple example of an infrastructure facility that provides a related service. The project has a number of design dimensions. Its output capacity (units / year, for example) can vary, thereby increasing or decreasing how much demand it can meet in an increment of time. Three different technologies (*tech1*, *tech2*, or *tech3*) are available to provide the same service. The project can install any one of these three. Assuming that they are identical in their performance attributes, the project is indifferent among them, except for their cost parameters. Each of the technologies has different capital and operating costs. The project will receive fixed-price volumetric payments, i.e a fixed price for every unit of service it provides over its lifetime. Given this context, how much service capacity should the project install and which technology should it use?

Uncertain demand makes the design choice non-trivial. If the project actors were to know the forecast of demand for the facility's services with certainty, they can select the project's capacity and technology in a relatively straightforward way. When demand is variable, the project's performance outcomes will also be variable. Project actors should select a configuration that promises to deliver the highest expected performance (probabilistic) over its design life.

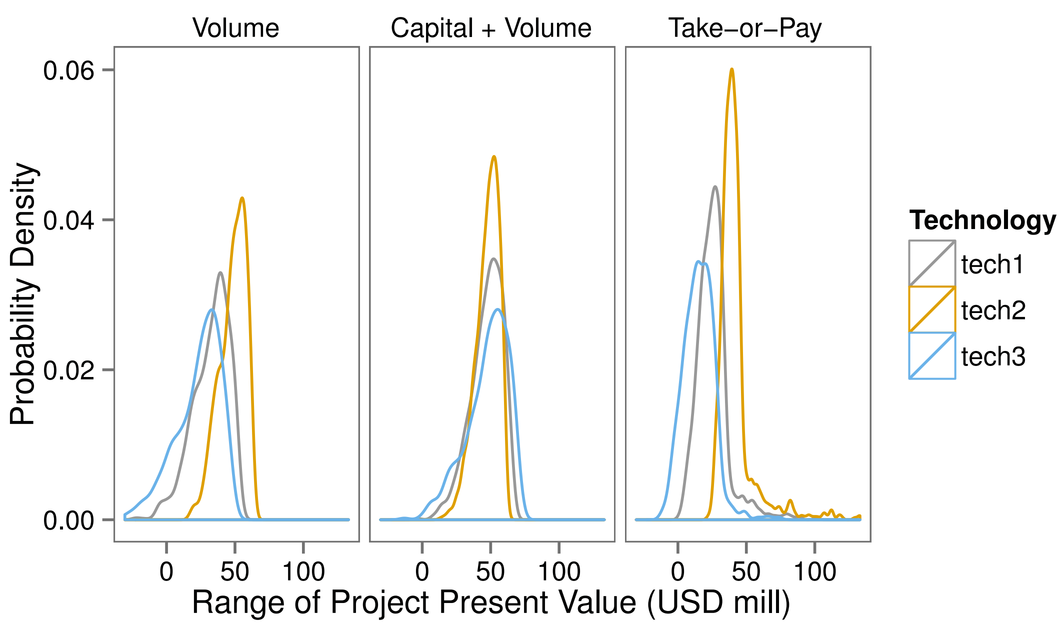
We can perform analyses to identify such a configuration. Figure 2.1 illustrates the results of this hypothetical setup. The leftmost panel in the upper half of the figure, Figure 2.1a, covers the basic example of volumetric payments introduced above. The panel shows expected performance in the form of Net Present Value (NPV) curves for each of the three technologies over a range of service capacity levels, under demand uncertainty.

This plot clearly shows that expected NPV depends not only on technology but also the service level. Going from left to right for each technology, NPV increases as the project's service capacity increases. NPV eventually peaks before it begins to decrease at very high capacity levels. The red dashed line marks the initial level of demand at the time the projects begins operation (25 units/year). Configurations to the left of this line are NPV positive, however they are small and do not meet much of the demand. This is reflected in the relatively low NPVs because payments to the project depend on the service level it delivers. Also, *tech3* provides higher NPV, and dominates other technologies for low service levels. To the right of the dashed line, the *tech2* delivers the highest expected NPV at a service level of 40 units/year. {*tech2*, 40 units/year} is the expected NPV-maximizing configuration given this simple setup of a volumetric payment under a fixed-price contract.

The expected NPV-maximizing configuration changes if the contract structure changes. The center and rightmost panel serve to show this effect. The center panel shows the NPV curves for a 'Capacity+Volume' contract where the project receives a small percentage of its upfront capital cost as a capacity availability payment in addition to the volumetric payment from the previous case. The choice of configuration should now shift to {*tech3*, 30 units/year}. In the panel on the right, a 'Take-or-Pay' contract changes the picture yet again. This structure insures the project



(a) An analysis of a project's expected performance under demand uncertainty for three different contract structures. The project's expected Net Present Value (USD mill) depends on the choice of technology as well as the project's service capacity (units/year). Further, no single configuration (choice of technology+service level) dominates because expected performance also depends on the contract structure.



(b) Project performance profiles for a configuration with a service level of 35 units/year. Expected Net Present Value (USD mill) is variable because of underlying demand uncertainty. Both the choice of technology and contract structure shape the distribution of performance.

Figure 2.1: Results of a general example to illustrate the perspectives of co-design. Average performance (expected NPV) and the project risk profile (distribution of NPV) both depend on the project's technical configuration as well as contract structure under conditions of uncertainty.

during low demand levels. It receives a stipulated level of payments if demand falls below a certain threshold, and otherwise receives a volumetric payment as in the basic setup. Under this structure, the configuration {*tech2*, 45 units/year} should be chosen.

The analysis in Figure 2.1a has thus demonstrated that a project's expected performance depends on both its technical configuration as well as its contract structure under conditions of uncertainty. No configuration dominates, and the choice of design is contingent on the contract structure and background conditions.

How does this type of insight avoid lock-out, or screening out designs that project actors may want to retain under consideration? The center panel showing the results for the Capacity+Volume contract is helpful in exploring this further. Consider a traditional project procurement process where the contract structure is specified along with the service delivery level of 35 units/year. In this 'over-specified' configuration, the project should be indifferent to the choice of technology since all three have the same expected NPV at this service level. However, decreasing the stipulated service level slightly to 30 units/year enables the NPV-maximizing configuration using *tech3*. On the other hand, increasing the service level to 40 units/year requires the use of *tech3* to realize a similar expected NPV as in the over-specified case. Further, if project actors preferred configurations with *tech2*, then a different contract structure ('Take-or-Pay') can raise the *tech2*, 40 units/year project's expected performance to a similar level as the expected NPV-maximizing configuration under the Capacity+Volume structure. This type of iterative analysis helps us understand how a project's technical configuration interacts with its contractual framework to shape performance under uncertainty. Project actors should therefore look across not only technical configurations under one contract formulation but also across contract structures. This systematic and iterative analysis is the process of co-design.

Co-design also helps to understand project performance as a risk profile. The example has thus far discussed performance (NPV) in expected terms, and the suggested design configurations are based on average performance. In fact, probabilistic distributions of performance underlie the expected NPV (average) results shown in Figure 2.1a because demand for service is uncertain. The set of panels in Figure 2.1b document illustrate distributions of performance. The three panels correspond to the three different contract structures, as before. The project considers the same three technologies which are different from each other only in their capital and operating costs. The range of project present value is the performance distribution for a 35 units/year service level, since this level of capacity was found to generate high expected NPV results as shown in Figure 2.1a.

Even configurations with high expected NPV outcomes have some chance of negative NPV under uncertainty. The results for Volumetric and Take-or-Pay contracts show the positive probability of less than zero NPV. The configuration with *tech3* is more prone to negative NPV outcomes because of its costs relative to other technologies and the contract price levels.

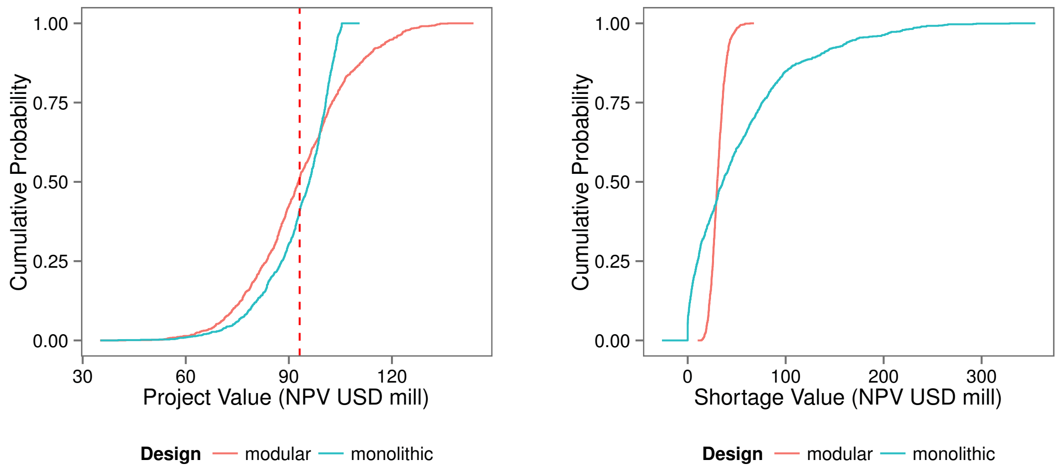
Contract structure can alter project risk profiles. The panel for the Capacity+Volume contract shifts the performance probability distributions to the right for *tech1* and *tech3*, which are more capital intensive technologies relative to *tech2*. Similarly, the Take-or-Pay contract stretches out the right-tails of the performance distributions compared to the Volume and Capacity+Volume contracts. The possibility of some very high NPV outcomes is what effectively raises the expected NPV levels of project design configurations with *tech2*.

Project performance has more than one dimension. The discussion of average performance as well as distributions of performance, i.e risk profiles, has thus far addressed project performance as a unidimensional construct. In reality, however, project actors focus on different measures of value, and make choices based on outcomes that affect them directly. In the hypothetical example we have been developing here, the project receives payments based on its service level under uncertainty. Designs with low service levels may have high NPVs, but they also result in a higher degree of unmet demand (or shortages). The client that is 'taking' service from the project and making payments to it may be highly sensitive to the reliability of service, measured as the value of shortage in service. Performance should therefore be construed more broadly and reflect the value dimensions of the project participants.

Co-design reveals the trade-offs of value to project actors along different dimensions as a consequence of both technical design choices and contractual structure. We now look at two value dimensions - project value (expected NPV) and the value of service shortages. Project value here is a measure of performance for the private owner and operator of the infrastructure facility. The private firm contracts with a client who wants reliable service. In other words, the client will prefer project design configurations that will reduce the value of service shortages.

Continuing the example from above, consider a project with two different possible configurations, both using the same technology under the basic volumetric contract structure. One technical design configuration is a small monolithic facility - it has low service capacity (ex. 50 units / year) which is fixed (single phase) and cannot be changed over its design life. The second plant is a large modular facility. This design is flexible in that it has a high potential service capacity (ex. 200 units / year) which can be built out in a number of phases (ex. 10 modules of 20 units / year each). Both these design configurations are found to have a very similar expected NPV outcome, as shown in the left panel of Figure 2.2a. The red dashed line denotes the average performance. Their performance risk profile is also similar. Since the value outcomes of the two configuration are similar, both on average and also in their distribution, the private firm is largely indifferent to the two. It is plausible that the private firm may prefer the small monolithic design because it can be delivered at once, whereas the large modular facility will require the effort of multiple expansions over time.

The client's view of the two possible configurations shows dramatically different value outcomes, on average as well as in their distribution (Figure 2.2b). The small monolithic design has a high probability of very large shortages under demand uncertainty. On the other hand, the large modular design truncates the shortage risk profile significantly. The client will prefer the large modular configuration, because of its own direct value dimension of reliability. The eventual project design will thus have to trade-off value to the private firm along the project value dimension with shortage value to client along the reliability dimension.



(a) The distribution of project value (NPV) is similar for the monolithic and modular configurations under an assumed contract structure. The red dashed line shows the same expected NPV of USD 92 mill for each.

(b) The risk of shortage is dramatically different between the two configurations. The modular design truncates much of the shortage risk relative to the modular design for the same contract structure.

Figure 2.2: Project design configurations can have different implications for value, depending on the project actor's view and value objective.

Technical design configurations and contract structure can thus reveal and help shape value trade-offs. Both average performances and risk profiles are important ways to assess value outcomes. The issue of trade-offs foreshadows the need for project actors to systematically co-design by iterating over possible design choices and negotiated design decisions to balance these trade-offs.

2.2 Tradespace Model

A general example above helped clarify the potential of co-design and how to relate performance to the views of participating project actors. In infrastructure P3s, the design conversation revolves around the project concept for a proposed facility. Project actors can benefit from a systematic evaluation of design alternatives for the project under active consideration. For this reason, we select a specific case example to make the discussion and results more tangible than in the general example above. This section thus demonstrates how to evaluate a specific project through co-design. The demonstration looks at the particular case of designing a large desalination facility under a P3 arrangement.

Desalination is a suitable example because most desalination projects are stand alone; they are not networked through transmission grids as in the case of power plants. In other words, the system boundary can be limited to the project itself and the actors participating in that project. [1] Many arid and water stressed countries are investing significant capital in desalination facilities, and the trend is likely to continue as a water resource management response. The choice of desalination is therefore timely and topical. Appendix A contains some supporting descriptive statistics on desalination investment trends that provide a sense of the importance and scale of this domain. A final reason for the choice of desalination is that engineering methods for desalination are well studied yet there are few studies that have considered contractual aspects of the design and delivery of such facilities. The opportunity for innovation is presented by the considerations of co-design, the *joint* choices of technical and organizational / institutional design. The Kingdom of Saudi Arabia is a a good example. Although it has been a world leader in the design and operations of large desalination facilities for many decades, only recently have the National Water Company and the Saline Water Conversion Corporation embarked on a systematic effort to partner with private sector firms that are at the frontier of technology development as well as project integration and delivery techniques.

2.2.1 Design problem: a desalination P3

For the purpose of co-design demonstration, we formulated a stylized design problem that resembles a real-world project design context, but is more abstract and general. The problem involves the conceptual design of a desalination project P3. Figure 2.3 depicts the structure of the problem.

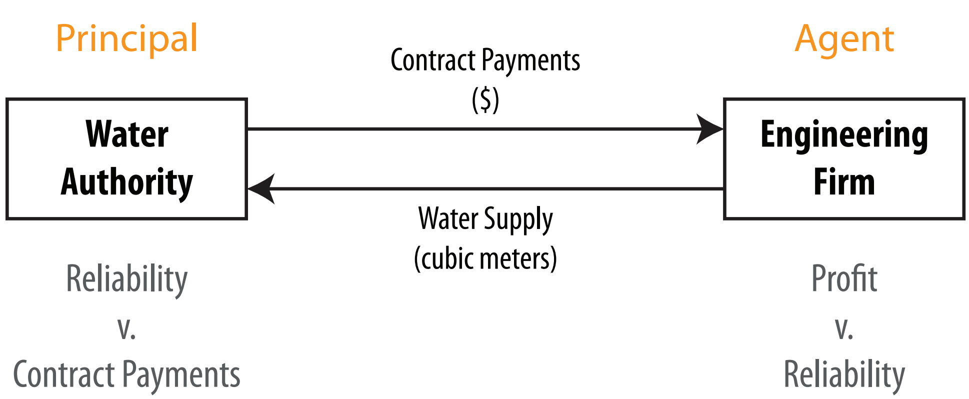


Figure 2.3: A desalination P3 project as a case example for the subsequent development of the co-design tradespace model. The water authority is the principal that enters into a long-term concession contract with the agent, an engineering firm, for reliable water supply. The principal trades-off value in terms of contract payments for reliability whereas the firm trades reliability for profit.

[1]This demonstration could have also selected other types of infrastructure P3s. Toll roads are another suitable example.

There are two project actors: a public sector entity (the principal) and an engineering firm (the agent). The principal and the agent are entering into a long-term concession contract in which the principal will compensate the agent for a service it provides. In the chosen setting, the principal is a pubic water authority entering into a long-term Water Purchase Agreement (WPA) with an engineering firm. The firm will build and operate a large-scale desalination facility to supply treated water to the public authority. This is a relationship-specific investment, i.e. the agent firm would not invest in and operate this facility without the assurance of a contract with the water authority.

Each of these actors has different objectives and perceives the value of designs correspondingly. The principal wants to ensure the public interest. As a water authority, it desires reliable water supply and is willing to make contractual payments in return. It trades off payments for reliability. On the other hand, the agent's objective is profit. It is willing to deliver a reliable water supply for profit. The firm trades off reliability for profit. There are thus three ways to express value in these problem, in the three dimensions of contractual payments (water authority's view of the problem), profit (firm's view of the problem), and reliability which trades off the other two and links the outcomes to both the principal and the agent.

The technical configuration affects how the project creates value. The desalination facility uses energy to transform saline water into potable water. Since water is valuable to society the water authority (as a proxy for society) benefits from water supply. Under conditions of demand uncertainty, the reliability of the project is its ability to deliver water as and when demand arises over time. Some design configurations may be more reliable than others.

The long-term concession agreement creates a mechanism for the exchange of value. It provides the project with a structure to link the decisions of the two project actors. It also that governs how risk affects the principal and the agent. For example, the contractual price terms and other provisions determine the payments that the water authority makes to firm. The contract may also include risk allocation mechanisms such as a take-or-pay structure to accommodate the demand risk to which the project is exposed.

The specific co-design dimensions tested for desalination are the project capacity and degree of modularity in the technical domain, as well as the unit water price and minimum revenue guarantee in the contractual domain. Each of these dimensions presents difficult choices even when considered individually because of considerations such as demand uncertainty, energy price volatility or shifts in industry structure, changing regulations, etc. Clubbing the dimensions together makes the design problem more complex because of non-linear interactions.

In this sense, the co-design problem involves both value creation through technical design and value exchange through contract design. As the first chapter explained in depth, both academics and practitioners often treat these two types of design separately. Here we use the case of desalination to demonstrate how design shapes value creation and exchange with the use of a tradespace model.

2.2.2 Tradespace model architecture

A tradespace model visualizes how changes in design result in trade-offs in different dimensions of performance (McManus et al., 2007; Ross et al., 2010). In the desalination project design problem, we must address three challenges to be able to identify value trade-offs through co-design. The first challenge is to make uncertainty explicit, the second is to determine the structural relationships between design variables, and the third is translate design to a visual interpretation of performance. The model architecture that addresses these three challenges is shown in Figure 2.4.

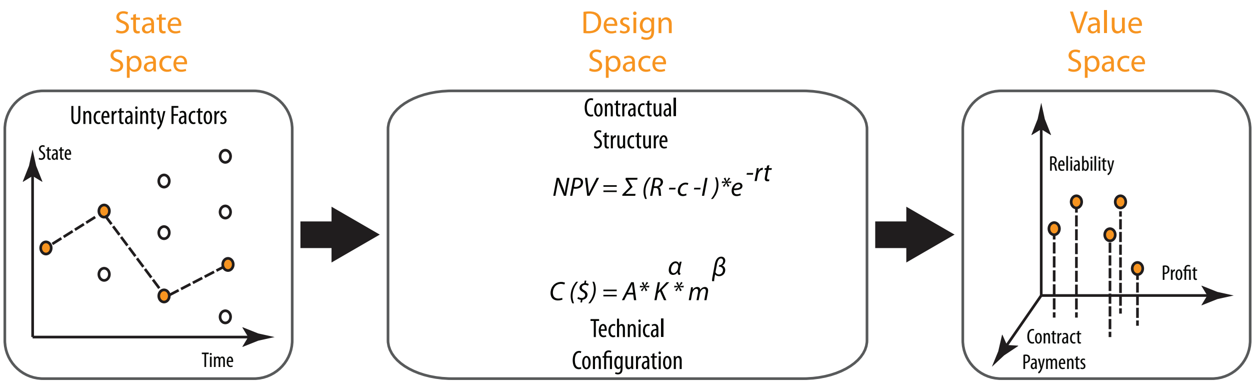


Figure 2.4: The tradespace model architecture develops and links the two constructs of an uncertainty state space and a design space to a value space, the third construct. These three components enable project actors to identify and relate design alternatives to value trade-offs under uncertainty.

- **State Space**: The state space represents uncertain 'states of the world' over a time horizon of interest. It makes explicit the background uncertainties that create risk for the project. As Section 2.1 illustrated, project performance is variable because of risk factors such as demand uncertainty. The state space enables us to model these risk factors and study how they affect project performance for different design alternatives. The state space component of the tradespace model is on the left in Figure 2.4, showing a schematic of states of the world evolving over time in an uncertain manner.

  In the desalination project design problem, the state space models two risk factors: (i) uncertain water demand, and (ii) volatile input energy prices. Monte Carlo simulation techniques create the states over time in the state space. The modeling approach is outlined in Section 2.2.3.

- **Design Space**: The design space specifies the structural relationships and parameter values for the project design concept. The technical configuration of the facility includes design variables such as technology, potential output capacity, and number of modules for flexible design. The design variables in the structure of the contract include the price terms for service level, and any risk sharing mechanisms such as minimum income guarantees and revenue caps under a take-or-pay structure.

In the desalination facility design problem, the model evaluates four mainstream technology options of electrodialysis, reverse osmosis, multi-stage flash and multi-effect distillation. Both monolithic (unphased) and modular (phased) configurations are available for the option of flexible design. Statistical analysis of a large dataset of real facilities gives the parameter values (Section 2.2.4). The model evaluates technical design under two different contract structures - a fixed-price volumetric contract with no risk sharing mechanism, and a take-or-pay contract with the option of income guarantees and revenue caps which shares risk between the water authority and the firm. A few key papers in the contracts literature, discussed in Section 2.2.5, inspire the choice of contract form in the tradespace model.

- **Value Space**: The value space visualizes the different value dimensions on which project actors focus. It is a multi-dimensional space that plots the value outcomes of many possible design configurations. In the P3 context, the principal focuses on contract payments to the agent firm. The agent is ultimately motivated by the profit outcomes of its choices under the concession contract. In addition to these two economic value dimensions, a third technical dimension such as reliability is a trade-off that links both the principal and agent. The value space component on the right in Figure 2.4 conceptually shows the multi-dimensional value outcomes of project design configurations interacting with the contract structure. A multi-objective optimization analysis gives the the value trade-offs along these dimensions.

  For the desalination project, the value space helps the principal water authority to address questions such as: "*what level of reliability is available in return for a given level of contract payments?*" and "*how much does reliability increase (decrease) with a certain increase (decrease) in payments?*" Similarly, the agent engineering firm can ask: "what level of reliability can the project deliver at a given profit?" and "*how much does profit decrease (increase) with a specified increase (decrease) in reliability?*"

The tradespace model thus links a series of models to ultimately determine the value outcomes of designs. [2] The rest of this section summarizes how the tradespace model architecture was implemented. The appendices provide supporting information and technical details.

2.2.3 State space: modeling risk

An infrastructure P3's expected performance depends on its risk-profile. A number of risks affect the project at the center of infrastructure P3. These risk factors affect investment choices, project operations, and shape the project's performance profile. For example, demand risk for the project's services are a major influence on its performance, as discussed in Section 2.1. Toll road P3s are an example of infrastructure P3s that are especially vulnerable to traffic demand risks because the concessionaire's revenues depend on the number of vehicles that transit through toll

[2] Laughton, Guerrero, and Lessard (2008) have also proposed a similar linked-model approach for dynamic asset valuation to clearly separate the factors of decision alternatives, uncertainty, cash flows, and valuation. Their emphasis is on market-based valuation however.

collection gates. The operations of power plants and desalination facilities is also sensitive to changing price of inputs such as energy and materials. To understand a project's performance profile, we must model its exposure to the relevant risk factors.

The statespace component of the tradespace model assumes that two risk factors affect desalination projects over their life. The first is uncertain water demand and the second is volatile energy prices. Water demand from desalination is uncertain in the short-term because of weather fluctuations and seasonal variation in consumption. In the longer term, population growth, and economic activity influences water demand. Here we only focus on the variability of demand over a long-time horizon. The model is agnostic to the causes of demand variability. Energy prices are volatile because energy markets equilibriate frequently to reflect the underlying supply and demand dynamics. There are many reasons for volatile demand, and many factors and constraints that govern energy supply. Once again, the model here focuses on the price volatility, and ignores underlying market dynamics. Both water demand and energy prices are therefore exogenous to the project.[3] In this subsection, I summarize the formulation of the state space and show examples of simulated states of the world.

Demand Risk: The risk model formulation applied to uncertain water demand is general. Let X_t denote the demand for an infrastructure service at time t. Then uncertain demand can be modeled as a random walk, a continuous stochastic process using Geometric Brownian Motion (Brennan and Schwartz, 1985; Paddock, Siegel, and Smith, 1988) :

$$d[ln(X_t)] = ln(\frac{X_t}{X_{t-1}}) = \mu dt + \sigma dz \tag{2.1}$$

where
$d[ln(X_t)]$ is the instantaneous return to the stock variable X_t
μ is the drift, or continuous growth rate
σ is the volatility in growth
dz is the Brownian motion parameter, signifying that the underlying variation is normally distributed

If R_t is the cumulative return across the time horizon $[t_0, t]$, and X_0 is the initial stock value at t_0, then the stock value X_t at time t is

$$X_t = X_0 e^{R_t} \tag{2.2}$$

[3]There are many other risks that affect infrastructure projects, which this model does not address. These include construction risk, market risk for other input materials such as steel, and geopolitical and sovereign risks which are present in the project's environment. Miller and Lessard (2001) describe these in detail and Lessard, Sakhrani, and Miller (2014) relate them to project outcomes.

The state space component of the tradespace model uses a discretized version of the continuous stochastic process in a Monte Carlo simulation. The per period growth rate is $m = \mu\Delta t$ and the per period volatility is $\nu = \sigma\sqrt{\Delta t}$. Then Eq (2.1) becomes $R_i = m + \nu\varepsilon_i$, where ε_i is a draw from a standard normal distribution. Further, the cumulative return R_t across the horizon $[t_0, t]$ is $R_t = \sum_{i=0}^{t} R_i$. This result can be substituted in Eq (2.2) to calculate X_t at any time t.

The Monte Carlo simulation generates random walks using this formulation. Beginning with the same initial conditions X_0, the simulation creates a very large number (for ex. 1,000; 10,000; or 100,000) of evolutionary paths for the stock variable X. Figure 2.5a below shows an example of a stochastic simulation of uncertain demand. Water demand (units: m^3/d) is the uncertain stock variable with $X_0 = 5,000 m^3/d; \mu = 2\%/year; \sigma = 4\%/year$, and it evolves over a long time horizon shown on the horizontal axis. The figure plots every realization of demand in the simulation on the vertical axis. These represent the "states" of water demand. The darkness of each state in the figure indicates its frequency, the number of times a random walk crossed that state at an instant in time. The black lines show the $5^{th}-, 50^{th}-$ (median), and 95^{th}-percentile values of water demand over time. The lines diverge over time, because risk in this formulation is a function of time as well as random changes in the stock value. Water demand is therefore more uncertain further out in the forecast horizon.

Energy Price Volatility: The energy price model for the state space simulation is a general mean-reverting process (Gibson and Schwartz, 1990; Schwartz, 1997) The economics literature on commodity price and energy modeling has extensively debated whether a mean reverting model is more suitable than another stochastic models. The mean reverting model is adequate for the state space component of the tradespace model, since the purpose is to demonstrate the potential of co-design under uncertainty.

The specific version of mean reversion used here is a Geometric Ornstein-Uhlenbeck process (Dixit and Pindyck, 1994). This formulation models the log of prices so that they do not fall below zero. The model is written as:

$$d[ln(P_t)] = ln(\frac{P_t}{P_{t-1}}) = \lambda(\mu - P)dt + \sigma dz \tag{2.3}$$

where
$d[ln(P_t)]$ is the instantaneous return to the price variable P_t
λ is the rate of mean reversion
μ is the level, or the long-run mean to which the process reverts
σ is the volatility in growth
dz is the Brownian motion parameter, signifying that the underlying variation is normally distributed

If R_t is the cumulative return across the time horizon $[t_0, t]$, and P_0 is the initial price value at t_0, then the price value P_t at time t is

$$P_t = P_0 e^{R_t} \tag{2.4}$$

The state space once again uses a discretized version of the continuous mean reverting model in a Monte Carlo simulation. The model needs three parameter values to simulate energy prices: the long-run mean of prices, the rate of mean reversion, and the volatility in prices. The parameter values are obtained from regressing this equation on an empirical series of energy prices.

The OPEC basket of oil prices is used, since there are many desalination facilities in the Arabian peninsula. The OPEC series is thus a proxy for the local energy price, and a realistic assumption for the state space model for desalination projects. The regression model and simulation is documented in Appendix B. Once the cumulative return R_t across the horizon $[t_0, t]$ is found, this result can be substituted in Eq (2.4) to calculate P_t at any time t.

The Monte Carlo simulation creates a very large price series based on the empirical parameters. Figure 2.5b shows an example of the mean reverting process for 1,000 paths. Each of these series has a long run mean of μ=\$115 per barrel of oil. The reversion rate λ is 0.3 per period and the volatility is 0.27/period in this example. The three black lines for the $5th-, 50th-$, and $95th-$ percentile levels of oil price show how most of the probability weight is concentrated in the lower part of the figure.

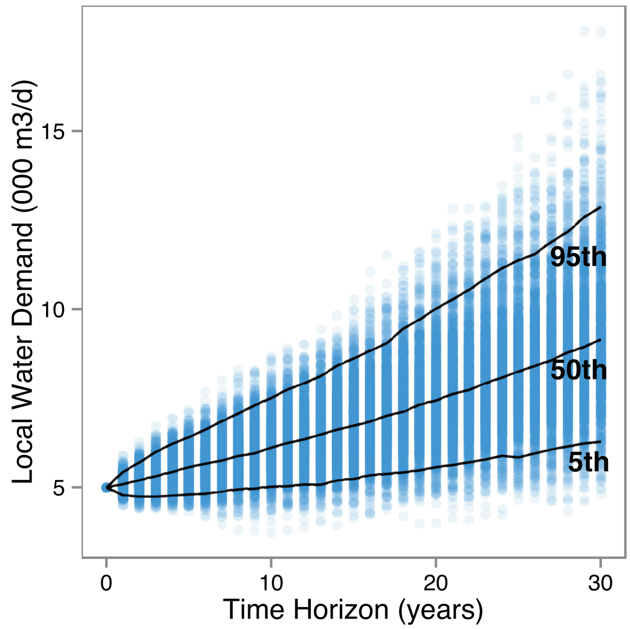
Bivariate State Space: The state space now has two models of risk, one for water demand and the other for oil prices. Both these risk factors affect plant performance. With the state space available, the tradespace model can evaluate (co) designs of both technical plant configurations as well as contractual structures in the design space. The next two subsections briefly discuss the technical and contractual aspects of the model formulation.

2.2.4 Design space: plant technical attributes

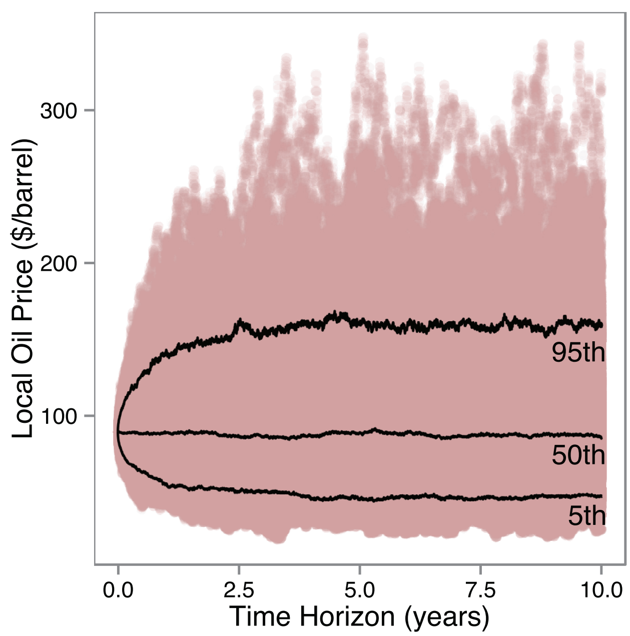
At the concept level of design, project actors must address the choice of technology, and architectural configuration of the facility in terms of its production capacity and modularity. The project's capital cost is related to these choices. The tradespace model will eventually relate design choices to both economic and technical value outcomes, so understanding the cost relationships is important for parameterizing the tradespace model.

As a first approximation, a plant's capital cost scales with its production capacity. I posited that the capital cost of a desalination facility can be modeled as a cost function of the form shown by Eq (2.5). This is consistent with other analyses of capital cost in desalination and other infrastructure sectors.

$$C = A \cdot K^{\alpha} \tag{2.5}$$



(a) A Monte Carlo simulation of 1,000 random walk series with d_0: 5,000 m3/d of initial demand at a location, mean growth rate μ: 2%/year, and volatility σ: 4%/year. The center line is the median level of demand in a given year, with the lower 5th percentile and upper 95th percentile confidence intervals.



(b) A Monte Carlo simulation of 1,000 mean reverting series with long-run price mean of $115 per barrel of oil, reversion rate λ: 0.3/period and volatility σ: 0.27/period. The center line is the median level of oil price, with the lower 5th percentile and upper 95th percentile confidence intervals.

Figure 2.5: Modeling uncertain water demand as a random walk process (Geometric Brownian Motion)(top) and volatile energy prices as a mean reverting process (bottom).

where

C - plant capital cost ($)

K - plant production capacity (cubic meters per day - m3/d)

α - output elasticity of production capacity

To estimate these parameters, I obtained a large data set of over 10,000 desalination facilities constructed globally between 1980 - 2013.[4] After cleaning and sorting the data, I was left with N=7,642 plants worldwide. Most of the plants in the dataset belong to four mainstream desalination technologies. Two of these technologies use mechanical processes, and the others are based on thermal processes:

1. Electrodialysis (ED): an electromechanical technology that separates electrostatically charged solutes in water (n=674 plants).

2. Reverse Osmosis (RO): a mechanical technology that separates dissolved solids by using pressure to pass water through a porous membrane (n=6,107 plants).

3. Multi-effect Distillation (MED): a thermal technology that distills water through evaporation and condensation (n=665 plants).

4. Multi-stage Flash (MSF): another thermal technology that uses the distillation or flashing process (n=196 plants).

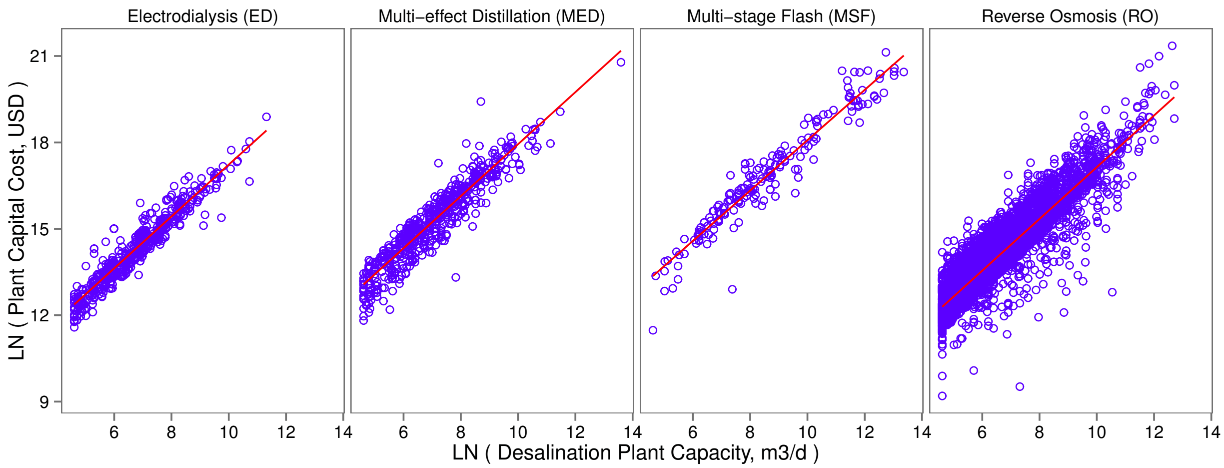
Some other important dimensions of the dataset are the total plant capacity, number of modules, award year, commissioning year, plant capital cost, and raw water or feedwater type.

I fit the hypothesized model to the data with linear regression. Since there are many small plants and a lower number of very large facilities, a logarithmic transformation of Eq (2.5) provides the best linear fit. This log-linear version of the model is written as

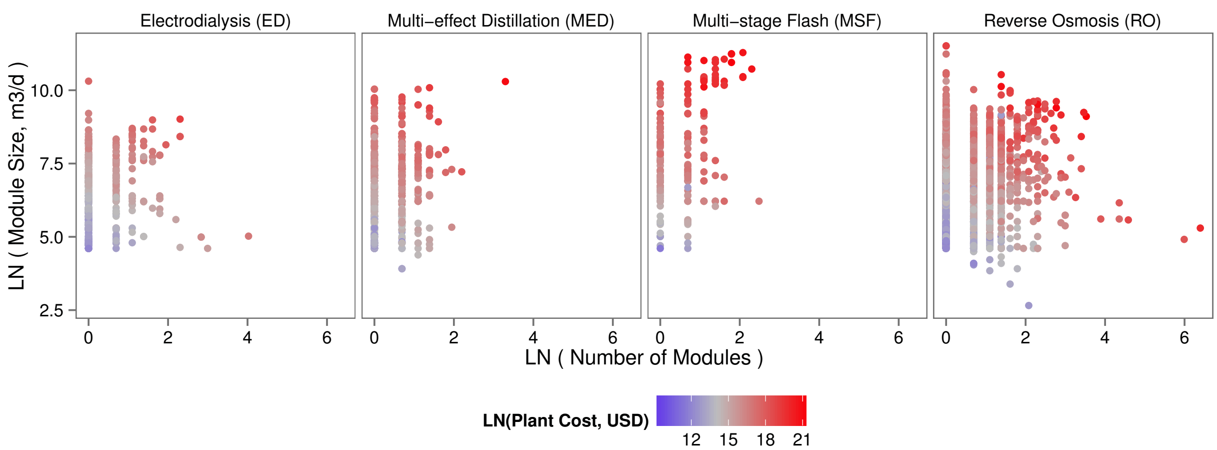
$$\ln(C) = \ln(A) + \alpha \cdot \ln(K) \tag{2.6}$$

The first term on the right hand side is thus the intercept in the linear fit, and the exponent α is the slope. Figure 2.6a depicts this analysis. The large number of observations is easier to visualize using separate panels for each mainstream technology. The RO technology has a large number of observations, an order of magnitude higher than the others. The range of production capacity is similar across all technologies. The cost relationships are comparable as a result. Table 2.1 summarizes the model fit. Model (1) shows the values of α, the coefficient of the plant capacity term, and the different intercept values $\ln(A)$ for each technology. This fit is a good first order approximation for the capital cost of a desalination facility based on its production capacity and technology. However, the other plant attributes available in the dataset could help explain more of the variation in data in Figure 2.6a.

[4]This data set is the IDA Desalination Inventory available by subscription from Global Water Intelligence (2014).



(a) Plant capital cost ($) as a function of plant capacity (m/3d), grouped by desalination technology. In Log units.



(b) Plant capital cost ($) as a function of unit size (m/3d) and number of units, grouped by desalination technology. In Log units. Cost is shown using the color index as a third dimension.

Figure 2.6: Exploring the relationship between plant capital cost and plant attributes – plant capacity, unit size, and number of units

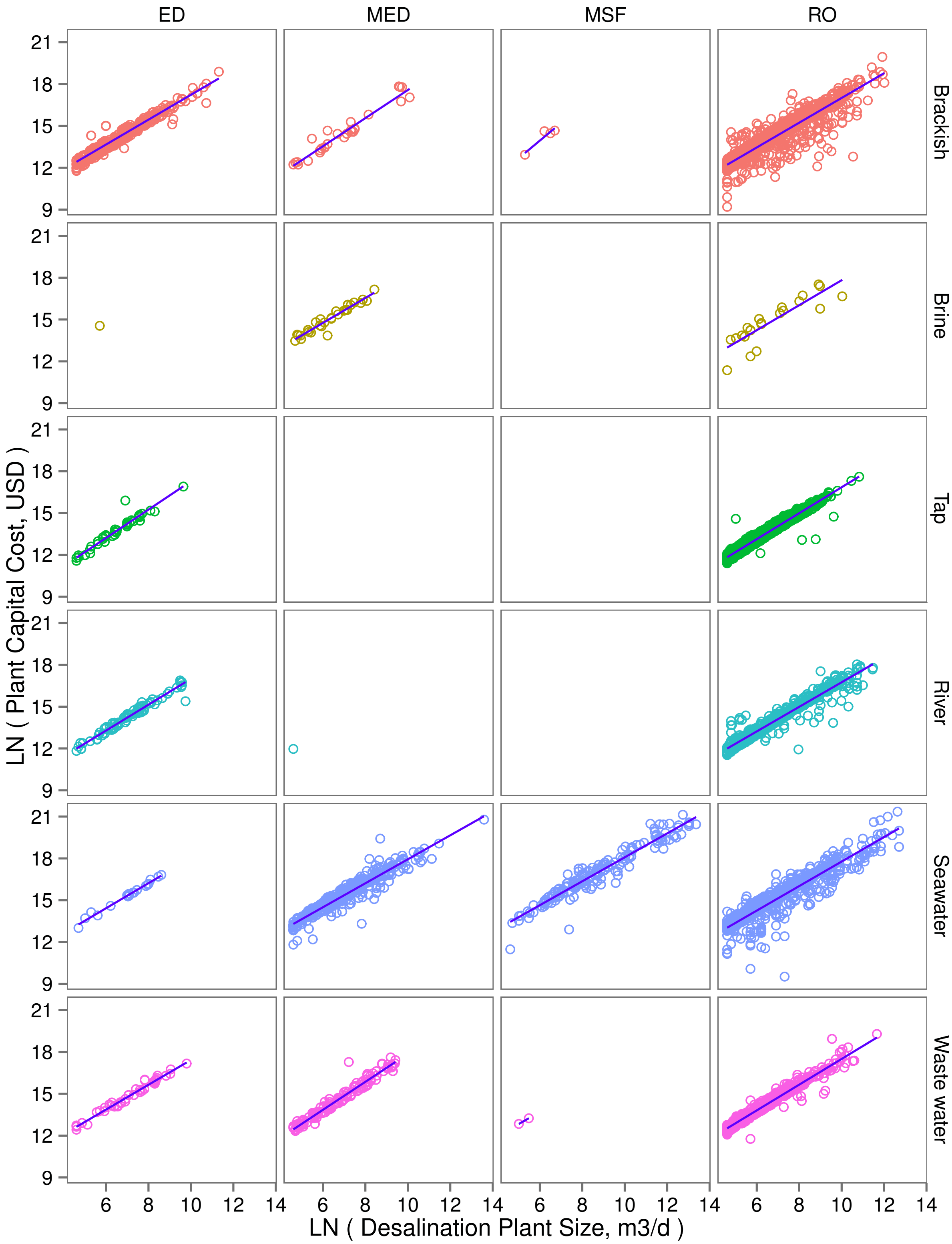


Figure 2.7: Plant capital cost ($) as a function of plant capacity (m3/d), grouped by desalination technology and feedwater quality. In Log units.

Table 2.1: Linear fits for the log-transformed capital cost model

	Dependent variable:		
	LN [Plant Capital Cost ($)]		
	(1)	(2)	(3)
LN [Capacity, m3/d]	0.898^{***}	0.892^{***}	
	(0.004)	(0.003)	
LN [Module Size, m3/d]			0.883^{***}
			(0.004)
LN [Modules, number]			0.923^{***}
			(0.009)
Electrodialysis	8.243^{***}	8.289^{***}	8.336^{***}
	(0.035)	(0.027)	(0.030)
Multi-effect Distillation	8.946^{***}	8.313^{***}	8.361^{***}
	(0.036)	(0.030)	(0.033)
Multi-stage Flash	9.133^{***}	8.414^{***}	8.466^{***}
	(0.053)	(0.042)	(0.045)
Reverse Osmosis	8.160^{***}	8.108^{***}	8.153^{***}
	(0.029)	(0.022)	(0.026)
Brine (TDS >50000ppm)		0.958^{***}	0.958^{***}
		(0.057)	(0.057)
Tap water (TDS <500ppm)		-0.310^{***}	-0.310^{***}
		(0.015)	(0.015)
River water (TDS 500ppm - <3000ppm)		-0.253^{***}	-0.253^{***}
		(0.016)	(0.016)
Seawater (TDS 20000ppm - 50000ppm)		0.792^{***}	0.788^{***}
		(0.014)	(0.014)
Wastewater		0.333^{***}	0.333^{***}
		(0.020)	(0.020)
Observations	7,642	7,642	7,642
R^2	0.999	0.999	0.999
Adjusted R^2	0.999	0.999	0.999
Residual Std. Error	0.542 (df = 7637)	0.413 (df = 7632)	0.413 (df = 7631)
F Statistic	$1{,}059{,}245^{***}$ (df = 5; 7637)	$911{,}718^{***}$ (df = 10; 7632)	$830{,}088^{***}$ (df = 11; 7631)
Note:	*p<0.1; **p<0.05; ***p<0.01		

Desalination plant capital costs are very sensitive to the input raw water type, i.e. feedwater quality. Feedwater quality is measured primarily in parts-per-million (ppm) of Total Dissolved Solids (TDS). The data includes plants that were constructed to treat seawater, brackish groundwater, fresh riverwater, tapwater, brine, and wastewater. The updated cost model controls for both technology and feedwater type to reflect this sensitivity.

$$C = A \cdot K^{\alpha} \Big|_{\substack{technology \\ feedwater}} \tag{2.7}$$

The effect of the controlling term is to move the intercept, $\ln(A)$, up or down to reflect the impact on capital cost. Figure 2.7 visualizes this effect. These results are similar to the analysis in Figure 2.6a, with the added grouping variable feedwater quality. The regression coefficients are given by Model (2) in Table 2.1. The coefficient values for each technology type have now changed (from Model (1)) to reflect the effect of feedwater quality. Positive coeficients for the feedwater type term are added to the technology-type intercept, whereas negative intercepts are subtracted. For example, the log of capital cost for treating seawater using a 10,000 m3/d Reverse Osmosis facility is given by:

$$\ln(C)_{10{,}000;\ RO;\ seawater} = \ln(8.108 + 0.792) + 0.892 \cdot \ln(10, 000)$$

Capital cost of facilities is lowest for treating tap water and river water, since these are "fresh" water sources with already low TDS. The cost of desalination for waster water treatment is in the middle of the range. Seawater and brine require the most capital for high pressure pumps, anti-corrosive materials, and a higher number of treatment stages to the bring the water down TDS down to potable quality.

Many desalination units are delivered in phases or modules. Modularity provides both design (capital) and operating flexibility. Design flexibility implies that plants can add modules as when demand conditions evolve over the long-term to require the additional production capacity at the plant location. Operating flexibility on the other hand allows plant operators to turn on and turn off modules in the short-term to balance (stochastic) variability in demand. This data allows us to update the capital cost model to pick up the effect of modularity. Since plant capacity (m3/d) = module size (m3/d) x number of modules (#), Figure 2.6b breaks the plant capacity dimension from 2.6a into 'module size (m3/d)' (vertical axis) and 'number of modules' (horizontal axis). Plant capital cost, the third dimension, is shown with a color gradient. The three-dimensional regression plane is not shown here.

The modularity dimension requires updating the cost function. The plant capacity term, K, is now split up into a module capacity term, k, with exponent α and a number of modules term, $m \geq 1$, with exponent β. Note that $K = k * m$, i.e. the total plant capacity will always be the product of the module size and the number of modules in that plant. The first power has the same notion as in Eq (2.5), in that governs the cost of a single module of production. When $m > 1$, then the modularity premium for additional modules is given by β.

$$C = A \cdot k^{\alpha} \cdot m^{\beta} \Big|_{\substack{technology \\ feedwater}} \tag{2.8}$$

The corresponding log-linear fit for the updated cost model is denoted by Model (3) in Table 2.1. There are now two 'slope' coefficients, which are the values of α and β. The β power is active when the plant has more than one module. The intuition of the rest of the coefficients is as explained earlier.

The analysis was repeated for a number of other dimensions in the data set. For brevity, I summarize and state the final cost relationships that are used in the tradespace model in Table 2.2. Two other dimensions were found to be revealing in the final cost relationship - the output quality of the produced water, and the delivery mode for the projects in the dataset.

Projects in the dataset delivered water at one of two levels, TDS<1000ppm (low quality) or TDS<10ppm (high quality). We would expect the capital cost of facilities to be higher for higher output quality, holding other factors constant. This is indeed the case for electrodialysis (statistically insignificant) and reverse osmosis (p<0.01) technologies. Multi-stage flash and multi-effect distillation (p<0.01) were found to be cheaper for higher output quality. A possible partial explanation for they exhibit the reverse trend is because they both employ distillation processes and already produce water of a very low TDS level. In fact, these types of plants typically *resalinate* or remineralize pure distillate to make it fit for potable use. This additional treatment step could explain the slightly higher cost for these facilities.

Projects were delivered in one of three ways - municipal provision (traditional public sector procurement), independent private ownership and operation, or through a P3 approach or its variants. The P3 approach was most expensive for both electrodialysis and multi-effect distillaton, although not in a statistically significant way. In contrast, the P3 approach was cheapest for both multi-stage flash (significant) and reverse osmosis facilities (insignificant). Private firms may have more experience with the lifetime ownership and operation of these latter two technologies, which could enable their delivery in a more cost-effective way. P3 approaches are also relatively new in the desalination domain, so these more recent projects may also benefit from technical innovation and cost reduction.

Table 2.2 documents the final results of the statistical analysis. The corresponding dimensions of the data give the parameter values for the technical configurations of the design space along with the cost relationships. The technical design variables interact with the contractual terms in the design space, which are explained next.

Table 2.2: Final cost model fits for each desalination technology

$$C = A \cdot k^{\alpha} \cdot m^{\beta} \Big|_{\substack{technology \\ feedwater \\ outputquality \\ deliverymode}}$$

	Dependent variable:			
	LN [Plant Cost ($)] for Concessions and Output Quality TDS < 1000 ppm			
	ED	MED	MSF	RO
LN [Module Size, m3/d]	0.903***	0.871***	0.842***	0.886***
	(0.010)	(0.012)	(0.025)	(0.005)
LN [Modules, number]	0.917***	0.980***	0.878***	0.932***
	(0.022)	(0.034)	(0.065)	(0.011)
Brackish water (TDS 3000ppm - <20000ppm)	8.252***	8.611***	8.073***	7.954***
	(0.298)	(0.392)	(0.593)	(0.089)
Brine (TDS >50000ppm)	9.417***	9.783***		8.752***
	(0.407)	(0.392)		(0.126)
Tap water (TDS <500ppm)	7.855***			7.609***
	(0.295)			(0.091)
River water (TDS 500ppm - <3000ppm)	7.897***	8.093***		7.686***
	(0.300)	(0.540)		(0.091)
Seawater (TDS 20000ppm - 50000ppm)	9.006***	9.448***	8.683***	8.773***
	(0.306)	(0.385)	(0.553)	(0.088)
Waste water	8.437***	8.988***	7.727***	8.302***
	(0.301)	(0.388)	(0.724)	(0.092)
Output Quality (TDS <10ppm)	0.017	−0.130***	−0.093	0.101***
	(0.023)	(0.036)	(0.081)	(0.013)
Municipal provision	−0.017	−0.136	0.985**	0.118
	(0.285)	(0.383)	(0.498)	(0.080)
Private provision	−0.630*	−0.322	1.109**	0.152
	(0.347)	(0.415)	(0.526)	(0.096)
Observations	663	639	194	6,042
R^2	1.000	0.999	0.999	0.999
Adjusted R^2	1.000	0.999	0.999	0.999
Residual Std. Error	0.280 (df = 652)	0.381 (df = 629)	0.492 (df = 186)	0.423 (df = 6031)
F Statistic	156,194.000*** (df = 11; 652)	103,206.900*** (df = 10; 629)	28,688.500*** (df = 8; 186)	610,302.000*** (df = 11; 6031)
Note:	*p<0.1; **p<0.05; ***p<0.01			

2.2.5 Design space: contract formulation

The concession contract is the key link for value exchange between the principal and agent in an infrastructure P3. In the desalination P3 tradespace model, the contract governs the economic value outcomes for the two project actors: the water authority and the firm. This subsection outlines the nature of the contract and summarizes its formulation for the tradespace model. The contract takes a general form; it applies to any infrastructure P3, even though the specific case here is desalination.

The same basic formulation informs the structure of two contract variants - without and with risk sharing. The first is a volumetric or fixed-price contract under which the principal pays the firm a fixed unit-price for services. In the tradespace, this translates to a $\$/m^3$ payment for the volume of desalinated water the firm delivers. The firm bears all the risk of the project under demand uncertainty with this type of contract, because it is only paid for the water it delivers, and the volume of water it delivers depends on realized demand. The second contract form is a take-or-pay arrangement in which the water authority pays the firm at least a pre-determined minimum even if water demand is very low. The water authority also bears risk under this contact structure. Additionally, the water authority can also limit the maximum revenue to the firm. Both the minimum revenue guarantee and the revenue cap are negotiated in advance in practice.

The co-design approach to modeling the concession contract is different from the broader contracts literature in a fundamental way. Modeling the welfare implications of infrastructure P3 contracts continues to receive attention (Iossa and Martimort, 2015). Much of this work assumes a fixed distribution of value that the project can capture. The importance of co-design is that technical design changes can change the distribution of value. The contract form must therefore be able to accommodate this type of value creation through technical design changes. Engel, Fischer, and Galetovic (2013)'s work on the public finance of P3s provides a starting point for the model developed here. In order to study the case of desalination investments, the contract model must also be able to accommodate the state space with a bivariate distribution of water demand and energy price risk factors.

The contract model begins with a traditional welfare description that captures the notion of value in terms of consumer and producer surplus. In this model, I denote expected welfare by Net Present Value (NPV), which sidesteps the issue of having to specify a utility function for either the principal or the agent.

In an infrastructure P3, the principal charges customers a tariff to pay for the service provided. From the customer's point of view, this price or tariff is a very specific tax, which customers pay in proportion to their consumption (ex. \$/cubic meter or $\$/m^3$ for water supply, or \$/trip for toll road access). The total collection is an important part, if not the full amount, of the revenues transferred to the agent firm. Let v denote the present value of total tariff payments. Since demand is uncertain and evolves stochastically along different paths (see 2.2.3), the present value of all tariff payments until the end of the concession for any path can be denoted by v.

Thus, v is one way for identifying the uncertain state of the world for the project. Then there is a distribution over v , denoted by a probability distribution function $f(v)$ with a cumulative distribution function $F(v)$. The expected present value of tariffs is therefore $\int vf(v)dv$. The principal's public interest outcome in a state of the world v is denoted by the metric for welfare as:

$$W = CS(v) + \alpha PS(v) \tag{2.9}$$

where
$CS(v)$ is the consumer surplus in state v
$PS(v)$ is the producer surplus in state v
$\alpha \in [0, 1]$ is the weight that the principal places on producer surplus in the welfare formulation.

The principal will try to maximize the public interest objective by maximizing the expected value of welfare (measured as a Net Present Value in dollar terms), written as:

$$E[W] = \int [CS(v) + \alpha PS(v)]f(v)dv \tag{2.10}$$

Consumer surplus depends on the present value of tariff receipts v, the share of the present value receipts $R(v)$ that the firm is allowed to retain, and the present value of the subsidy $S(v)$ that the principal may have to pay to the firm. The $CS(v)$ term can be unpacked as:

$$CS(v) = v - R(v) - (1 + \lambda)S(v) + \lambda(v - R(v))$$

$$CS(v) = (1 + \lambda)[v - (R(v) + S(v))] \tag{2.11}$$

The parameter λ is the marginal cost of public funds. Raising an amount corresponding to $S(v)$ as a subsidy payment, or reallocating it from elsewhere in the budget thus implies a total cost of $(1 + \lambda)S(v)$ to the public budget. In Eq 2.11, the collection of terms $R(v) + S(v)$ denotes the total payment transfer to the firm. The consumer surplus in any state of the world is thus the tariff receipts less the total transfer to the firm, adjusted by the marginal cost of public funds to show the gain of collecting it from tariffs instead of another form of taxation.[5]

Producer surplus is written as:

$$PS(v) = R(v) + S(v) - C(v) \tag{2.12}$$

where $C(v)$ is the present value of cost in that state of the world and includes both capital investment $I(v)$ as well as operating expenses $o(v)$. Substituting Eq 2.11 and Eq 2.12 in Eq 2.9, we have

[5] Engel et al (2013) show this as an important "irrelevance result". This is a theoretical rebuttal to the first argument in favor PPPs regarding off-balance sheet financing. Proponents of PPPs often claim that concessions substitute private finance for distortionary taxation and thus relieve the public budget. However, Eq 2.11 shows that the tax distortion depends on total transfers $R(v) + S(v)$, and not the division between share of tariff receipts and subsidies.

$$W = (1+\lambda)[v - (R(v) + S(v))] + \alpha[R(v) + S(v) - C(v)]$$

$$W = (1+\lambda)v - [(1+\lambda) - \alpha](R(v) + S(v)) - \alpha C(v) \tag{2.13}$$

To simplify the model we can adopt the "irrelevance" assumption. In other words, we neglect whether payments to the firm are valued differently if the firm collects it than if the water authority collects and it, and that a dollar in revenues is the same as a dollar in payments from the public authority based on other taxes. $R(v)$ and $S(v)$ being perfect substitutes, we can write the total transfer to the concessionaire firm as

$$\tau(v) = R(v) + S(v)$$

Further, if we assume that producer surplus is as important to the principal as consumer surplus then $\alpha = 1$, and Eq 2.13 becomes

$$W = (1+\lambda)v - \lambda\tau(v) - C(v) \tag{2.14}$$

and the expected value calculation is

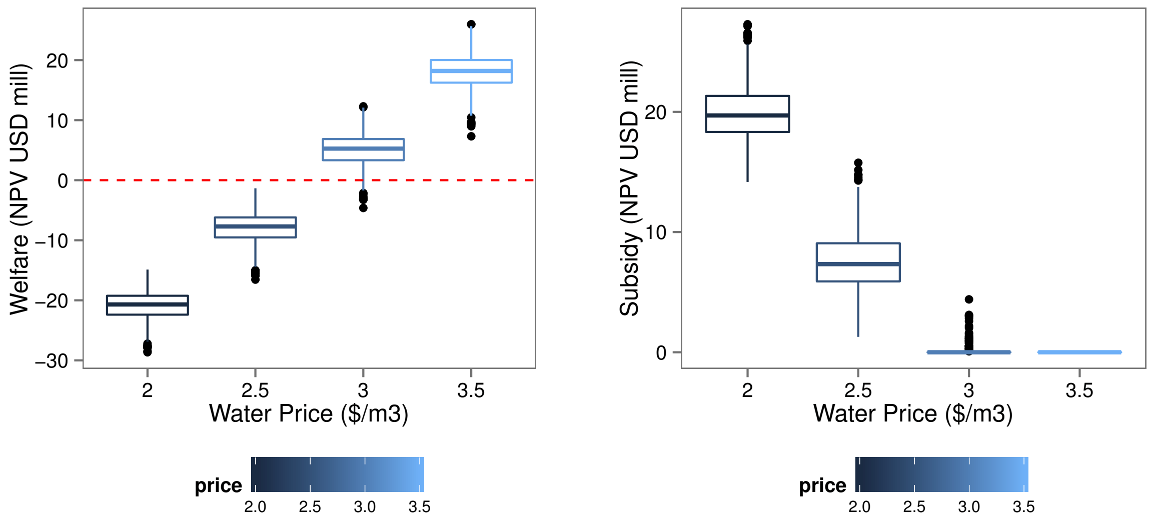
$$E[W] = \int [(1+\lambda)v - \lambda\tau(v) - C(v)]f(v)dv \tag{2.15}$$

A risk averse concessionaire firm will participate in this project only if its expected value of participation is positive ($NPV = 0$). This is the firm's "participation constraint". Mathematically,

$$\int [\tau(v) - C(v)]f(v)dv \geq 0 \tag{2.16}$$

The expected welfare formulation shows that the principal faces multiple objectives. Expected welfare increases with increasing revenue collection directly from customers, i.e. tariff levels, and increases with decreasing project costs and transfers to the firm. The principal must also balance the distortionary effect of subsidy payments through a payment guarantee while ensuring that the firm's NPV>=0 participation constraint is met. Payment transfers $\tau(v)$ can either depend on the state of the wold v or be state-independent as $\tau = \kappa$, whereas costs $C(v)$ are state-contingent.

In the special case of bundled service provision, where the principal both delivers and operates the project, welfare is fully captured by the consumer surplus term $CS(v)$. The intervening variable $R(v)$ vanishes since there is no firm retaining a share of revenues during the project's operating life. The subsidy term $S(v)$ retains its meaning for complete cost recovery, although it becomes implicit because there is no transfer in the case of bundled delivery. Assuming that all costs of any service provision must be fully covered, the implicit transfer $\tau(v) = C(v)$. Under this assumption, note that the general formulation in Eq 2.14 reduces to $(1+\lambda)(v - C(v))$ and the actual subsidy impact is $S(v) = min[0, v - C(v)]$ in cases where tariff receipts $v \leq C(v)$.



(a) Welfare for different water prices (tariffs). Welfare is the total tariff collection at a price level less total cost for the facility. The distribution of outcomes reflects demand risk. Low price levels are insufficient to recover the facility's cost, showing negative distributions of welfare.

(b) Project subsidy requirement for different water price levels. Low price levels are insufficient to recover the facility's cost, requiring a subsidy to complete cost recovery. The subsidy is only in effect in those states of the world where water revenue collection is less than costs.

Figure 2.8: Relative effect of water prices $R(v)$ and the corresponding project subsidy requirement $S(v)$ in the case of bundled provision

Figure 2.8 visualizes the case of bundled provision for a desalination facility with fixed production capacity. Services delivered are variable because of uncertain demand. The facility collects a fixed tariff ($/m3). Figure 2.8a shows the probabilistic range of consumer surplus, i.e. welfare $CS(v) = (1+\lambda)[v - C(v)]$, whereas Figure 2.8b shows the subsidy required when $v \leq C(v)$ for different tariff levels. These results are a function of the uncertainty in demand, observed using the state variable v. There are tariff-levels for which the present value of tariff receipts v is not sufficient to cover the possible range of the sum of investment and operating costs, $C(v)$. The entire range of resulting welfare is negative for all states for tariffs below $2.5/m3. At $3/m3, the tail extends into negative welfare, whereas above $3.5/m3, the project will result in positive welfare for any demand scenario. In demand states in which tariff receipts are not sufficient to cover $C(v)$, the sum of investment and operating costs, as subsidy is required. The subsidy is the excess cost of the project, $vC(v)$ adjusted for raising capital at the marginal cost of public funds, λ. Thus the subsidy impact is $(1+\lambda)(vC(v))$ when $vC(v) \leq 0$. The figure shows that S(v) is positive for low tariff levels, which can also be inferred from the left.

This brief example establishes an intuition for the results to come in the discussion of the value space below. The subsidy payments come into play as part of the risk-sharing variant of the contract, when a minimum income guarantee is established. The next section steps through the analysis that was performed with the desalination tradespace model.

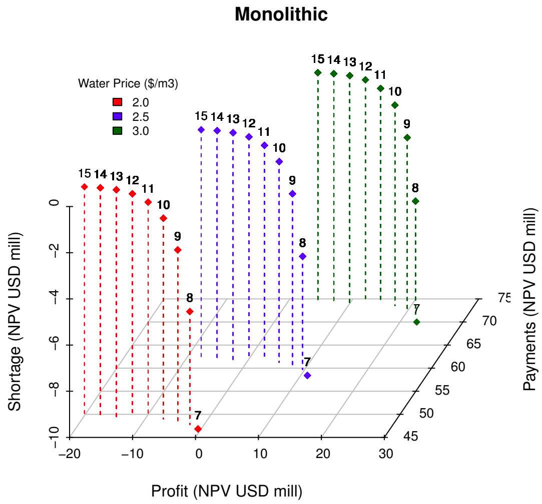
2.3 Value Space: Results from Co-design

The co-design study applied to a desalination P3 project builds up the intuition from co-design by stepping through a series of analyses. The first analysis evaluates fixed combinations of designs. The combinatorial approach gives a sense of the shape of the value space. Degrees of freedom are introduced one by one. For example, monolithic designs are evaluated before modular designs at fixed prices. Then prices are allowed to vary within a fixed range for multi-objective optimization, adding another degree of freedom to the co-design problem. The final degree of freedom is the introduction of risk-sharing structure through a minimum income guarantee and revenue collar. Although desalination technology (ED, MED, MSF, RO) is an available degree of freedom and was evaluated extensively, the results that follow use just the RO technology. Results of one technology are sufficient to build up the intuition.

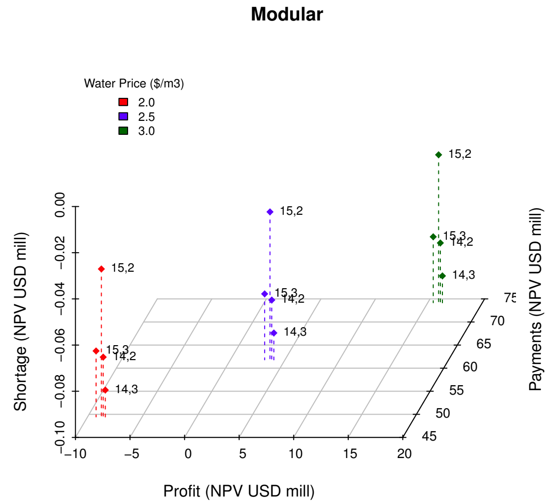
The intuition of fixed combinatorial design for monolithic facilities is that large plants and high water prices are needed to achieve high reliability levels for a given uncertain demand forecast. Figure 2.9a shows the value outcomes from co-design for monolithic RO facilities under a volumetric fixed-price contract. Reliability is on the vertical axis, measured as the life-time shortage over the duration of the concession. The horizontal plane shows both the profits to the firm, and the corresponding contract payments that the water authority For the assumed water demand statespace parameters, plant capacity was limited to the range 7,000 - 15,000 m3/d. The same range was analyzed at three different price levels ($ 2, 2.5, and 3 /m3 of water supplied). Large plants in the range 13 - 15 ('000 m3/d) approach zero shortage. Holding other variables constant, these large plants are the most expensive to build. The high cost of large monolithic facilities makes them unprofitable at low water prices. While no configurations are profitable befow $2/m3, only small plants are NPV-positive at $2.5/m3. The entire range of capacities is profitable at $3/m3, which also imposes the highest contractual payment obligation the public authority.

Adding modularity makes more plant configurations profitable while maintaining high levels of reliability. This technical degree of freedom was enabled by allowing plants to be phased into a maximum of 5 units, i.e. $modules : [1, 5]$ For example, a large monolithic plant of 15,000 m3/d implies that its full production capacity is built up front. A modular plant of 15,000 m3/d and 3 modules implies that its total potential capacity is 15,000 m3/d in modules with 5,000 m3/d capacity each. The first module is built at the start of the concession and the remaining two can be added during the concession's lifetime. Figure 2.9b shows only the {*potential capacity, modules*} configurations that deliver high reliability (shortage < NPV $ 0.1 mill). Many configurations with large potential capacity (ex. {15, 2},{14, 3}) are now profitable at $2.5/m3, whereas similar monolithic configurations were not. Modularity allows the public authority to secure these reliable configurations at lower payment obligations.

These initial results suggest that there is a range of prices that enables profitability while maintaining reliability. Allowing prices to vary reveals the shape of the front of possibilities. The effect of the additional degree of freedom is shown in Figure 2.10. The value outcomes of the



(a) Co-design for monolithic facilities. Labels indicate installed plant capacity ('000 m3/d). Only large plants approach high reliability levels. Also, these large monolithic facilities need prices in excess of $2.5/m3 to be profitable.



(b) Co-design for modular facilities. Labels indicate {*potential capacity* ('000 m3/d), *modules*(#)}. Only configurations with high reliability levels (shortage < NPV USD 0.1 mill) over plant life are shown. Large plants are now profitable at prices of $2.5/m3.

Figure 2.9: Co-design analysis showing the effect of modular facility design. Reliability is on the vertical axis, measured as the lost economic value of water shortage over the concession lifetime. Reliability trades-off against profit to the firm, and contract payment obligations by the water authority.

resulting design configurations are on a surface that stretches across the three value dimensions. Some designs deliver low outcomes on all three axes, i.e [low reliability, low or negative profit, low payments]. While these designs are not likely choices for project actors, they are feasible designs and represent a part of the trade-off surface in the value space. There are many design configurations that deliver intermediate as well as high outcomes, i.e. [high reliability, high profit, high payments. Likely candidates for design choices for the project are in the subset of configurations that are highly reliable, and at least NPV-positive. It is easier to visualize some of these design configurations and their value outcomes as projected on the respective planes.

Modular and highly reliable plants are profitable above a price threshold, approximately $2.25/m3 for the particular parameters chosen in this problem. Plants will continue to be reliable below this price level, however with this co-design configuration, they are unlikely candidates because they don't deliver value to the firm. The reliability-profit front is shown in Figure 2.11a along with the zero profit cut-off marked by the red-dashed line. The front is the upper-most set of outcomes aligned with the zero level of shortages.

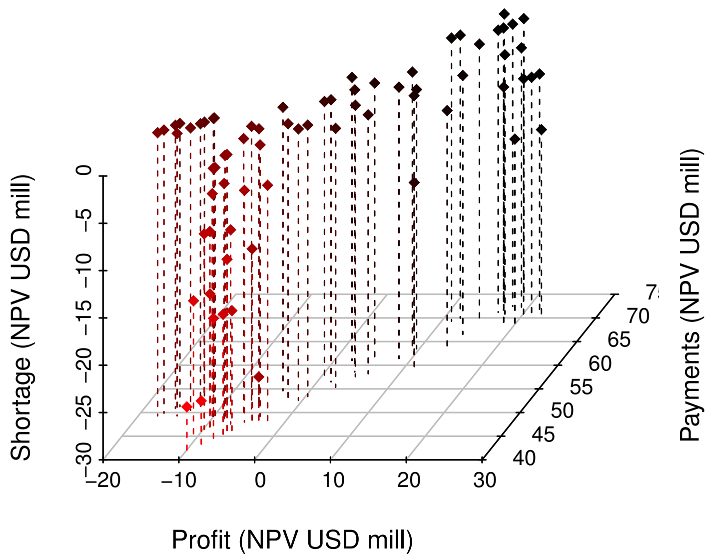
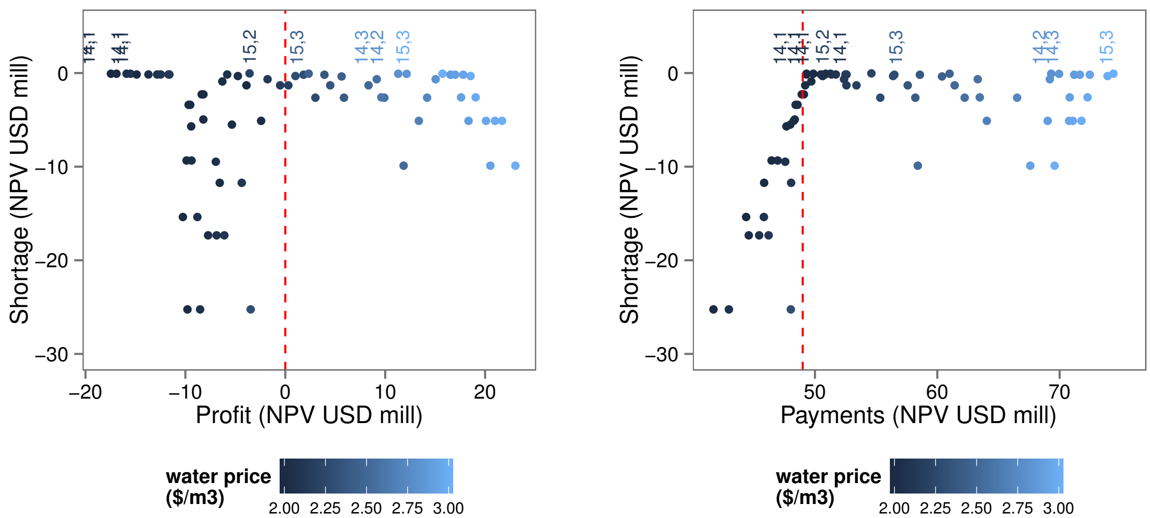


Figure 2.10: Results of multi-objective optimization using the co-design tradespace model for the RO technology under the fixed price contract. Modularity is enabled and prices can vary within the range \$2 – 3 /m3. The resulting configurations are on a surface that stretches from [low reliability, low (negative) profits, low payments] to [high reliability, high profit, high payments] across the three value dimensions.

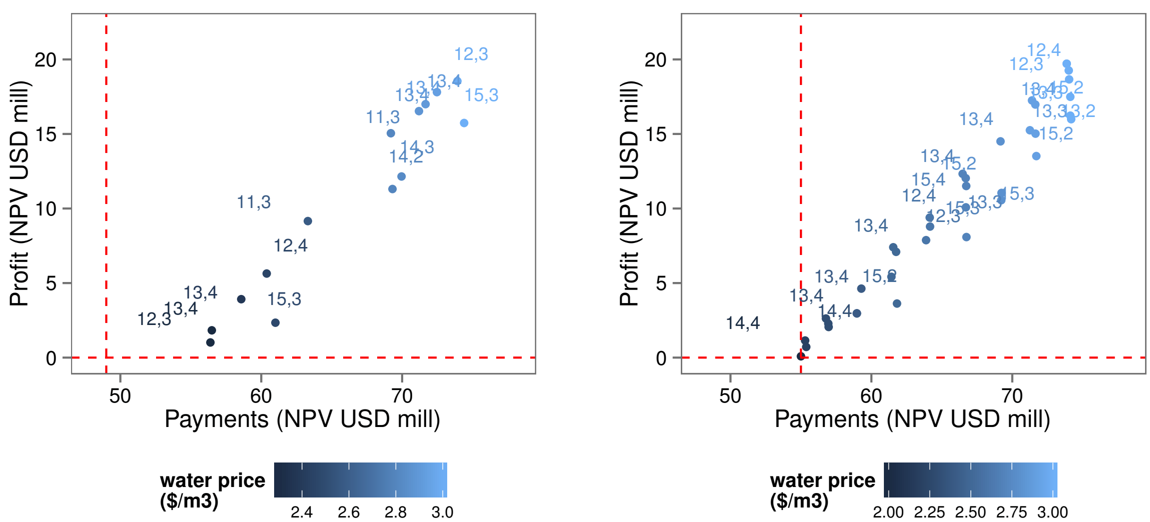
The water authority can only obtain reliable service above a payment threshold, which is slightly less than NPV USD 50 mill for the chosen parameters. A number of highly reliable modular design configurations are available at different water price levels above the threshold, which translate to higher payments obligations. Figure 2.11b shows these candidates on the reliability-payments front, along with the threshold value marked by the red dashed line.

The results suggest that there is a subset of (co) designs that both project actors could accept. Even though all the value outcomes in 2.11 represent true trade-offs in three value dimensions (they are pareto-optimal), some design configurations appear dominated from the respective (two dimensional) views of the firm and the public authority. The candidate designs they are both likely to consider will be those that seem acceptable from both viewpoints. We can consider this region of the value space as a "zone of negotiated agreement" in which there are a number of promising candidate designs, and the ultimate choice of design is a negotiated decision between the project actors. Figure 2.11c shows the zone generated by co-design with the capacity, modularity, and price variables as degrees of freedom.



(a) A two-dimensional view of value outcomes from the firm's view showing reliabilty and profit outcomes. The red line marks the partition above which designs are profitable over a range of prices. Large, modular plants that are reliable appear labeled on the reliability-profit value front.

(b) A two-dimensional view of value outcomes from the water authority's view showing reliability and payment outcomes. The red line marks the space above which payments can obtain highly reliable plants for a range of prices. Some of these dominant configurations are labeled on the reliability-payments front.



(c) Collapsing the regions with candidate designs from fig. 2.11a and fig. 2.11b above into a "zone of negotiated agreement". Project actors can eventually negotiate a design choice within this zone.

(d)

Figure 2.11: Two dimensional views of the value space shown in Figure 2.10 from the perspectives of the firm (left) and the water authority (right). The observations are labeled to denote their technical design configuration coded as {*potential capacity, modules*}. The gradient color scheme denotes the water price dimension. A collapsed "zone of agreement" also shown at the bottom.

The volumetric contract structure evaluated thus far exposes the agent firm to the entirety of the risk in the statespace. The value outcomes in Figure 2.11c are *expected* outcomes, the average result of a distribution of possible outcomes driven by the state space of exogenous risk factors. The expected values summarize the range of possible outcomes, and obscure the risk exposure to the firm. Some design configurations are unavailable from the firm's point of view with the filter of expected profit > 0 because the cumulative area under the risk curve of negative NPV outcomes outweighs that of the positive outcomes.

A risk-sharing structure between the water authority and the firm may alter the set of available designs in the zone of agreement. A take-or-pay structure is one type of contract that enables risk-sharing. Constructing this type of contract requires adding another dimension or degree of freedom in the form of a minimum income guarantee. With this provision, the water authority assures the firm of a minimum payment in all the states of the world in which the firm's revenues fall below the income guarantee threshold. Receiving the guaranteed minimum income in some states of the world can shift the distribution of outcomes for some design configurations, thereby altering their expected values.

An updated zone of agreement with a minimum income guarantee in a take-or-pay contract structure shows that many more previously unprofitable, yet reliable designs are now available for consideration by the project actors. 2.11d shows the effect of this extra degree of freedom. The vertical dashed red line is the level of the minimum income guarantee, fixed at NPV USD 55 mill in this example. For example, configurations such as {14, 4} and {15, 2} now appear in the zone at lower price levels than in the case of no income guarantee (Figure 2.11c).

The minimum income guarantee is in effect a *reliability premium*. The premium is the incremental payment obligation that the water authority assumes to enable additional reliable design configurations. In this example, the premium is approximately NPV USD 6 mill. By incurring this premium, the water authority can also lower the applicable water price in many configurations. The lowest water price level in any configuration in the zone without risk sharing (Figure 2.11c) is \$2.3/m3 whereas the lowest price with risk-sharing (Figure 2.11d) is \$2.0/m3.[6]

The zone of negotiated agreement without and with the minimum income guarantee is consolidated in Figure 2.12. The value outcomes with dots do not enforce the payment floor, whereas the hollow diamonds enforce a payment floor of NPV USD 55 mill. The red target zone shows a region where many design configuration have identical potential capacity, modules and their relative position in the value space depends on the income guarantee level and price term. In a process of negotiated decision-making project actors will intend to adjust the guarantee level and price to meet their profit and payment goals. There may also be a ceiling on the level of payments (and consequently allowable profits).

[6]The particular contract formulation used in the tradespace model makes the firm indifferent between payments received from the water authority as the "pay" part of the take-or-pay arrangement, or income directly received from the water price (a tariff on customers). Engel, Fischer, and Galetovic (2013) show that the subsidy of the minimum income guarantee can create welfare distortions. The tradespace model ignores these effects.

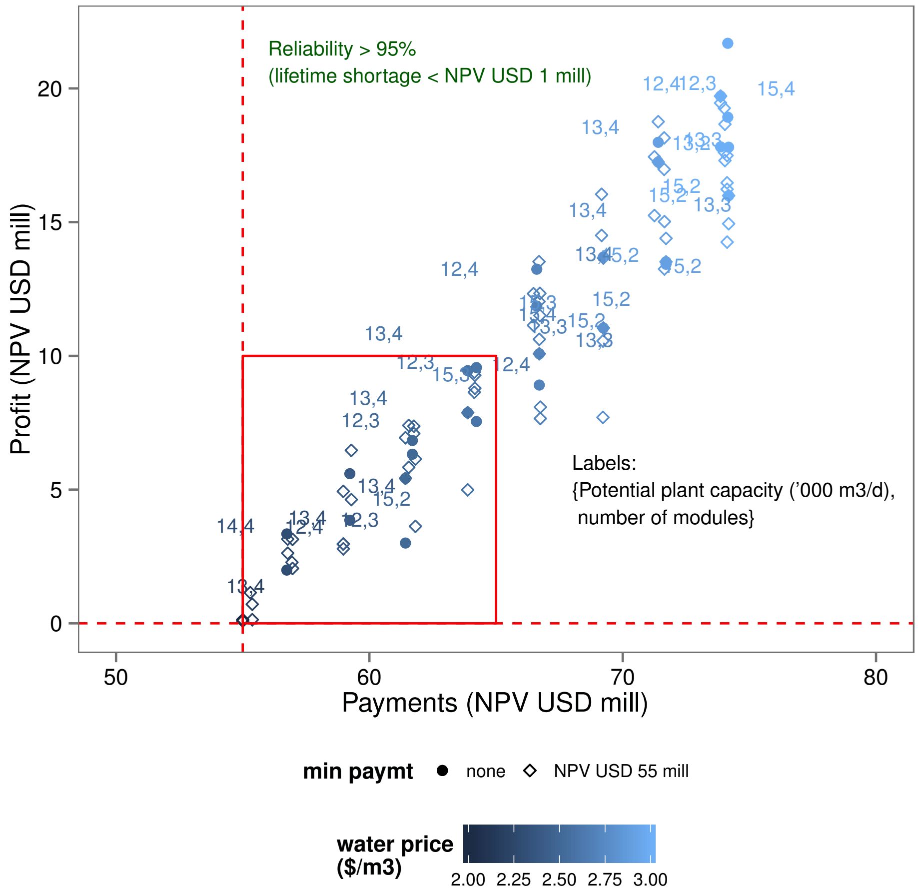


Figure 2.12: A zone of negotiated agreement with both volumetric (no minimum income guarantee) and take-or-pay value (with a payment guarantee) outcomes. The red target area shows many similar design configurations for which the project actors can fix price and payment terms.

Just as the minimum income guarantee in the take-or-pay contract truncates the downside risk of many designs, the water authority may also wish to limit the available profit upside to the firm to prevent excessive profit. Bounding the profit possibilities in this manner creates a "revenue collar" (Shan, Garvin, and Kumar, 2010). The collar idea is similar to the negotiation band approach proposed by Liu and Cheah (2009). The tradespace model can adopt a collar in the take-or-pay contract structure by setting a revenue cap.

The effect of setting a revenue cap is a more tightly bounded zone of negotiated agreement. Figure 2.13 shows a set of designs that meet the highly reliability value goal, are profitable, and also contained within a collar of payment obligations acceptable to the water authority. The revenue cap in the collar of NPV USD 65 mill was selected to allow some variation in the combination of water price and payment obligations. The minimum guarantee is still set at NPV USD 55 mill to ensure that high reliability designs are at least NPV-positive. Project actors can negotiate both technical configurations, and water price within this zone.

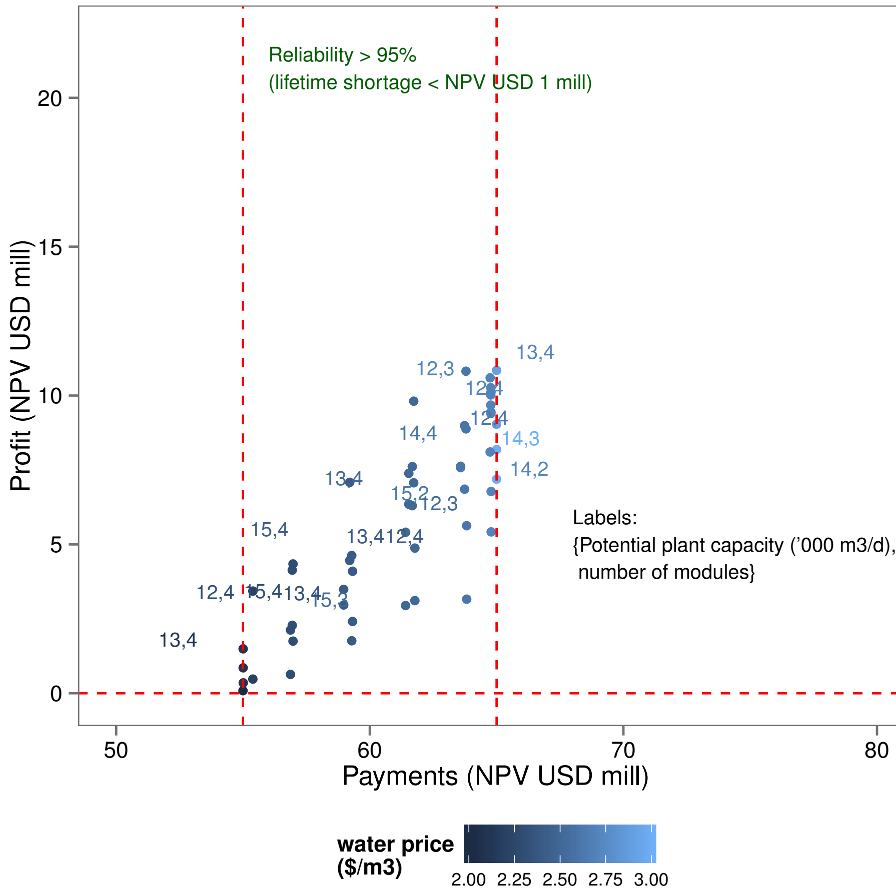


Figure 2.13: The zone of negotiated agreement updated to reflect the imposition of a minimum income guarantee as well as a revenue cap, in a collar arrangement. There are many reliable designs over which the project actors can converge to an agreement in terms of technical features as well as price and payment guarantees.

2.4 Chapter Summary

This chapter makes a case for the importance of co-design in infrastructure P3s. The first part of the chapter used a general example to illustrate how facility size interacted with technology choice and contractual structure to influence value outcomes. There was no dominant solution, and a main observation was that co-design leads to contingent solutions.

A second important aspect of co-design was the shaping of project risk profiles, once again as a consequence of the facility's technical characteristics and also its contractual structure. Some contract structures such as take-or-pay arrangements can truncate downside risk as well as manage upside exposure.

A final aspect of the case for co-design was to show that while one project actor may be indifferent among designs because they lead to similar outcomes from that actor's point of view, these designs could have dramatically different outcomes for another project actors. Modularity in design through flexible, phased designs illustrated this effect in the general example, as a mechanism for value creation. The three ideas of contingency, risk-shaping and value co-creation and exchange are the pillars of the case for co-design.

The second part of the chapter then presented a tradespace modeling framework and details for co-design applied to a desalination P3 project. The state space component of the model creates a background environment for decision-making under uncertainty for the project actors. The design space encapsulates the technical and contractual features of the project's co-design and relates them to value outcomes. Finally, the value space juxtaposes and visualizes the value outcomes corresponding to different co-design configurations.

The main result of the co-design process is that there exists a zone of negotiated agreement in which a number of feasible designs can meet preferred value outcomes for project actors. Co-design clearly identifies these designs and shows their relative positions in the value space. Project actors can iteratively explore the zone of agreement to converge on a design that is acceptable to both. While the chapter demonstrates this with specific parameter values for a desalination P3, this approach can be valuable for the co-design of any infrastructure P3 facility, or engineering projects more broadly.

References

Brennan, Michael J and Eduardo S Schwartz (1985). "Evaluating natural resource investments". In: *Journal of business*, pp. 135–157.

Dixit, Avinash K and Robert S Pindyck (1994). *Investment under uncertainty*. New Jersey: Princeton University Press.

Engel, Eduardo, Ronald Fischer, and Alexander Galetovic (2013). "The basic public finance of public–private partnerships". In: *Journal of the European Economic Association* 11.1, pp. 83–111.

Gibson, Rajna and Eduardo S Schwartz (1990). "Stochastic convenience yield and the pricing of oil contingent claims". In: *The Journal of Finance* 45.3, pp. 959–976.

Iossa, Elisabetta and David Martimort (2015). "The Simple Microeconomics of Public-Private Partnerships". In: *Journal of Public Economic Theory* 17.1, pp. 4–48.

Laughton, David, Raul Guerrero, and Donald Lessard (2008). "Real Asset Valuation: A Back-to-basics Approach". In: *Journal of Applied Corporate Finance* 20.2, pp. 46–65.

Lessard, Donald, Vivek Sakhrani, and Roger Miller (2014). "House of Project Complexity—understanding complexity in large infrastructure projects". In: *Engineering Project Organization Journal* 4.4, pp. 170–192.

Liu, Jicai and Charles YJ Cheah (2009). "Real option application in PPP/PFI project negotiation". In: *Construction Management and Economics* 27.4, pp. 331–342.

McManus, Hugh, Matthew Richards, Adam Ross, and Daniel Hastings (2007). "A Framework for Incorporating "ilities" in Tradespace Studies,"" in: *AIAA Space*. Vol. 1, pp. 941–954.

Miller, Roger and Donald Lessard (2001). "Understanding and managing risks in large engineering projects". In: *International Journal of Project Management* 19.8, pp. 437–443.

Paddock, James L, Daniel R Siegel, and James L Smith (1988). "Option valuation of claims on real assets: The case of offshore petroleum leases". In: *The Quarterly Journal of Economics*, pp. 479–508.

Ross, Adam M, Hugh L McManus, Donna H Rhodes, and Daniel E Hastings (2010). "Revisiting the tradespace exploration paradigm: structuring the exploration process". In: *AIAA Space*.

Schwartz, Eduardo S (1997). "The stochastic behavior of commodity prices: Implications for valuation and hedging". In: *The Journal of Finance* 52.3, pp. 923–973.

Shan, Liang, Michael J Garvin, and Raman Kumar (2010). "Collar options to manage revenue risks in real toll public-private partnership transportation projects". In: *Construction Management and Economics* 28.10, pp. 1057–1069.

Chapter 3

Design Experiment on Negotiated Collaboration

This chapter covers the design and key results of a controlled experiment to study negotiated collaboration. In this exercise, participants play the functional roles of project actors to engage in the process of co-design. Co-design is used with the same connotation as in the previous chapter - the simultaneous technical and contractual design of a project. Another implied sense of co-design is the collaboration between actors of different functional roles (such as a water authority and a firm) who approach the design problem with different value objectives.

The previous chapter developed the idea that the process of co-design requires designers to make trade-offs in value. To do so, they have to explore the design space by modifying design variables. The early stage design of a desalination infrastructure P3 illustrated how the co-designers find themselves in a zone of agreement in which they must negotiate the specific terms of a design to balance competing objectives. Making these choices is central to the process of negotiated collaboration.

In co-design, project actors can explore design possibilities along dimensions such as technology, production capacity, phasing, or operational fuel switching in the technical domain. In the contract domain, they can alter contract length, price terms, risk allocation arrangements such as revenue or profit guarantees, and so on. Making choices for one or a few dimensions under conditions of uncertainty and risk already presents a large design space. The interaction of many dimensions, some of which may be coupled, makes the design problem even more complex. Project actors may prematurely reduce the design space by constraining one or more of the design dimensions mentioned above, and end up preferring different solutions because of their value objectives.

The experimental collaboration exercise described in this chapter observed role-playing collaborators who engaged in a such a process of co-design and negotiation. The exercise was designed to test hypotheses about two mechanisms of collaboration (i) communication and (ii) common knowledge which are rarely separated in the literature. Parsing these two mechanisms in the collaboration exercise helps us to understand their relative effects on design and value outcomes.

To make the complexity of the experimental design task manageable in a short time frame with limited tools, the participants explore a design space generated by only four variables: total potential capacity, degree of modularity (phasing), contractual unit price, and minimum revenue guarantee. The first two are technical, whereas the last two are contractual.

The experimental study found that collaboration systematically affects design choices. Communication dominates as a mechanism for developing the shared understanding that is necessary to balance competing value objectives. Common knowledge can either reinforce or amplify the effect of communication, and thus play a supporting role. Collaboration enhances actors' learning, which can be traced through their evolving design choices during the exercise.

Three characteristic patterns of behavior emerged from collaborator interaction in the exercise. These behavioral archetypes are *aligning*, *anchoring*, and *sensitive*. The degree of agreement in design choices is associated more with the *aligning* and *sensitive* archetypes than the *anchoring* archetype.

The implications of these findings for the co-design of infrastructure P3s is that the negotiating project actors should communicate early and often to be able to make better sense of the trade-offs they will eventually have to make through the process of negotiated collaboration.

The chapter is structured as follows. Section 3.1 reviews the theoretical framework and the relevant subset of literature introduced in the first chapter. This framework establishes the premise and hypotheses for the collaboration exercise. Section 3.2 provides a brief overview of the design and logistics of the collaboration exercise itself. The main results of the analysis of design outcomes follow in Section 3.3 identifying the relative effects of collaboration mechanisms. Section 3.4 then presents the results of a behavioral archetype analysis which uncovered emergent patterns from participant behavior during the exercise. Finally, Section 3.5 summarizes the contributions of the experimental study of collaboration mechanisms.

3.1 Review of the theoretical framework for negotiated collaboration

This thesis began with the question: "Why collaborate?" in the context of complex design problems such as the early stage design of infrastructure P3s. The question is important because as a society we often exert large amount of effort to either create collaboration structures or to restrict it (through arms length transactions, example). Through this investigation, we want to gain a sense of how mechanisms of collaboration create value for the participating project actors.

The chapter on co-design showed that design solutions to complex design problems often present trade-offs in value. Value is in the eye of the beholder, in the sense that the value dimension depends on the perspective and role of the decision-maker. For example, a public sector agency prioritizes the reliable supply of an infrastructure service, whereas a firm's primary objective is profit. The co-design analysis illustrated that there is a zone of negotiated agreement where there are many feasible designs that can simultaneously meet project actors' value objectives. The final choice depends on the ability of the designers to first identify the existence of those designs and then agree on the specific attributes to balance trade-offs. Whereas the co-design analysis shows that suitable designs are *available*, the process of negotiated collaboration allows project actors to *capture* the available value.

The experimental collaboration exercise is about understanding how project actors engage with each other to capture value and balance trade-offs. This work uses the following as a formal definition of the 'negotiated collaboration' process:

Definition: Negotiated Collaboration

Negotiated collaboration is a process in which project actors with competing objectives and asymmetric information co-create a solution to balance trade-offs through communication and knowledge exchange.

The specific design context for the collaboration exercise is identical to the setting of the co-design analysis, and is worth reviewing here. The objective is to design the early stage concept of a large infrastructure facility under conditions of long-term uncertainty. There are two key design roles, a principal and an agent. The two parties are linked to each other through a concession contract. The contracting parties have different and often competing objectives that can result in trade-offs. The design problem consists of simultaneously making technical as well as contractual choices.

3.1.1 Framework

Figure 3.1 presents a framework for connecting the different aspects of this type of design problem. It links the mechanisms of negotiated collaboration and the construct of co-design to multi-dimensional value outcomes. Value outcomes are at the top of the schematic, since they emerge from the design process. Outcomes are conceptually represented along two dimensions. The 2 x 2 shows the project actors' roles along the horizontal axis and type of outcome value along the vertical.

- **Outcomes by Role Type**: Along the horizontal, 'Public' and 'Private' indicates the project actors playing two key design roles, the principal and the agent respectively. In a real project, the principal is a public authority that must ensure the delivery of an infrastructure service. The agent is a private firm (or consortium) that contracts with the authority to deliver this service. Figure 1.3 covered a number of contracting options; this stylized design problem assumes a concession approach between public and private actors.

- **Outcomes by Value Type**: Along the vertical, outcome values are of two types. The first type, Objective Value (OV), represents the economic and technical payoffs to the principal and agent in the project. Profits and contract payments are examples of economic payoffs

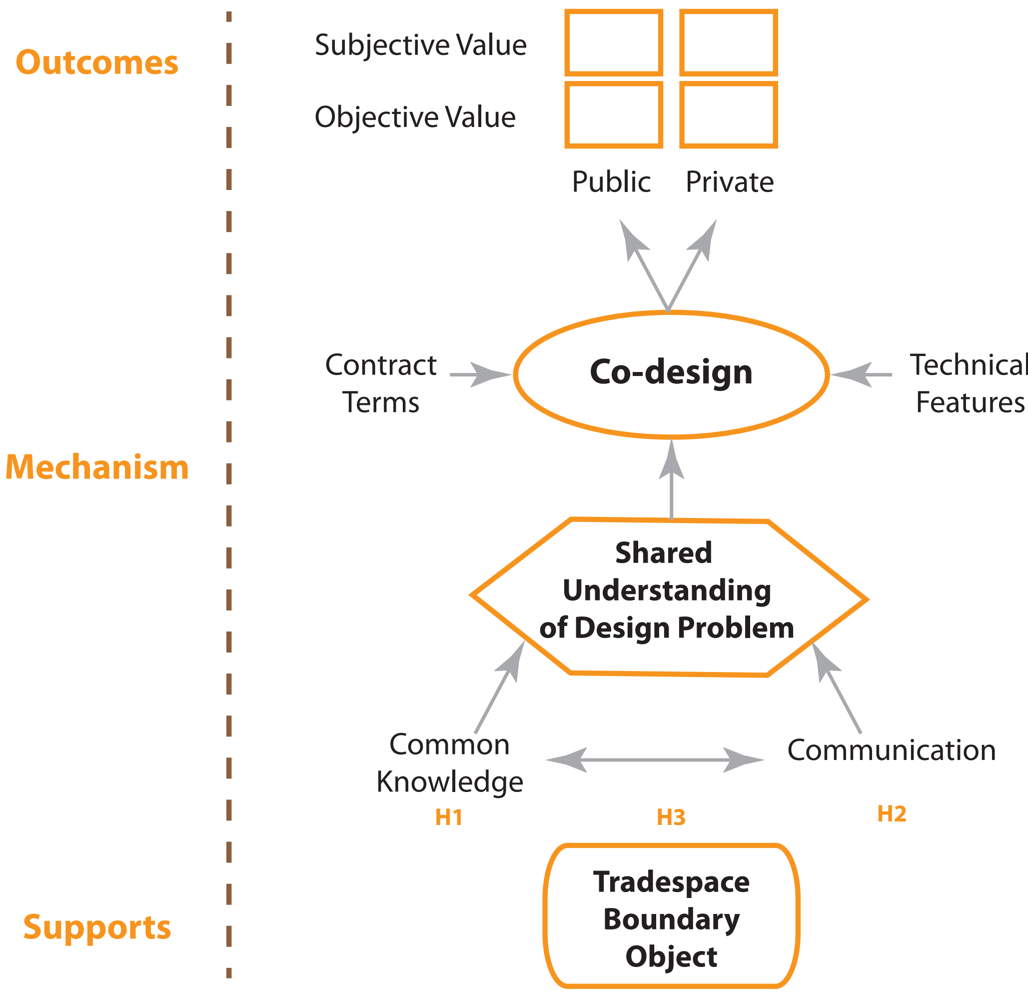


Figure 3.1: A theoretical framework linking the cognitive sub-mechanisms of negotiated collaboration to multi-dimensional value outcomes that emerge from co-design.

for the firm and the authority. System reliability is a technical payoff, and it is experienced by both actors. The bulk of the design and negotiation literature has focused on outcomes in terms of Objective Value. On the other hand, Subjective Value (SV) has received less attention. Subjective Value (SV) denotes the project actors' psycho-social outcomes. These are of an emotional and relational variety. The SV type captures phenomena such as sense of self, rapport, trust, and satisfaction from the engagement process.

The design process composed of co-design as well as collaboration mechanisms is in the middle of Figure 3.1. Project actors design both the concession as well as some high-level technical features of the project. Contract terms such as contract price ($/unit) and payment levels are important parameters for concession design. Technical design features could include technology type, output production capacity of the project, number of production phases, etc. Technical choices and contractual terms interact to deliver Objective Value outcomes for the actors. The dynamics of negotiation influence Subjective Value outcomes.

For project actors to reach agreement in the collaboration process, they must develop a shared understanding of the design problem. This requires them to reconcile their own interests with those of the negotiation counter-party. In other words, designers' mental models must become similar over time. A designer's individual understanding develops through searching for relevant information, and learning by observing the effect of choices on outcomes. Additional cognitive mechanisms are necessary for shared understanding to develop. After this, collaborators make a number of moves and counter-moves to propose design choices until they approach agreement.

The framework posits how two separate mechanisms of collaboration can contribute to shared understanding, along with a third mode in which they two mechanisms are simultaneously active and interact:

H1 – Common Knowledge:

Common knowledge enables collaborators to achieve a shared understanding of the design problem by making explicit the relationship between negotiated choices and the co-designer's expected outcomes.

Common knowledge is the converse of information asymmetry. The more knowledge the designers have about each others interests, objectives and expected outcomes, the lower the degree of information asymmetry. When common knowledge is low, designers must find a way to exchange information with each other to develop a shared understanding. Documents, graphics, and other visual artifacts can all support information exchange. In this sense, these boundary objects are factual. The story is in the data, and collaborators must connect the dots to tell the story.

H2 – Communication:

Communication enables collaborators to achieve a shared understanding of the design problem through a process of discussion and reasoning in which they selectively pass information to alter co-designer's mental models.

Communication is an interactive and iterative process in which designers use language laden with facts to convey meaning through dialogue. Dialogue can be written or verbal. It is characterized by high frequency exchanges composed of individual messages. In other words, communication occurs in real time or over short time spans. Designers propose and evaluate offers and choices iteratively. Communication biases information in that it always represents one party's version of the design story. The bias can be unconscious, or it can be an intentional strategic representation.

H3 – Knowledge - Communication Interaction:

Common knowledge and communication interactively enable collaborators to achieve a shared understanding of the design problem by enhancing the sense-making process.

Common knowledge provides broader factual representations of the collaborator's selective narrative that the recipient can use to question, verify and validate the altering mental model. Common knowledge may reinforce the effect of communication, whereas communication can amplify the effect of common knowledge by by identifying salient information. While collaborators can rely on their language and training for sense-making and problem-solving, formal artifacts for information exchange can serve as External Memory aids to reduce cognitive burden.

Supports for information exchange are at the bottom of the framework schematic in Figure 3.1. Computer models that relate design choices to expected performance outcomes are an important form of artifacts that enable information exchange. In the stylized design problem presented here, outcomes are multi-dimensional. Designers are therefore trading off expected outcomes by making changes through co-design. Computer models that support the analysis of trade-offs of co-design and enable project actors to collaborate are called tradesapce boundary objects.

In summary, the theoretical framework for this research thus captures a process in which collaborators make design choices through co-design. To negotiate choices effectively, they must develop a shared understanding of the design problem by arriving at similar mental models. Computer models of the co-design problem can support the mechanisms of information exchange and communication in collaboration. The dynamics of negotiation and design choices result in multi-dimensional value outcomes both in terms of the roles of project actors as well as the nature of the payoffs, whether economic or pyscho-social.

3.1.2 Relevant literature

Problem-solving by human actors is central to the conceptual design of systems like infrastructure projects. Hernandez, Shah, and Smith (2007) suggest that in product design, 70 - 80% of product cost is committed during the conceptual stage as a consequence of design choices. While a similar statistic is unavailable for infrastructure projects, it is clear that the conceptual stage of design has cascading implications for the rest of the project design process, and indeed over the project's life (Lin et al., 2009; Lessard and Miller, 2013; de Neufville and Scholtes, 2011). This section discusses research on cognitive aspects in conceptual design.

Design cognition as a field of research applies cognitive science to design. It takes on questions of how human designers think about a problem, how they find and reason through relevant information, and how they create solutions (Linsey et al., 2010; Dinar et al., 2015). Under the umbrella of design cognition, the topics of shared understanding through collective mental models, information exchange, and communication are germane to negotiated collaboration.

For designers to co-design and negotiate design outcomes they must develop a shared understanding of the design problem (Lawson, 2006). Prior research on team cognition has looked at how interaction and collaboration can lead team members to converge on a single problem solving outcome (Fiore et al., 2010; Reiter-Palmon, Wigert, and de Vreede, 2012). In these situations, designers transform a single or small number of ideas into a creative solution to a technical problem by developing a similar view. Mental models are one way to capture designers' shared understanding (Badke-Schaub et al., 2007).

Wood et al. (2014) study the effect of team interaction structure, i.e. independent versus collaborative design, on the designers' mental models. Representations of mental models are produced with Latent Semantic Analysis (LSA), essentially an analysis of bodies of text (Dong, 2005). They found that collaborating designers had mental models that were more similar than those of independent designers. Collaboration also decreased fixation, the tendency to focus on a subset of features or ideas, and led designers to think openly about possible solutions. Collaboration can thus increase shared understanding between designers.

Information exchange and communication (dialogue, more specifically) are two distinct mechanisms of collaboration. Dialogue between designers embeds relevant information, although dialogue is neither necessary nor sufficient as a means of exchanging relevant information. Written documents such as proposals, graphs and charts, presentations, and other such objects all deliver information without requiring dialogue. Designers may however need to engage in further dialogue over these objects and seek clarity to truly understand their meaning and importance. Too much information can also be burdensome and fail to improve outcomes (Clevenger, Haymaker, and Ehrich, 2013). Conversely, designers may intentionally withhold or bias information in some competitive situations when revealing objects are not available.

When designers possess asymmetric information about the design problem, the mechanism of information exchange becomes critical (Honda et al., 2015). Designers' style or approach towards information exchange can shift system-level design outcomes. Austin-Breneman, Yu, and Yang (2014) show that design practitioners behave strategically while negotiating design trade-offs. They hedge their future needs by representing their view of the problem conservatively and through "worst cases". This biases the collaborators' mental models.

The complexity of the problem can also affect whether designers are able to develop productive mental models and how they exchange information. Hirschi and Frey (2002) find a geometric relationship between problem solving time and the degree of coupling, i.e. interdependence between design parameters. Flager, Gerber, and Kallman (2014) also look at the effects of coupling for a building design problem although they find that coupling becomes less important as the scale of the problem (number of design variables) increases. Instead, solution quality decreases sharply as scale increases. The design process must account for these effects as designers explore complex problem spaces.

Communication (dialogue) can thus assist designers in developing a useful mental model of a complex problem when information is limited, biased or asymmetric. Studies have demonstrated the importance of face-to-face communication for distributed design problems, where designers often work separately and meet infrequently. Others have also studied the effects of collocation. When face-to-face meetings and colocation is infeasible, designers may use computer-based collaboration spaces or methods to support one or both of information exchange and communication (Ostergaard et al., 2005).

As designers negotiate choices in the collaborative design process, they rely on information exchange and communication. Klein et al. (2003) suggest that interdependent designers exhibit tendencies such as "hill climbing" (securing a local maximum) or "annealing" (temporarily accepting lower payoffs to continue the search process). The engineering literature has emphasized the mathematical formulation of strategies and game design to secure desired system-level outcomes (Honda et al., 2015). When human designers engage with each other in real time however, cognitive biases and other psychological effects affect negotiation dynamics (Simon, 1987).

Cognitive biases can lead negotiators to deviate from normative prescriptions and rational behavior in the negotiation process. Of the many systematic biases in two-party negotiations (Bazerman, Curhan, et al., 2000; Tsay and Bazerman, 2009), three in particular are very relevant to design-related negotiations. The first is 'bounded awareness' which causes negotiators to give undue attention to readily available information even if it is unimportant. They may also be unable to make use of less noticeable but available salient information (Pinkley, Griffith, and Northcraft, 1995). They may fail to focus, and some "known" variables may therefore become peripheral to the vision and attention of the decision-makers in the design negotiation (Bazerman and Chugh, 2005; Chugh and Bazerman, 2007; Lessard, 2007). The second bias relevant to design is 'egocentrism'. Negotiators may ignore the perspective of other parties (Valley, Moag, and Bazerman, 1998) and overlook valuable available information by failing to consider the opponent's cognitive perspective (Bazerman and Carroll, 1987). Often the egocentric view arises because a negotiator believes that the other party is overstating its case (Tsay and Bazerman, 2009). The third bias is the 'fixed pie effect.' Negotiators may falsely assume that the available payoffs from negotiation are constant sum - the size of the so-called negotiation pie is fixed (Bazerman, Magliozzi, and Neale, 1985; Gimpel, 2008). They miss opportunities for mutually beneficial trade-offs that increase the size of the pie (Fukuno and Ohbuchi, 1997).

These cognitive biases often surface in design-related negotiation interactions. They are important to consider because they affect the negotiating designers mental models and understanding. The literature on mental models in negotiation is parallel to that in design cognition. Studies of negotiation define a mental model as a cognitive representation of the expected negotiation

(Bazerman, Curhan, et al., 2000). This research shows that cognition and the negotiation structure are reciprocally intertwined - structure influences mental models and cognitive perception shapes structure and behavior.

Mental models of the negotiation situation, the other parties in the negotiation, and the self affect negotiator behavior and outcomes. Thompson and Hastie (1990) suggested that negotiators who modified their 'fixed pie' perception, did so early in the negotiation; the bias persisted throughout for negotiators who didn't. Studies on attribution and interpersonal perception (Gilbert, 1994) have demonstrated how negotiators often overestimate the ideological difference or incompatibility of interests of others (Keltner and Robinson, 1997).

Role theory addresses mental models of the self (Montgomery, 1998), showing that in negotiation situations with the same economic structure, individuals behave differently depending on the meta-rules of their roles. The same individual may also modify behavior depending on how they perceive their role changing in different situations. How negotiators understand and define the game for themselves can thus be a critical determinant of how they engage.

Even though individual negotiators may start out with different or contradictory perceptions, asymmetric mental models do not persist over the course of the negotiation interaction. Negotiators eventually create a shared understanding of the situation, their perception of other negotiators, and the rules of engagement (Messick, 1999). This phenomenon is precisely what we are looking to leverage in developing shared understandings of design problems in collaborative processes.

3.2 Overview of Experiment

This section provides a brief overview of the design and logistics of the experimental collaboration exercise.

3.2.1 Design problem: a desalination P3

The collaboration exercise uses the same stylized design problem formulated for the co-design analysis for consistency. The problem resembles a real-world project design context, but is more abstract and general. The problem involves the conceptual design of a desalination project P3. Figure 3.2 depicts the structure of the problem.

There are two project actors: a public sector entity (the principal) and an engineering firm (the agent). The principal and the agent are entering into a long-term concession contract in which the principal will compensate the agent for a service it provides. In the chosen setting, the principal is a pubic Water Authority entering into a long-term Water Purchase Agreement (WPA) with an engineering firm. The Firm will build and operate a large-scale desalination facility to supply treated water to the public authority. This is a relationship-specific investment, i.e. the agent firm would not invest in and operate this facility without the assurance of a contract with the water authority.

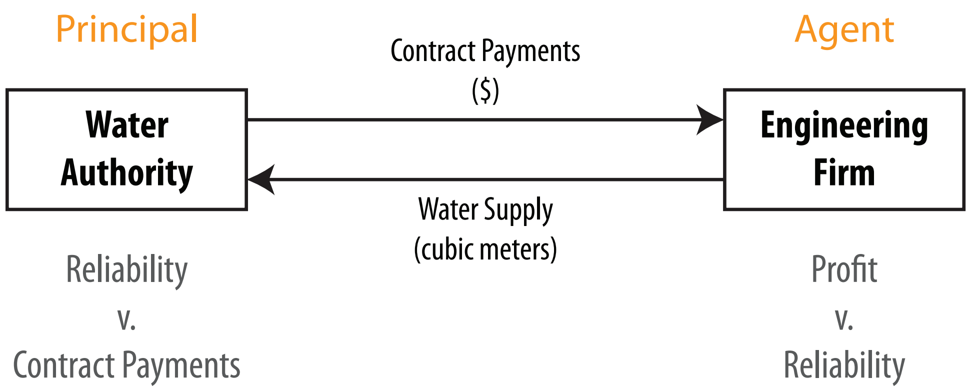


Figure 3.2: A desalination P3 project as a case example for the collaboration exercise. The Water Authority is the principal that enters into a long-term concession contract with the agent, an engineering Firm, for reliable water supply. The principal trades-off value in terms of contract payments for reliability whereas the firm trades reliability for profit.

Each of these actors has different objectives and perceives the value of designs correspondingly. The principal wants to ensure the public interest. As a water authority, it desires reliable water supply and is willing to make contractual payments in return. It trades off payments for reliability. On the other hand, the agent's objective is profit. It is willing to deliver a reliable water supply for profit. The firm trades off reliability for profit. There are thus three ways to express value in these problem, in the three dimensions of contractual payments (water authority's view of the problem), profit (firm's view of the problem), and reliability which trades off the other two and links the outcomes to both the principal and the agent.

The technical configuration affects how the project creates value. The desalination facility uses energy to transform saline water into potable water. Since water is valuable to society the water authority (as a proxy for society) benefits from water supply. Under conditions of demand uncertainty, the reliability of the project is defined as its ability to deliver water as and when demand arises over time. Some design configurations may be more reliable in meeting demand than others.

The long-term concession agreement creates a mechanism for the exchange of value. It provides the project with a structure to link the decisions of the two project actors. It also that governs how risk affects the principal and the agent. For example, the contractual price terms and other provisions determine the payments that the water authority makes to firm. The contract may also include risk allocation mechanisms such as minimum income guarantee provision in a take-or-pay structure to mitigate the demand risk to which the project is exposed.

The design problem for the collaboration exercise is thus the same co-design problem as the premise for the tradespace model. The setup involves both value creation through technical design and value exchange through contract design.

3.2.2 Co-design software: DesalDesign

The collaboration exercise requires a mechanisms for participants to co-design and explore the value outcomes of those design in real time. I therefore converted the tradespace model that Chapter 2 discussed into an interactive software tool. The tradespace model studies how changes in designs relate to trade-offs in performance across key dimensions of interest. This is essentially a parameter design problem with coupled variables. In other words, changing the levels (or parameter values) of key input variables affects the performance of the design, and the relationships between performance and input values also depends on how the variables interact with each other. These interactions can be easily analyzed outside of the design experiment, so that the full tradespace is already known before participants engage with the experimental version of the model.

The DesalDesign computer simulation model was developed in MATLAB with a graphical user interface, as a 'support' for conducting this exercise. Figure 3.3 shows a screen shot of the user interface. The software tool acts as a boundary object (Iorio and Taylor, 2014) because it can help the principal and agent span the gap between their information and objectives. In other words, the boundary-object is an interactive common calculator that the fixes the relationships between input and output variables, so that the decision-makers can focus on how changes in inputs affect outputs. By performing complex calculations in real-time, the computer model allows us to study how collaborators, i.e. the participants engage the design problem conceptually without getting bogged down in calculations. Users can modify both technical design variables as well as contractual variables in a process of co-design.

The tool collects data on every design iteration that a participant explores, along with process information such as time stamps. It also records design choice 'submissions', the final design a collaborator may choose in response to a design task. These data are sent to me for later analysis.

3.2.3 Exercise protocol

The sample of participants in the exercise can be described as follows:

- The original size was N=140. After attrition and logistical issues, about 112 participants completed the exercise
- Average age = 32
- Average years of work experience = 10
- Sectors: Mechanical aerospace engineering (product/system design, manufacturing, procurement and contracting); information technology (software, services and enterprise systems)
- Location: 90 subjects on campus, and 50 remote

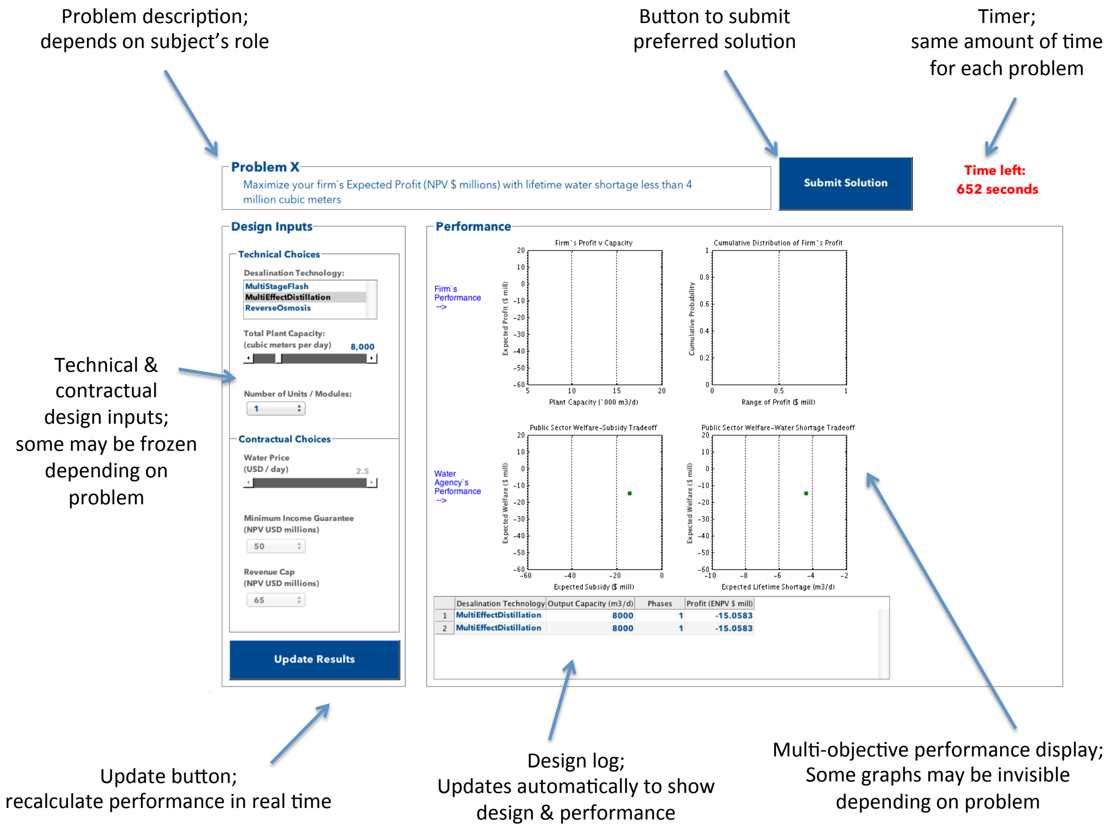


Figure 3.3: The user interface for the DesalDesign tradespace co-design model

The schematic in 3.4 depicts the structure of the experimental collaboration exercise. At the start of the design session, the administrator simultaneously gave all participants a ten-minute tutorial on the essential elements of the design problem and setting. The tutorial consisted of a pre-recorded movie clip, with embedded presentation slides and a voice recording. The tutorial included an example of a desalination plant, and the long-term concession contract approach for procuring such facilities. The presentation slides and verbal description covered the principal-agent nature of the procurement with each party's objective functions, constraints and the design variables that affected them. The presentation also included an overview of the DesalDesign software with an introduction to the interface, problem description readouts, and key input and output indicators. By the end of the tutorial, participants had thus had a full overview of the general design problem, and also the workings of the software tool they were about to use.

In addition to the tutorial, participants also received a one-page role sheet that summarized the information from the tutorial, in a way that emphasized their role. This served as a reinforcement of the information and as an easy resource and reminder. The roles sheets are included in Appendix I. With the recorded movie clip and printed role information, participants received the information using three media to support a number of differential learning styles.

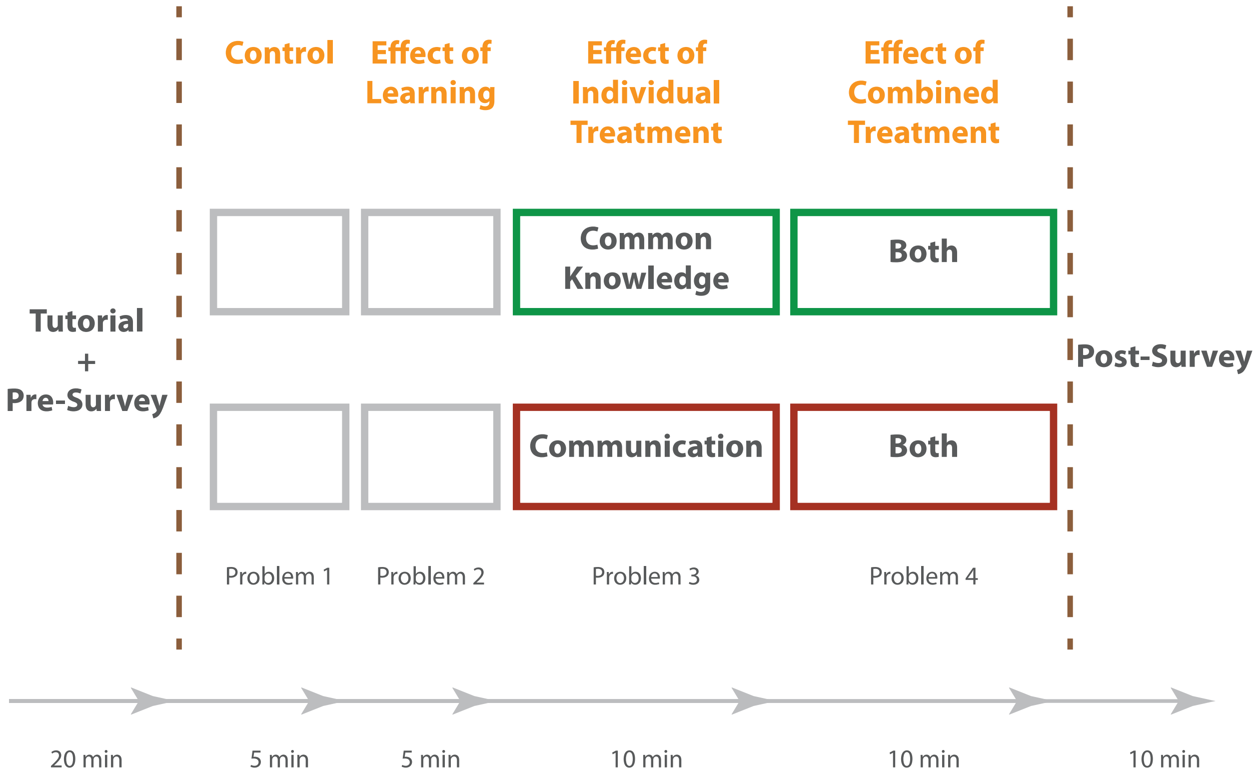


Figure 3.4: The design of the experiment for studying the relative effects of collaboration mechanisms.

Immediately after the tutorial, participants responded to a series of survey questions comprising the 'pre-experiment survey' (see Appendix J for the full survey). Some questions addressed factual details covered in the tutorial and printed role sheet. These were designed to capture participant's understanding of the facts of the design problem. Participants were also asked to explicitly rank how well they thought they understood the design task and objectives. The first subset of questions had 'correct' responses with binary scoring (correct: 1, incorrect: 0) and total scores could range from 0 to 20. The rest of the questions were marked on seven-point Likert scales with a 1: 'Not at all', to a 4: 'Moderately', and 7: 'Extremely'. These scores were used to populate the measures of Objective Understanding (ObjU) and Subjective Understanding (SubjU) respectively (see Subjective Value analysis in Chapter 4)

Prior to the exercise, I created pairs through stratification and random selection. I also randomly assigned pairs of participants (one the Firm and the other the Water Authority) to two groups. These groups were called 'Communication first' and 'Information first' - the logic becomes evident below. Pairs in both groups had to solve the same design problem four times. The design problem was identical in each round for both groups. This provides a natural control in the experiment since the structure of the task does not change.

For the first two problems, the control round and test of learning round, participants were told to design independently. One aspect of 'Independent Design' is that there was no communication between collaborators. This implied that each person in a co-design pair would work individually on the design problem on their computer device, without interacting with their pre-assigned counterparty in any way. The second aspect of 'Independent Design' is that participants would only see performance results that affected their performance objective. In other words, the Firm would see the trade-off rofits versus reliability, whereas the Water Authority would see the trade-off of contract payments with reliability. The experimental treatments were obtained by relaxing each one of these implied constraints. Treatments were thus only applied after the first two problems.

'Communication' treatment:
Under this treatment, participants were asked to communicate with their pre-assigned collaborator to complete the design problem. This treatment comprised the relaxation of the first implied constraint of the control rounds. Pairs of co-designers communicated using a private chat room created specifically for their dyad. The chat room recorded a transcript of their communication. The group that received Communication as the only individual treatment in Problem 3 is labeled the 'Communication first' treatment group.

'Common Knowledge' treatment:
In this treatment, participants saw information corresponding to both their own value outcomes as well as their counterparty's outcomes their computer screen. The treatment case was obtained by relaxing the second implied constraint from the control rounds. Participants now had access to both their own results as well as the counterparty's results. The information asymmetry in performance between the two thus vanished. The group that received Common Knowledge as the treatment in Problem 3 is the 'Information first' treatment group.

Note that these two treatments are independent. A group of participant pairs could have Communication, Common Knowledge or both. All participants received both treatments in the final round, Problem 4. Thus both groups received both treatments, albeit in different orders (order switching). This allows us to isolate the effects of the two treatments in some parts of the analysis.

After all four problems, participants responded to a post-experiment survey (Appendix J). Some questions elicited their perceived experience of the treatments. Specifically, participants stated whether completing the exercise resulted in an *Improvement (Im)* in their understanding. They also stated how much they attributed any improvement to ability to communicate. Finally, the survey also queried them about the whether see additional information about the counterparty led to confusion, thereby detracting from their understanding.

The chapter has thus far presented the theoretical framework, literature, and the experimental design of the collaboration exercise. The rest of this chapter discusses the results.

3.3 Outcomes Analysis

This section presents the main results of the analysis of submitted design choices. Participants in the collaboration exercise submitted a 'final' design as their choice at the end of every problem round. The term "design choice" in this analysis refers to the submitted design, and not to the many preceding iterative trials.

These design submissions were automatically logged in the software and sent to me for later analysis. The logged data tracked not only the independent design variables but also the multi-dimensional value outcomes and identifying information about the treatment group, problem round, and whether the participants had designed independently or collaborated in each round.

We first focus on value outcomes of design choices. There are three dimensions of value in this problem - the reliability of meeting demand (expressed as a %), expected profit for the Firm (NPV USD million), and expected contract payments by the Water Authority. Values are automatically calculated by the tradespace model.

Value outcomes in any one problem are meaningful only in relation to outcomes for the same individual or group across problems and across groups. The statistical tests therefore use the information on distributions of outcomes for a group (ex. mean and variance of value in a group) or the distribution of the change or *delta* in value ($\Delta V_i^{\Delta p}$) for the same individual i across problems p for a particular value dimension V in each sub group. For example, the change in profit for a Firm role-player i between problems 2 and 3 is

$$Profit_i^{\Delta 23} = Profit_i^3 - Profit_i^2$$

The analysis can therefore handle both 'within-subjects' variation using the differenced data or 'between-subject' and 'between-group' variation using the undifferenced value outcomes.

The following sub-sections report the results from tests of the effect of learning, the effect of individual treatment - either communication or common knowledge, and then the effect of the combined treatment with both communication and common knowledge conditions active.

3.3.1 Effect of learning

We can expect that a designer (or any problem-solver more generally) gets better at solving a simple but novel problem over time through learning. In a goal seeking problem like the one in the collaboration exercise, the participant's first few attempts may fall far from the goal. Given more time to make additional attempts, a participant may get closer. Performance in this sense can improve over time because the participant cumulatively learns about the structure of the problem and develops an understanding of the sensitivity of outcomes to different variables. This process of learning is *individual* because there are no other stimuli or interactions, either with artifacts, information, or other collaborators. We contrast this with shared understanding developed through collaboration. We can formally state the individual learning hypothesis in the collaboration exercise as follows:

$H_{Learning}$: Given more time, a participant working independently will increase their value outcome because of individual learning.

$H^{F}_{Learning}$: The Firm will increase its profit over time.

$H^{WA}_{Learning}$: The Water Authority will decrease its contractual payments over time.

The objective of Problem 2 in the collaboration exercise was to provide a means of testing for the effect of learning. Problem 2 was identical to Problem 1 in all respects across both Role and Treatment groups, except for the passage of time. Problem 2 gave participants more time to see if they could do better. Each participant therefore worked independently in Problem 2, similar to the task assigned in in Problem 1. The differences in value outcomes between Problems 1 and 2 along participants respective value dimensions allows us to test the learning hypothesis.

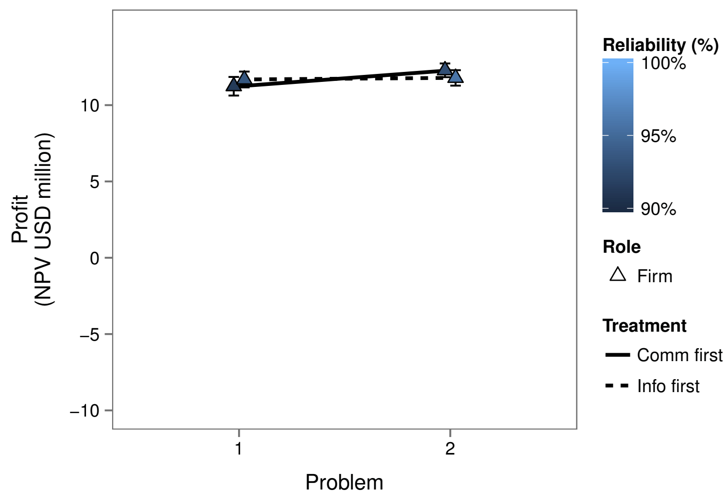
Note that the meaning of treatment groups is irrelevant for the testing the effect of learning. I maintain the two groups as separate throughout the analysis for parsimony. The separation becomes important in the following section, Section 3.3.2, which tests the effect of individual treatments.

The test of the learning hypothesis finds that participants captured most of the available gains from individual learning in Problem 1. Figure 3.5a shows the mean and standard error of profit outcomes for the Firm. The outcomes are comparable across Problems 1 and 2, in both treatment groups. Participants in the Firm's role accomplished their primary objective (profit -> NPV USD 10 million, and no less than 5 million) in both problems. A t-test for differences in means cannot reject the null hypothesis that the mean difference in profit for each participant between the two problem rounds is zero ['Communication first' group: p=0.09; 'Information first' group: p= 0.85]. Similarly, test results for the reliability outcomes did not reject the null hypothesis.[1]

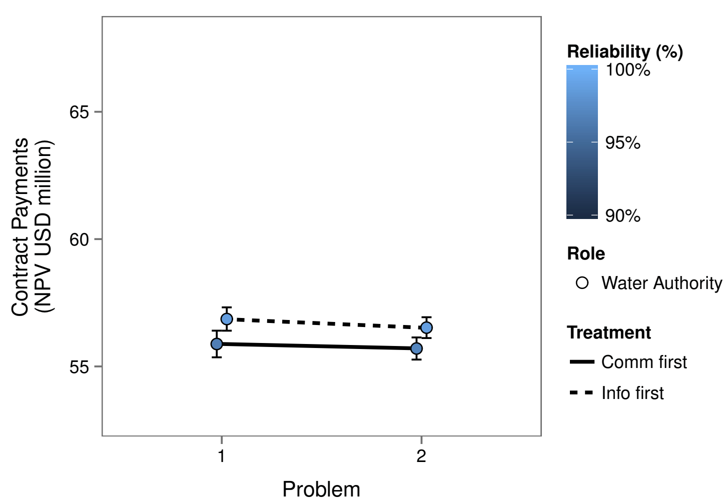
Similarly, the Water Authority role's outcomes are comparable between Problems 1 and 2 across the treatment groups (Figure 3.5b) showing similar means and standard errors for contractual payments. Participants submitted designs that accomplished their main objective of high reliability of meeting demand at very low contractual payment levels (payments -> NPV USD 55 million, and no more than 60 million). A statistical test of the mean difference for each participant's payment outcomes is not significantly different from zero ['Communication first' group: p=0.77; 'Information first' group p= 0.44]. Test results did not reject the null hypothesis for the reliability outcomes either.

Based on these tests, we do not find support for the individual learning hypothesis $H_{Learning}$ as formulated, but can conclude that the experimental participants demonstrated a saturation in individual learning in Problem 1, because they were able to accomplish their objectives in both problems in a comparable manner. This conclusion lends confidence in later analysis that participants already knew how to individually accomplish their objectives before collaborating. We can thus decouple the effects of learning from the effects of the experimental stimuli of interest. Since we have concluded that learning was saturated by Problem 2, this round can be

[1]See Appendix E for the full suite of differences in means tests



(a) Firm's profit outcomes are comparable between Problems 1 and 2, across both treatment groups. The mean difference in profit for individuals is not significantly different from zero.



(b) Water Authority's contractual payment outcomes are comparable between Problems 1 and 2, across both treatment groups. The mean difference in payments for individuals is not significantly different from zero.

Figure 3.5: Comparing value outcomes for both the Firm and the Water Authority across Problems 1 and 2 to assess the effect of learning.

treated as the saturated control round. Next steps of the analysis therefore drop design choices from Problem 1 to simplify the analysis and make it easy to explain. The subsequent analysis therefore shows measurements with the saturated control round of Problem 2 as the starting point.

3.3.2 Effect of individual treatments

We now parse the relative effect of communication (dialogue) as a collaboration mechanism from that of having or acquiring knowledge in common with the collaborator. Section 3.1.2 reviewed the literature on design cognition and negotiation to develop the argument that both communication and information sharing can influence designers' shared understanding (mental model) of the design problem. With this premise, we look at how the ability to engage in dialogue ('Communication' condition) without any information about counter-party performance affected value outcomes for collaborators. The effect of receiving new information about the collaborator's expected performance ('Common Knowledge' condition) without any ability to engage in dialogue is also studied. This approach allows us to study the relative effects of collaboration mechanisms on value outcomes.

We formulate hypotheses about the effects of the two separated collaboration mechanisms examined individually.

H_{Comm}: The ability to engage in dialogue with the collaborating counterparty is associated with a systematic shift in value outcomes. Participants make trades across value dimensions in favor of their collaborator's objective.

- H^{F}_{Comm}: A communicating Firm will trade profit for reliability.
- H^{WA}_{Comm}: A communicating Water Authority will maintain reliability by increasing contract payments.

H_{Info}: The ability to know the collaborating counterparty's expected value outcomes is not associated with a shift in value outcomes. Participants will remain fixated on their own value dimensions, and will not make value trades across dimensions to support their collaborator's objective.

- H^{F}_{Info}: A knowledgeable Firm will egocentrically anchor to its initial high expected profit at the expense of reliability.
- H^{WA}_{Info}: A knowledgeable Water Authority will anchor to low contract payments, while expecting high reliability.

Problem 3 executes the individual treatments. In this problem, each participant received one of two treatments, corresponding to one of the two mechanisms of interest. Participants experienced either the 'Communication' condition, or the 'Common Knowledge' condition.

The treatment group that first experienced the Communication condition was labeled 'Communication first'. With Communication, participants were asked to collaborate with their pre-assigned partner. Each participant could now use their online chat system to discuss the design task with the counter-party role player in their collaborating pair. The only restriction placed on the type of dialogue between participants was that they should not self-identify or ask about the identity of the collaborator. There was also no requirement that participants had to agree on their individual design choice by the end of the round.

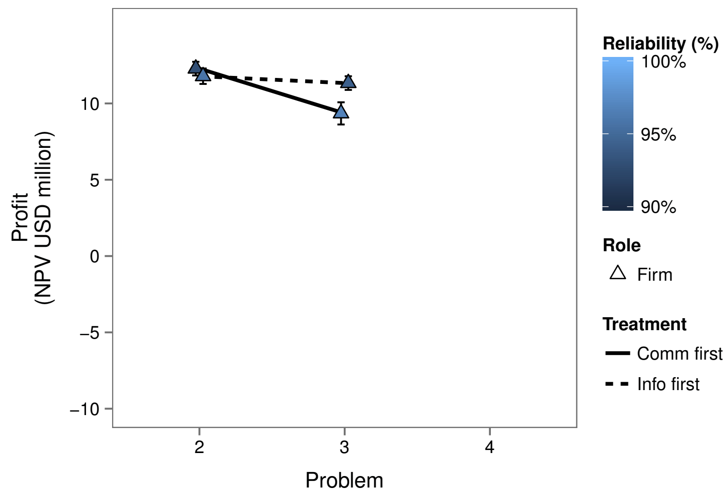
The treatment group that first experienced the Common Knowledge condition was labeled 'Information first'. In this group, participants continued to work independently, i.e. they could not engage in dialogue yet. These participants however received additional information about the effect of their own design choices on the counterparty's expected value outcomes. The Firm saw outputs on its screen that showed the consequence of its designs not only on profits and reliability as in Problems 1 and 2, but also on expected contractual payment obligations for the Water Authority. The Water Authority also now received information about the effect of its design choices on the Firm's expected profit. This is how both roles came into Common Knowledge, by receiving additional information.

The plots in Figure 3.6 show the outcomes for both the Firm and the Water Authority across the two different treatment groups. The value outcomes from both Problems 2 and 3 are compared. The triangle shape denotes the Firm's outcomes in the upper plot. The circles in the lower plot denotes the outcomes for the Water Authority. Reliability (%) is a common dimension of interest to both roles and is indicated by the color gradient. Lines representing the treatment groups connect the observations - solid for 'Communication first' and dashed for 'Information first'.

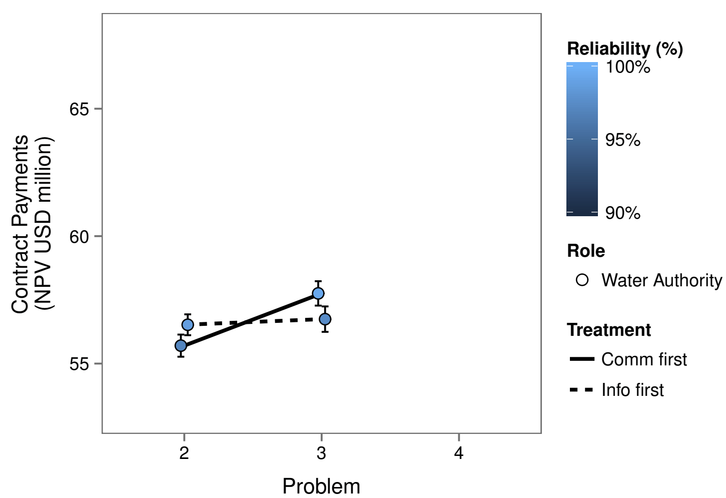
The upper plot, Figure 3.6a, shows that the Firm in the 'Communication first' treatment group traded its expected profit for increasing reliability. It shows a marked shift in comparison with the Firm in the 'Information first' treatment whose value outcomes seem comparable across Problems 2 and 3. This visual inspection lends support for H^F_{Comm} and H^F_{Info}. A statistical test of differences rejects the null hypothesis that difference in profit outcomes was the same for the Firm only in the Communication first case (p=0.004). In other words, the Firm systematically shifted its value outcomes when it was allowed to communicate and made trades in value in favor of reliability (p=0.1).

The Water Authority's outcomes, shown in the lower plot Figure 3.6b, also depict a similar story. The 'Communication first' treatment groups shows a pronounced shift between Problems 2 and 3, whereas the 'Information first' group remains level between the two. The Water Authority systematically increases its expected contractual obligations (p=0.003) to maintain reliability (p=0.09) when it is allowed to communicate. These observations lend support for H^{WA}_{Comm} and H^{WA}_{Info}.

The analysis shows that both the Firm and the Water Authority demonstrated systematic shifts only when communicating, which is convincing evidence for H^{Comm} by rejecting the null under this condition. There is also some less convincing support for H^{Info}, and we cannot reject



(a) Value outcomes for the Firm in Problems 2 and 3 in both treatment groups. The Firm shifts profit noticeably only under the 'Communication first' treatment.



(b) Value outcomes for the Water Authority in Problems 2 and 3 in both treatment groups. The Water Authority systematically shifts payments under the 'Communication first' treatment.

Figure 3.6: The comparative results of Problem 3 which depicts the effects of collaboration mechanisms as individual treatments on value outcomes. The upper plot is the Firm's perspective (triangles) while the lower is the Water Authority (circles). The solid line connects the observations in the 'Communication first' treatment whereas the dashed line joins the 'Information first' observations.

the null under this condition. We conclude that, when separated and tested individually in this manner, communication dominates common knowledge as a collaboration mechanism for securing trade-offs in value outcomes.

3.3.3 Effect of combined treatments

Although this collaboration exercise separated the two mechanisms of communication and information in Problem 3, we are also interested in their joint effect on outcomes. For this reason, we introduce the second collaboration mechanism in each treatment group. Since the 'Communication first' set of participants did not have Common Knowledge in Problem 3, they receive it in addition to Communication in Problem 4. In the same way, participants in the 'Information first' treatment group can engage in dialogue with their collaboration partner in Problem 4, which was previously unavailable to them in Problem 3.

The combined effect of Communication and Common Knowledge may create a more systematic shift in value outcomes than either of them alone. The pathways for a stronger shift may however be different. Communicating collaborators may use the additional information from Common Knowledge to validate or refine their mental model. On the other hand, knowledgeable collaborators who have never communicated may still have to undergo significant sense-making to develop a shared mental model. They have however already processed a large amount of information through the Common Knowledge condition, which dialogue can help to clarify. The hypothesis for the combined treatment is:

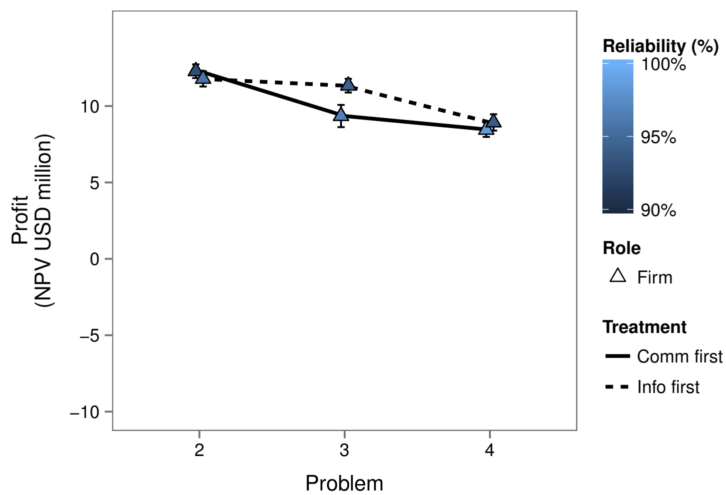
$H_{Combined}$: The combination of dialogue and common knowledge is more effective on value outcomes than the conditions separately. Participants will systematically shift choices to make sharper value trades in the combined treatment than in the individual treatments.

$H^{F}_{Combined}$: The Firm will trade profit for reliability more sharply to support the Water Authority's value objective than in previous conditions.

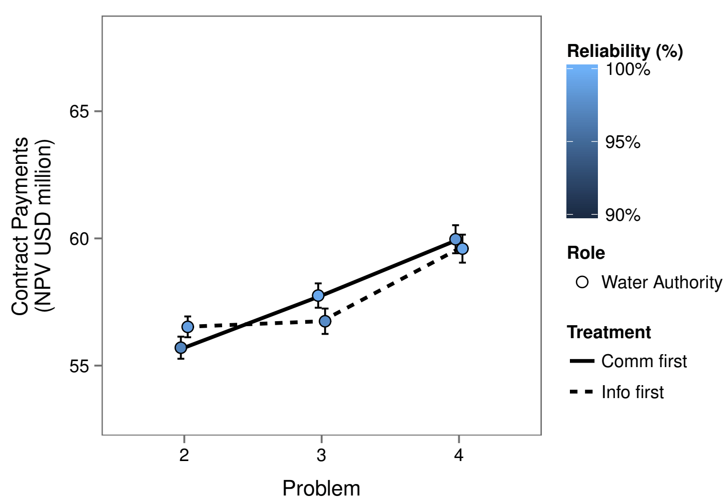
$H^{WA}_{Combined}$: The Water Authority will increase payments more sharply to maintain reliability in support of the Firm's value objective than in previous conditions.

Figure 3.7 shows the effect of the combined treatment on both the Firm and the Water Authority. The two treatment groups 'Communication first' and 'Information first' are still separate so as to track the trajectory of outcomes for each group over the course of the problems.

The upper plot shows that the Firm lowers profit incrementally to increase reliability over its choices from Problem 3. Even though the degree of the shift differs by treatment group, both groups converge to the same point in term of their mean level of profit. Both treatment groups for the Firm arrive at the same value choices in the final Problem, albeit through different pathways. The effect of Common Knowledge on the Firm, in addition to Communication (i.e. in the 'Communication first' treatment group) is to reinforce its choice of trade-offs. In the other



(a) Both treatment groups converge to similar profit and reliability levels under the combined effect of communication and common knowledge. Common knowledge reinforces the preceding effect of communication as seen in the 'Communication first' group.



(b) Both treatment groups converge to similar contractual payment and reliability levels under the combined treatment. Common knowledge amplifies the preceding effect of communication in this case.

Figure 3.7: Value outcomes for the Firm (upper) and Water Authority (lower) in a comparison of the control (Problem 2), individual treatment (Problem 3) and the combined treatment (Problem 4).

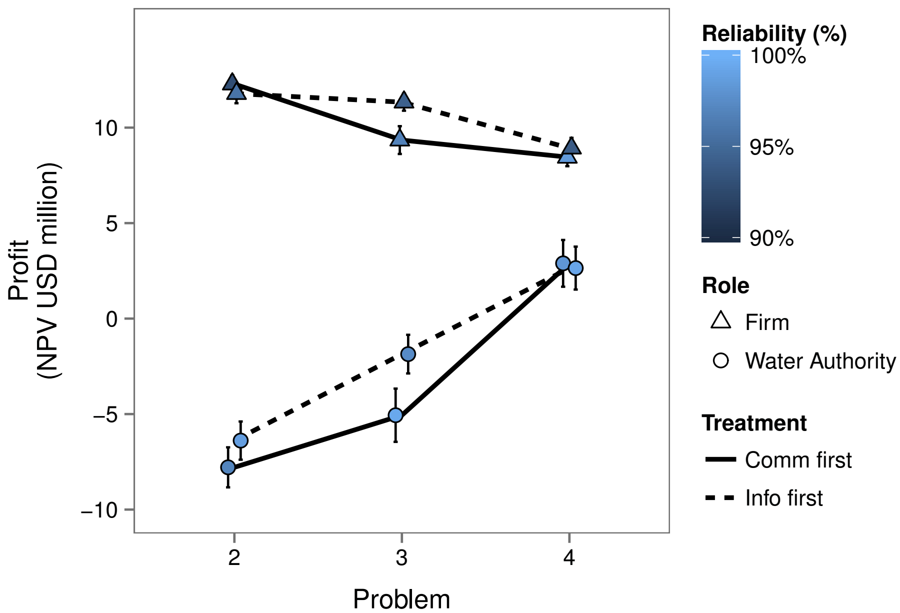


Figure 3.8: Value outcomes for both roles and treatment groups as seen from the Firm's dimensions of interest - profit and reliability.

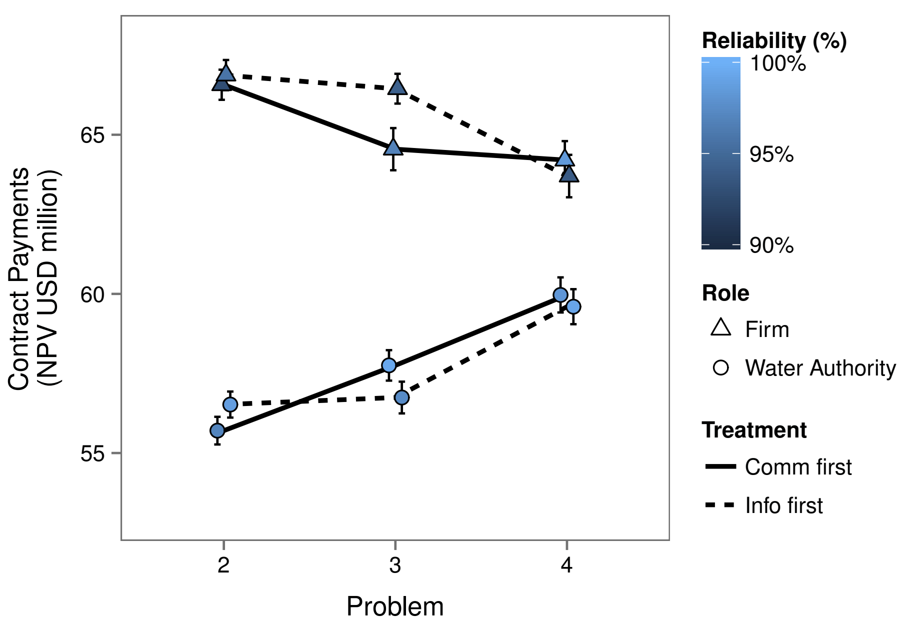


Figure 3.9: Value outcomes for both roles and treatment groups as seen from the Water Authority's dimensions of interest - contract payments and reliability.

treatment group 'Information first', trade-offs systematically occur (p=0.002) for the first time only in Problem 4. Although the participants already had Common Knowledge, it is only when they communicated that they made sharp trade-offs bringing them to the same level of outcomes as the other treatment group.

The final value outcomes for the Water Authority in the two treatment groups also converge under the effect of the combined treatment in Problem 4. In the 'Communication first' group the Water Authority continues to make sharp trade-offs by increasing contractual payments (p=0.003) to maintain reliability. The effect of Common Knowledge in this case is to amplify the effect of Communication. In the 'Information first' group where a sharp trade-off occurs for the first time relative to the previous Problems the shift is significant enough (p<0.001) for payments to reach the same level as in the other treatment group.

The evidence from the effects of the combined treatment in Problem 4 support $H_{Combined}$ in that the combined conditions of Communication and Common Knowledge result in sharper trade-offs than the individual conditions alone, in both treatment groups. Further, communication as a mechanism continues to dominate over information in shaping mental models to secure trade-offs in value. Common knowledge plays a supporting role, it can either reinforce or amplify the preceding effect of communication.

The visual representations in this analysis have always shown the participant's view of their own value dimensions. We have discussed the Firm's value outcomes by looking at its value dimensions of interest, profit and reliability, and the Water Authority's outcomes by looking at contractual payments and reliability. We can also look at the "other side of the coin". For example, we could observe the implications of the Firm's choices by looking at both the profit and payment outcomes, and vice versa for the water authority. Figure 3.8 and Figure 3.9 both do just this, they show the trends for both roles using the same value dimensions. In Figure 3.8, the Water Authority's design choices are translated to profit and reliability outcomes to compare with those of the Firm. We can see that the Authority's choices in all but the last problem would have resulted in negative profit for the firm. In the process of collaboration, the Water Authority groups eventually made choices that resulted positive expected NPV profit outcomes on average, with a standard error that does not include zero or negative profit. The Water Authority's outcomes in terms of reliability also tend to be higher in comparison to that of the Firm.

Similarly, Figure 3.9 shows outcomes for both roles and treatment groups from the Water Authority' point of view. The Firm's choices generally result in higher contractual payment obligations for the Water Authority, however, the two roles are able to approach each others objectives through collaboration by the end of the exercise.

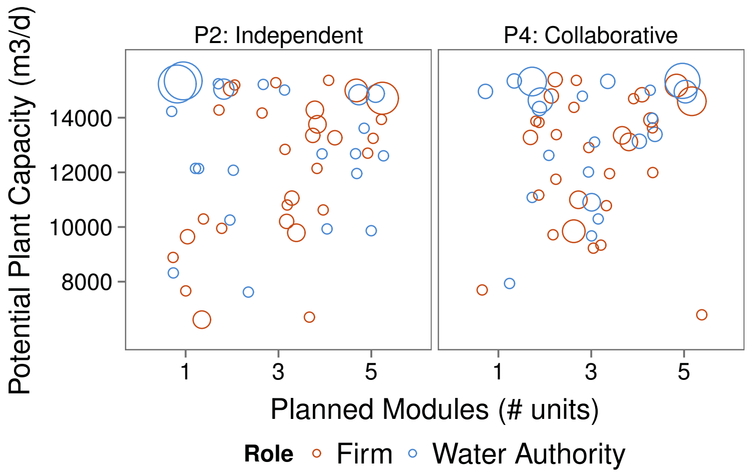
3.3.4 Relating design choices to value outcomes

The results demonstrate that participants shifted value outcomes over the course of the collaboration exercise, particularly when the Communication condition was active. The analysis now sheds light on how participants actually made changes in independent design variable to affect value trade-offs.

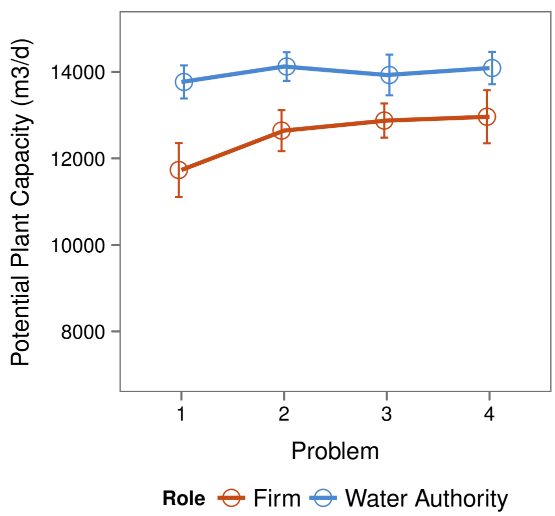
From the technical perspective of co-design, participants relied on modularity, i.e. flexibility in terms of phasing plant designs to affect value. The three charts in Figure 3.10 document this process. Figure 3.10a shows the unique combinations of [*potential plant capacity (m3/d), number of planned modules*] chosen by both the Firm and the Water Authority. The size of each bubble represents the relative frequency of that unique combination. The figure compares the design choices between the independent control round (Problem 2) and the final round with the combined treatment of full collaboration using communication and common knowledge (Problem 4). In the control round, the design choices are more dispersed over the entire grid. In the collaboration round, there is a lot more overlap in design choices in the central and upper region of the grid. The Water Authority systematically chose designs with larger potential plant capacity than the Firm throughout the exercise (Figure 3.10b, which did not change much between Problems 2 and 4. The Authority mainly altered designs to secure value trade-offs by making designs more modular (3.10c). In contrast, the Firm always chose designs with a higher number of modules than the Authority, however it affected trade-offs by increasing the potential capacity of facilities. Modularity helped both the Firm and Authority to lower the costs of increasing reliability.

The contractual aspects of co-design also show how both the roles made changes in design choices to affect value trades. The minimum income guarantee and contract price both came into play. Figure 3.11 follows a similar visualization approach for contractual variables. Figure 3.11a shows the unique combination of [*contract price ($/m3), income guarantee (NPV USDmillion)*] in the independent control and collaboration rounds for both the Firm and the Water Authority. While designing independently the Firm chose both high contract price and high income guarantee levels. On the other hand, the Water Authority chose mainly low contract prices as well as low income guarantees. In the collaboration round, there was much more of an overlap and an even dispersion across the grid. While the Firm did not alter the minimum income guarantee choice much over the course of the exercise, the Water Authority relied on this to secure value trade-offs (Figure 3.11b). In contrast, both the Firm and Water Authority altered designs in terms of contract price by the end of the exercise. In this manner, the income guarantee was the primary mechanism from the contractual point of view for securing value trade-offs.

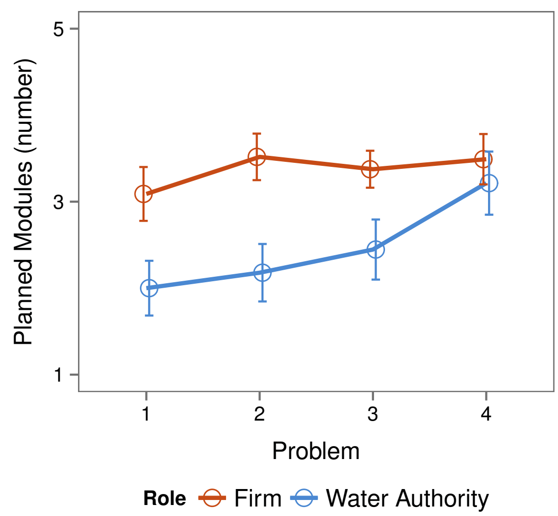
In summary, the analysis of design choice and value outcomes has demonstrated that communication is an important mechanism for securing value trade-offs through co-design. Project actors made changes in their design choices because they learned about the effects of those choices on expected value outcomes. Both the Water Authority and the Firm relied on specific levers such as modularity and the minimum income guarantee to make value trade-offs. These



(a) Technical co-design choices for each role. Bubble size marks the relative frequency of unique combinations. Choices cluster in the upper central region under collaboration, showing increasing similarities in technical designs for both roles

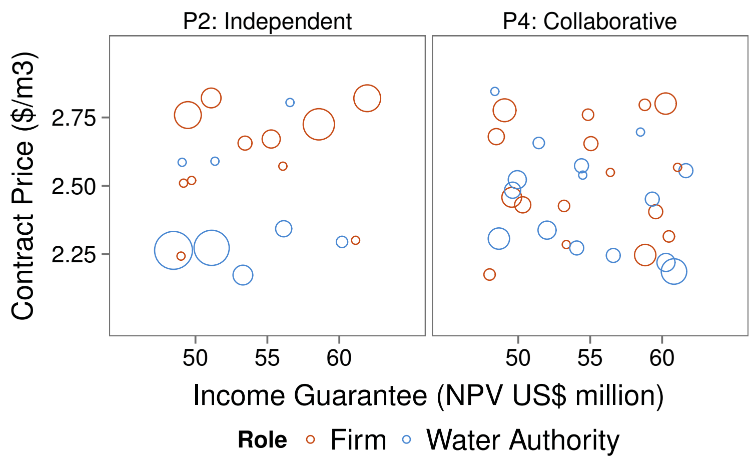


(b) Chosen potential plant capacity levels for both roles. The Water Authority systematically selects designs with higher planned capacity to meet its reliability objective. The Firm approaches the Authority's choices through collaboration.

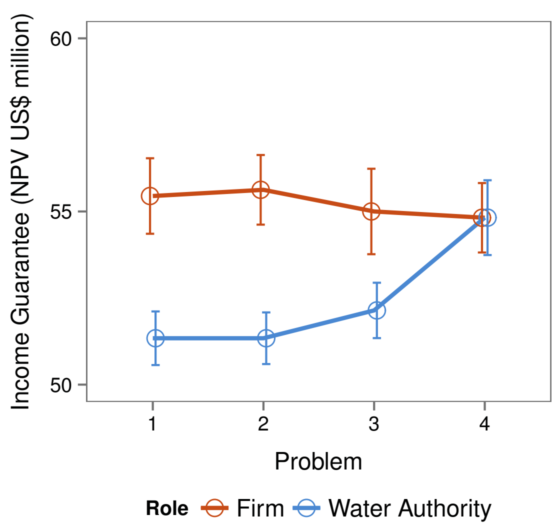


(c) Chosen number of planned modules for each role. The Water Authority increases the degree of planned modularity over the course of the exercise to decrease the cost of reliability and approach the Firm's choices.

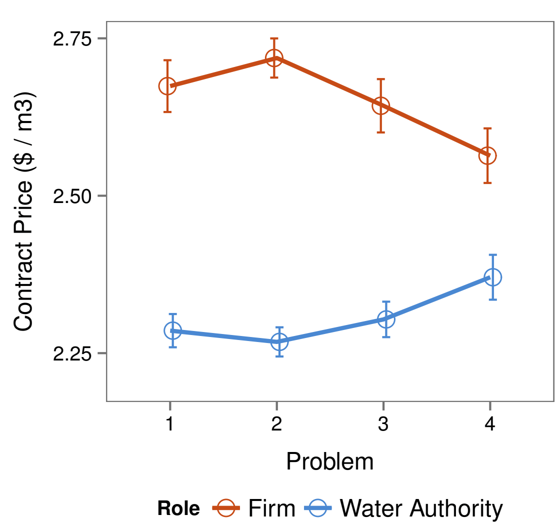
Figure 3.10: Design choices in terms of the technical aspects of co-design that enabled participants to trade value across dimensions.



(a) Contractual co-design choices for each role. Bubble size marks the relative frequency of unique combinations. While choices are disparate under independent design in the control round, there is significant overlap under collaboration.



(b) Chosen minimum income guarantee levels for both roles over the course of the exercise. The Firm decreases its expectations slightly, however the Water Authority dramatically increases its guarantee obligations.



(c) Chosen contract price levels for both roles. Both the Firm and the Water Authority move away fro their original anchors for the price variable.

Figure 3.11: Design choices in terms of contractual aspects of co-design that helped participants trade value across dimensions.

insights were generated mainly through an analysis of design and value outcomes. The next section looks at the same data and also the communication transcripts generated through participant dialogue more qualitatively to study emergent participant behavior.

3.4 Behavioral Archetype Analysis

This section addresses the question of whether behavioral archetypes - typical patterns of participant behavior - emerged during the collaboration exercise. Although the exercise was very structured, we can expect each participant to exhibit differences in behavior based on their personality, training, and other individual traits. They may also respond differently to the same structured conditions and stimuli in the exercise. After acknowledging this 'within-subject' variation, are some patterns of actions recognizable across the sample of participants? Put another way, did participants with *a priori* differences and tendencies show similar patterns of behavior during and by the end of the collaboration exercise, as a response to the conditions of the exercise? Participants did in fact behave in a small number of characteristics ways. The following analysis summarizes the systematic behavioral archetypes that emerged as well as highlights the types of interactions that were associated with the emergent behaviors.

A number of interactions between the structural conditions of the collaboration exercise and participant traits could influence participant behavior. Processing information that appears on the screen is a 'participant-information' type interaction. Given the same controlling conditions, different participants may process information differently. This interaction is what leads to some of the within-subject variation in design choice outcomes. Communicating with collaborators is an interaction of the 'participant-participant' type. Outcome variation in pairs of collaborators may arise due to differences in how a pair engages with each other. The detailed design submission data and communication protocol allows us to link some of these interactions to patterns of observations.

Two of the three types of data collected in the exercise are suitable for archetype analysis. Design choice submissions at the end of every problem in the exercise and the transcripts of communication between pairs of collaborators are both informative. The detailed survey responses, the third type of data, are left to Chapter 4 for the Subjective Value analysis.

Archetype analysis involved the three tasks of identifying archetypes, determining archetype scoring reliability, and relating archetypes to negotiated agreement outcomes through statistical analysis. The rest of this section summarizes the results of the three steps, beginning with archetype identification.

3.4.1 Identifying archetypes

Archetype identification was a qualitative process in which I subjectively inspected the data to uncover behavioral patterns as possible candidates. The identification inspection revealed three archetypes: *anchoring*, *aligning*, and *sensitive*. The archetype *anchoring* emerged from observations where collaborators fixated on their own objective and did not change design choices to make trades in value over the course of the exercise. *Aligning* represents cases where collaborators discovered each others' competing value objectives and made gradual trades in value outcomes. The final archetype *sensitive* indicates situations where collaborators were highly aware of the counter-party's objective and made sharp trades in value to ensure that their collaborator could meet its competing objective. The discussion that follows illustrates the identification process and uses an example to show how the *aligning* archetype was identified, before generally discussing all three archetypes.

First, the value outcomes of design choice submissions over time were plotted for each participant to understand how similar or different they were. The value dimensions in these plots depends on participants' role and is identical to what the participants observed before making their design choices. For the participants in the role of the water authority, a behavioral pattern is revealed by the outcomes of contract payments and associated reliability of meeting demand. Profit and associated reliability give the behavioral pattern for the participants in the role of the firm. The time dimension in these plots is the problem number, since design choice submissions at the end of every problem marked discrete steps in time for all participants, and made the time steps comparable.

Figure 3.12 shows an example each of the patterns for the water authority and the firm, from one collaborating pair of participants. The horizontal axis in both plots is the problem number, indicating passage of time in the design exercise. Each point in the plot has a label that gives the shortage value outcome as a result of the individual's submitted design. The vertical axis for the water authority (left) reflects expected contract payments, and the corresponding metric is expected profit for the firm (right).

The candidate behavioral archetype for both roles in this case is termed *aligning* because each participant exhibits gradual trade-offs in favor of the collaborator's objective. Judging from the value outcomes in the four problems, the water authority began with a low level of contract payments (NPV USD 55 million) and the lowest possible level of shortage (NPV USD - 0.036 million) in Problems 1 and 2. It then raised its contract payments (to NPV USD 60 million) in Problem 3 while at the same level of shortages. In the fourth and final Problem, it continued to hold shortage levels constant and further increased contract payments (about NPV USD 68 million). The water authority thus successively traded contract payments over the course of the exercise to be able to hold reliability at a constant level. Since an increase in contract payments for a constant level of shortage implied a relative increase in profits for the firm, the water authority was gradually aligning itself with the firm's objective of increasing profit. Looking at the firm's pattern, we can see that it gradually decreased its profit expectation over the course of the four problems (from a high of about NPV USD 14 million to 10 million). At the same time, the firm also gradually increased the reliability of meeting demand through minor decreases in shortage

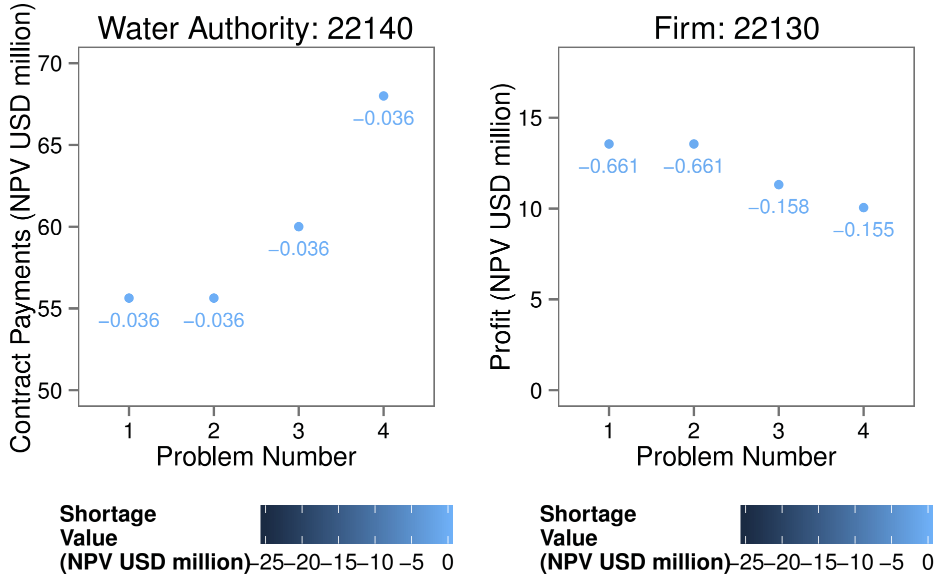


Figure 3.12: Two plots of individual participants' behavior over time in the collaboration exercise. The problem number marks the passage of time in the exercise, shown on the horizontal axis in both plots. Point labels give the value of shortage (i.e. reliability of meeting demand for that design). Behavior for a water authority participant on the left, increasing in contract payments over time while holding the shortage value (reliability) constant. For the firm participant on the right, profits decrease over time while shortage value decreases (becomes less negative and moves towards zero).

level (from NPV USD -0.661 million to - 0.155 million). The firm also aligned with the water authority's objective by trading profit for increased reliability. Since both participants in this pair exhibited the *aligning* archetype, their pair archetype is [*aligning*, *aligning*] [2].

In this manner, I inspected all 112 participants' design submission plots to generate archetypes. Appendix F contains all the plots categorized by the collaboration role, i.e. water authority or firm. Since Problem 2 was identical to Problem 1 in all respects, except for the passage of time, and designed to allow participants to saturate their independent learning by this stage of the exercise, most participants had identical or very similar value outcomes in Problems 1 and 2. They had already learned as much of the problem structure by Problem 2 as they could on their own. The archetype analysis therefore dropped the observation from Problem 1 and used the observation from Problem 2 as a starting point. The inspection process resulted in the general patterns for the three archetypes of *anchoring*, *aligning* and *sensitive*.

As an example, an abstraction of the aligning archetype for both the water authority and the firm along is shown in Figure 3.13. For the water authority, this is marked by a low value of contract payments in Problem 2 (the saturated control condition), a possible gradual increase in Problem 3, and a more pronounced increase in payments by the last problem. An aligning

[2] The convention I follow for labeling pair archetypes is [water authority, firm].

pattern for the firm mirrors this trend. Firms begin with a high value of profit in the control condition and show a pronounced decrease by Problem 4. If both the water authority and the firm in a collaborating pair exhibit the aligning archetype then they form an [*aligning, aligning*] pair as in the example in Figure 3.12 above. However, other pair combinations are also possible with the other two archetypes.

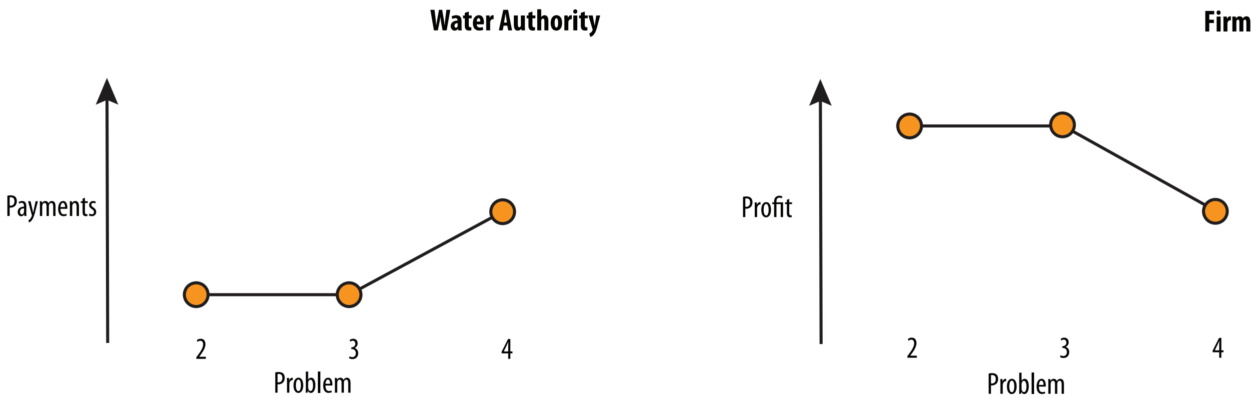
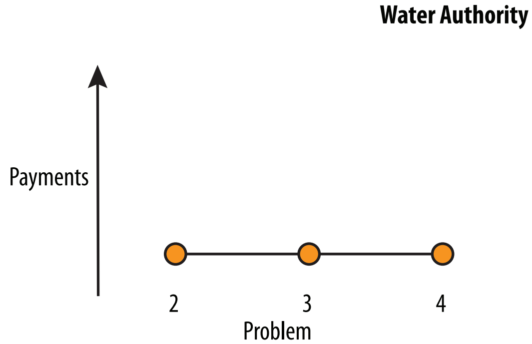


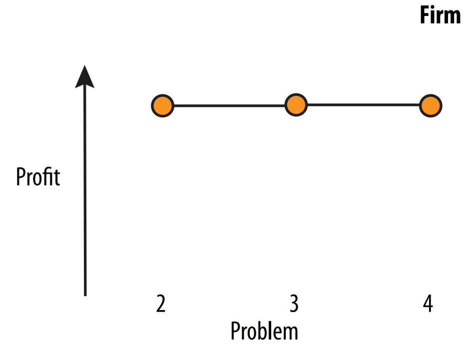
Figure 3.13: The abstractions for the *aligning* archetype, with one variant each for the water authority and the firm. The water authority begins with a low level of payments in Problem 2, may show a possible gradual increase by Problem 3, and then a pronounced increase by Problem 4. Mirroring this trend, the firm begins with high profit, and then shows a pronounced decrease by the end of the exercise. If both the water authority and the firm exhibit the aligning pattern, then they form an [*aligning, aligning*] pair archetype.

The *anchoring* archetype (fig. 3.14a and fig. 3.14b) indicates cases where each role fixated on their primary value objective. The water authority (n = 16) focused mainly on lowering contract payments and its value outcomes did not change much during the exercise. On the other hand, the firm (n= 19) focused on high profits, without much change in value outcomes even after collaboration. Almost one third of participants exhibited the *anchoring* archetype.

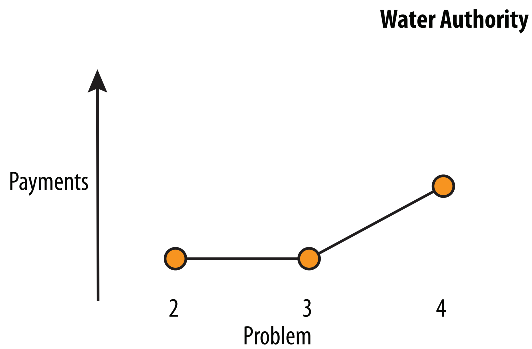
The *sensitive* archetype (fig. 3.14e and fig. 3.14f) represents situations where each role was highly aware of the collaborator's objective and made sharp trade-offs to help them accomplish it. The water authority (n = 11) substantially increased contract payments by Problem 3 to ensure a high reliability of meeting demand, as well as allowing the firm to gain profit. It's choices in Problem 4 were very similar because it had already exhausted the ability to trade in Problem 3. The firm (n = 13) was also very aware of the water authority's objective of low contract payments, and substantially decreased its profit expectation early on in Problem 3. It's value outcome remained the same in Problem 4 because it had already traded away much if not all of its ability to provide reliability of meeting demand while maintaining non-zero profits. Only a fifth of the participants exhibited the *sensitive* archetype.



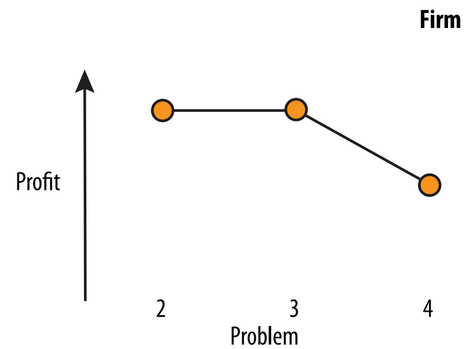
(a) *Anchoring* archetype for water authority. The authority is fixated on making low contract payments. Value outcomes do not change noticeably over time. n = 16 participants.



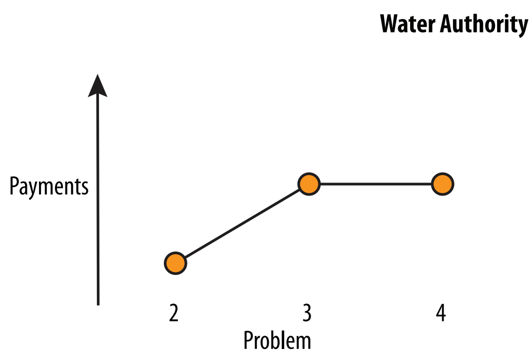
(b) *Anchoring* archetype for firm. The firm is fixated on high profit. Value outcomes do not change noticeably over time. n = 19 participants.



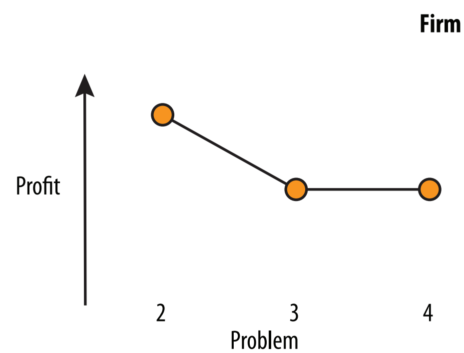
(c) *Aligning* archetype for water authority. The authority recognizes the firm's objective and gradually increases contract payments to ensure a high reliability of meeting demand. n = 29 participants.



(d) *Aligning* archetype for firm. The firm recognizes the authority's objective and gradually decreases profits to increase reliability of meeting demand. n = 24 participants.



(e) *Sensitive* archetype for water authority. The authority makes a sharp trade and increases payments to ensure reliability as well as allow for firm profit. n = 11 participants.



(f) *Sensitive* archetype for firm. The firm sharply trades profit to increase reliability as well as lower the level of contract payments. n = 13 participants.

Figure 3.14: The three emergent archetypes anchoring, aligning, and sensitive with a variant for each role. This gives a total of six patterns that were observed in design submissions from N = 112 participants.

The *aligning* archetype has already been discussed in detail above (fig. 3.12 and fig. 3.13) and its abstraction variants are repeated in Figure 3.14c and Figure 3.14d for completeness. Slightly more than half of the participants exhibited this archetype, making this the archetype with the largest frequency in the exercise. This is plausible in a large sample of individuals as it is an intermediate type of behavior when compared with the extreme patterns of *anchoring* or *sensitive*.

The subjective process of archetype identification discussed thus far involved only one coder, myself. To mitigate subjectivity to a reasonable extent, two additional coders performed a matching exercise where they categorized each participant's plot (see Appendix F for the full set of plots). The degree of inter-coder agreement between all three coders is one way to quantitatively test whether subjectivity is mitigated. The next sub-section summarizes the results of the inter-coder agreement analysis, i.e. the reliability of scoring the archetypes themselves.

3.4.2 Determining archetype scoring reliability

Interpreting archetypes from plots of design submissions is a subjective task. The primary coder's (me) scoring can reflect a bias, often unconscious, in matching patterns. The effect of any bias is a possibly erroneous report of what the data represents. The validity of the claims can come into question if the analysis does not sufficiently reflect the "truth" of the observed phenomenon. To account for the bias, and to mitigate interpretation errors, researchers making subjective interpretations can seek a second or third opinion through an inter-coder agreement exercise.

An inter-coder agreement exercise tests the reliability of subjective coding (Stemler, 2001). For the analysis to be *valid*, the data must be *reliable*. Artstein and Poesio (2008) state that data in subjective coding analysis are reliable if the coders can be shown to agree on the categories assigned to the items, i.e. the coded observational units. If different coders are consistent in how they match items to categories, then they can be assumed to have a similar understanding of the coding guidelines and what to look for in the data. We can then expect them to code data reliably (Krippendorff, 2004).

To test inter-coder agreement, I asked two other coders to classify observations into the three archetypes of *anchoring*, *aligning*, and *sensitive*. This gave a total of three coders, including myself, between whom we could compare archetype codes.

There are a number of techniques to assess the reliability of data from inter-coder agreement scores (Krippendorff, 2012). Percentage agreement A, the S coefficient which assumes a uniform underlying distribution (Bennett, Alpert, and Goldstein, 1954), Scott's coefficient π with the non-uniform, but single underlying distribution assumption (Scott, 1955), and Cohen's κ and its variants (Cohen et al., 1960; Cohen, 1968).

My scoring reliability analysis used all of these techniques to mitigate the subjectivity of the archetypes and their frequencies. The derivations of the tests and their application is developed in Appendix G and the main results of the test statistics are stated here. The test statistics are chance-corrected, i.e. they have been adjusted to account for the random chance that a coder might assign an observation (item) to a category. This provides a more robust estimate of scoring reliability. All of the estimates take values in the interval [0, 1].

Table 3.1 shows the chance-corrected test results. The upper half of the table lists the probability with which we should expect agreement between pairs of coders due to chance, and all three coders simultaneously. For the assumptions used and the structure of the test statistics, the expected agreement due to chance A_e is almost always between 0.33 - 0.35. The lower half of the table lists the statistic values S, π, and κ. The reliability of scoring archetypes is high, between 0.78 - 0.85, across both pairs of coders as well as when all three coders' results were tested together.

Table 3.1: Chance-corrected inter-coder agreement results for archetype scoring reliability

$$\text{Statistic} = \frac{A_o - A_e}{1 - A_e}$$

Expected Agreement	Coders 1 and 2	Coders 1 and 3	Coders 1, 2, and 3
A_e^S	0.333	0.333	0.111
A_e^π	0.357	0.353	0.353
A_e^κ	0.353	0.351	-

Statistic	Coders 1 and 2	Coders 1 and 3	Coders 1, 2, and 3
S	0.82	0.82	0.84
π	0.81	0.81	0.78
κ	0.81	0.82	0.85*

* calculated in software; the rest were calculated by hand using the derivations in Appendix G

High scoring reliability indicates a high degree of agreement between different coders. This allows us to claim that different coders inspecting the design submissions will mostly agree on how participant behavior is matched to abstracted archetypes. It allows us to be more confident while using these archetypes in further analysis.

3.4.3 Relating archetypes to negotiated agreement

This discussion covers the final step of the archetype analysis - relating archetypes to the degree of agreement that collaborating pairs were able to achieve during the collaboration exercise. The analysis above has shown that there are a small number of archetypes that emerged from participant behavior, and that these archetypes can be identified reliably by multiple coders. This piece of the analysis asks whether one or more of the three archetypes *anchoring*, *aligning*, and *sensitive* are associated with the degree of agreement. For example, were sensitive archetypes more likely to exhibit a high degree of agreement? This question is interesting because participants were not required to agree on designs as part of the negotiated collaboration to be able to submit their design choices.

Agreement is defined here as the number of design variables for which the participants selected and submitted identical levels. For instance, a collaborating pair 'agreed' on the 'potential plant capacity (m3/d)' variable if they both submitted 15,000 m3/d as their design choice at the end of a round. At the same time, a pair could disagree on another variable 'number of modules' even though their choice of potential plant capacity was identical. With four independent design variables, participants could agree on a minimum of zero variables ('no agreement') and at most four ('max agreement'). Agreement calculated in this manner is an ordinal variable, and we can think of it in terms of the relative degree of agreement across participants in the context of this particular collaboration.

We are thus relating the categorical variable of Archetype with the ordinal variable of Agreement. We can posit and test a relationship between the two because they are two separate variables constructed using different parts of the data. Archetypes were identified as general patterns from value outcomes, whereas agreement is based on the specific parameter levels of the independent design variables. Archetype and Agreement are thus two factors which may be related, but they indicate different things (behavior versus agreement).

The degree of Agreement is an important outcome primarily in Problems 3 and 4 of the collaboration exercise, because those were the problem-solving rounds that involved at least one of the treatments. In the beginning control round (Problem 1) and the saturated control round (Problem 2), participants focused on their own 'sub-problem' i.e. making choices based on their individual value perspectives. As such, there was no agreement attributable to an experimental stimulus, and any case of agreement was due to chance.

Exploratory diagnostics for the degree of Agreement by Archetype are summarized in Appendix H. Mosaic plots illustrate the distribution of agreement scores for each archetype separately for Problems 3 and 4. These diagnostics reject the null hypothesis that Agreement and Archetype are independent, both in Problems 3 and 4. The *sensitive* archetype showed a higher degree of agreement ($p < 0.001$) than the others whose scores were more comparable in Problem 3. On the other hand, in Problem 4, the anchoring pattern showed significantly lower agreement scores ($p = 0.1$). For continuing analysis we therefore hypothesize that Agreement is associated with Archetype.

In addition to Archetype and Agreement, the third factor of Treatment is also important as it may differentially influence the relationship between the first two. For example, we may believe that communication was an important mechanism for enabling participants to exchange ideas and reach agreement on design choices. Then a plausible hypothesis is that participants in the 'Communication first' treatment type will tend to show more agreement than those in the 'Information first' treatment, controlling for archetype. To explore this, Appendix H provides further diagnostics to support the idea that the relationship between Agreement and Archetype should be conditioned on Treatment. Contingency analysis using mosaic plots suggests that in Problem 3, all three archetypes in the 'Communication first' treatment group showed higher agreement scores than in the 'Information first' group. This observation supports the hypothesis above. The picture changes in Problem 4 where the 'Communication first' group shows a similar distribution of scores to its score from Problem 3, but the 'Information first' group shows significantly higher agreement scores as compared to Problem 3. This is because collaborator pairs in the 'Information first' treatment group were allowed to communicate in Problem 4. This second observation lends further support to the importance of understanding the effect of the Treatment condition.

The diagnostic analysis shows that there was an shift in the distribution of agreement scores for one treatment group but not the other. We can test if this shift was systematic by comparing the degree of agreement for a participant in Problem 3 to the same participant's degree of agreement in 4, while controlling for treatment group and archetype. This type of test allows us to account for 'within-subject' variation in agreement scores.

For this test, we define a modified agreement variable, *deltaAgree* which is the difference between a participant's score for the variable Agreement in Problem 4 and 3. Since there are four design variables on which any participant could agree with a collaborator, the minimum value of *deltaAgree* is 0 - 4 = -4 (minimum agreement in Problem 4 and max agreement in Problem 3) . Similarly, the maximum value for *deltaAgree* is 4 - 0 = 4 (max agreement in Problem 4, and minimum agreement in Problem 3). A diagnostic of this raw data in Appendix H shows that the range of *deltaAgree* is from - 2 to 4. However, some cells in the mosaic table have a count of zero, which is likely to produce incorrect statistical results from a test of association. The deltaAgree scores are therefore re-categorized into just three ordinal levels (instead of a possible 9). The new categories are [decreased, same, increased] corresponding to *deltaAgree* scores of less than zero, zero and greater than zero respectively.

Contingency analysis for the *deltaAgree* variable rejects the null hypothesis of independence, and shows that some archetypes changed their degree of agreement more than others (p = 0.009). Figure 3.15 provides a visual summary of this analysis, using the schema first introduced by Friendly (1994) and refined by others (Hornik, Zeileis, and Meyer, 2006; Zeileis, Meyer, and Hornik, 2007). It is a mosaic table of the change in Agreement, del(Agreement), with respect to the three different archetypes. The area of each cell in the mosaic table represent the overall proportion of observations in that sub-category relative to the complete sample. The table also controls for the treatments and breaks out the observations for 'Communication first' (top half) separately from 'Information first' (bottom half). The legend bar on the right shows the residuals of the Pearson's χ^2 test of independence which measures whether the frequency count in each case is statistically different from what should be expected due to chance. If a cell is blue, its observed frequency was more than expected and it is colored in only if the deviation is statistically significant ($\alpha = 0.05$). Similarly, for a cell with a red dashed border, the observed count is lower than expected. There are no red shaded boxes, so none of the cells with lower than expected deviations show statistical significance. However, there are two blue-shaded cells. We can infer that many more participants than expected of the *sensitive* archetype in the 'Communication first' treatment group decreased their degree of agreement in a statistically significant way. This means that many *sensitive* participants in this treatement group actually agreed on fewer design variables in Problem 4 than in Problem 3, as a consequence of receiving additional information as a second treatment. In the 'Information first' group, the *aligning* archetype showed a much

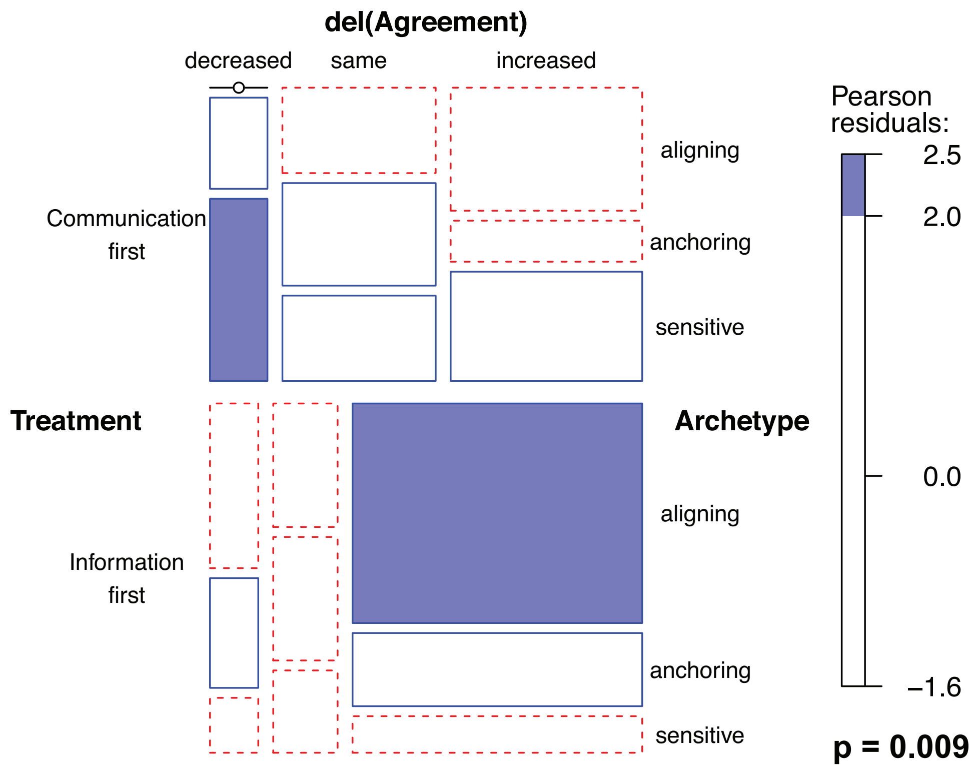


Figure 3.15: A mosaic table of the change in Agreement, del(Agreement), with respect to the three emergent archetypes and grouped by experimental treatment. The Pearson's χ^2 test of independence rejects the null hypothesis that change in the degree of agreement is independent of archetype (p = 0.009). Many *Sensitive* archetype participants in the 'Communication first' treatment group agreed on fewer design variables in Problem 4 than in Problem 3 shown by the shaded blue cell in the top half of the figure. A substantial number of *aligning* archetype participants agreed on more design variables in Problem 4 than Problem 3.

higher than expected increase in the degree of agreement. A substantial number of these individuals agreed on more design variables in Problem 4 than in Problem 3, because of the ability to communicate with their collaborators.

3.5 Chapter Summary

This chapter builds on the idea that project actors co-design to make trade-offs in different value dimensions. They work within the zone of negotiated agreement to identify designs that help them balance competing value outcomes. Whereas the tradespace model enumerated the feasible designs that are available to project actors, this chapter investigated the mechanisms by which project actors could search for and reach agreement over those designs in the process of negotiated collaboration.

The chapter first reviewed the theoretical framework for the research. The framework posits that project actors can balance competing value outcomes if they develop a shared understanding of each others objectives and the structure of the problem. A review of the relevant literature on design cognition and negotiation showed that actors enhance their understanding by jointly shaping their mental models of the design task. There are specific mechanisms in the process of negotiated collaboration such as communication (dialogue) and information sharing that help actors develop their understanding to ultimately make negotiated design choices.

The chapter then presented the design and results of an experimental collaboration exercise to test the relative effects of communication and information as separate mechanisms of collaboration. Participants played the roles of a Water Authority and a Firm that are engaged to co-design a desalination infrastructure P3. These role-players made design choices independently and collaboratively in a series of four problems. The experimental setup collected data on the participants' submitted design choices, their communication transcripts, and detailed survey responses.

An analysis of the submitted design choices found that communication dominates as an enabling mechanism for the project actors to be able to make trades in value. Communication was effective even in the absence of common knowledge between actors. In fact, common knowledge plays a supporting role in helping project actors develop their shared understanding. When project actors who have already been communicating also acquire common knowledge, the additional information either reinforces or amplifies the effect of communication on participants' choice to make trade-offs. The implication of this finding for the co-design of infrastructure P3s is that project actors should communicate early and often in the process of negotiated collaboration to understand the types of value trade-offs they will have to eventually make through design choices.

Further analysis of submitted designs and communication transcripts revealed that three types of behavioral archetypes emerged during the collaboration exercise. These archetypes are *aligning*, *anchoring*, and *sensitive.* The reliability of subjectively identifying these archetypes was established through tests of inter-rater agreement between multiple coders. Members of some archetypes tended to agree more than those of others, conditional on their treatment group. In particular, the *aligning* archetype was associated with a higher propensity to agree on more aspects of the design in later collaboration rounds. The *sensitive* archetype actually decreased its degree of agreement in some cases, counter to intuition. A possible explanation is that sensitive archetype initially traded away too much in the absence of common knowledge. The implication for the co-design of infrastructure P3s is that the structural conditions might lead to the emergence of one more of these behavioral patterns, which may make participants more or less likely to eventually agree on specific design variables.

This chapter has mostly focused on the Objective Value- type outcomes (profits, payments and reliability as objective payoffs) of the negotiated collaboration exercise by analyzing submitted design choices and the supporting communication transcripts. Subejctive Value outcomes are treated in detail in the following chapter.

References

Artstein, Ron and Massimo Poesio (2008). "Inter-coder agreement for computational linguistics". In: *Computational Linguistics* 34.4, pp. 555–596.

Austin-Breneman, Jesse, Bo Yang Yu, and Maria C Yang (2014). "Biased Information Passing Between Subsystems Over Time in Complex System Design". In: *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, V007T07A023–V007T07A023.

Badke-Schaub, Petra, Andre Neumann, Kristina Lauche, and Susan Mohammed (2007). "Mental models in design teams: a valid approach to performance in design collaboration?" In: *CoDesign* 3.1, pp. 5–20.

Bazerman, Max H and John S Carroll (1987). "Negotiator cognition". In: *Research in organizational behavior*.

Bazerman, Max H and Dolly Chugh (2005). "Bounded awareness: Focusing failures in negotiation". In: *Frontiers of social psychology: Negotiation*, pp. 7–26.

Bazerman, Max H, Jared R Curhan, Don A Moore, and Kathleen L Valley (2000). "Negotiation". In: *Annual review of psychology* 51.1, pp. 279–314.

Bazerman, Max H, Thomas Magliozzi, and Margaret A Neale (1985). "Integrative bargaining in a competitive market". In: *Organizational behavior and human Decision Processes* 35.3, pp. 294–313.

Bennett, Edward M, R Alpert, and AC Goldstein (1954). "Communications through limited-response questioning". In: *Public Opinion Quarterly* 18.3, pp. 303–308.

Chugh, Dolly and Max H Bazerman (2007). "Bounded awareness: What you fail to see can hurt you". In: *Mind & Society* 6.1, pp. 1–18.

Clevenger, Caroline Murrie, John Riker Haymaker, and Andrew Ehrich (2013). "Design exploration assessment methodology: testing the guidance of design processes". In: *Journal of Engineering Design* 24.3, pp. 165–184.

Cohen, Jacob et al. (1960). "A coefficient of agreement for nominal scales". In: *Educational and psychological measurement* 20.1, pp. 37–46.

Cohen, Jacob (1968). "Weighted kappa: Nominal scale agreement provision for scaled disagreement or partial credit." In: *Psychological bulletin* 70.4, p. 213.

de Neufville, Richard and Stefan Scholtes (2011). *Flexibility in engineering design*. Cambridge, USA: MIT Press.

Dinar, Mahmoud, Jami J Shah, Jonathan Cagan, Larry Leifer, Julie Linsey, Steven M Smith, and Noe Vargas Hernandez (2015). "Empirical Studies of Designer Thinking: Past, Present, and Future". In: *Journal of Mechanical Design* 137.2, p. 021101.

Dong, Andy (2005). "The latent semantic approach to studying design team communication". In: *Design Studies* 26.5, pp. 445–461.

Fiore, Stephen M., Kimberly A. Smith-Jentsch, Eduardo Salas, Norman Warner, and Michael Letsky (2010). “Towards an understanding of macrocognition in teams: developing and defining complex collaborative processes and products”. In: *Theoretical Issues in Ergonomics Science* 11.4, pp. 250–271.

Flager, Forest, David Jason Gerber, and Ben Kallman (2014). “Measuring the impact of scale and coupling on solution quality for building design problems”. In: *Design Studies* 35.2, pp. 180–199.

Friendly, Michael (1994). “Mosaic displays for multi-way contingency tables”. In: *Journal of the American Statistical Association* 89.425, pp. 190–200.

Fukuno, Mitsuteru and K-i Ohbuchi (1997). “Cognitive biases in negotiation: the determinants of fixed-pie assumption and fairness bias”. In: *Japanese Journal of Social Psychology* 13.1, pp. 43–52.

Gilbert, D. (1994). “Advanced Social Psychology”. In: ed. by A Tesser. McGraw-Hill. Chap. Attribution and interpersonal perception, pp. 99–147.

Gimpel, Henner (2008). “Cognitive Biases in Negotiation Processes”. English. In: *Negotiation, Auctions, and Market Engineering*. Ed. by Henner Gimpel, Nicholas R. Jennings, Gregory E. Kersten, Axel Ockenfels, and Christof Weinhardt. Vol. 2. Lecture Notes in Business Information Processing. Springer Berlin Heidelberg, pp. 213–226.

Hernandez, Noe Vargas, Jami J Shah, and Steven M Smith (2007). “Cognitive Models of Design Ideation”. In: *ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers, pp. 135–144.

Hirschi, N and D Frey (2002). “Cognition and complexity: An experiment on the effect of coupling in parameter design”. In: *Research in Engineering Design* 13.3, pp. 123–131.

Honda, Tomonori, Francesco Ciucci, Kemper E. Lewis, and Maria C. Yang (2015). “Comparison of Information Passing Strategies in System-Level Modeling”. In: *AIAA Journal* 53.5, pp. 1121–1133.

Hornik, Kurt, Achim Zeileis, and David Meyer (2006). “The strucplot framework: visualizing multi-way contingency tables with vcd”. In: *Journal of Statistical Software* 17.3, pp. 1–48.

Iorio, Josh and John E Taylor (2014). “Boundary object efficacy: The mediating role of boundary objects on task conflict in global virtual project networks”. In: *International Journal of Project Management* 32.1, pp. 7–17.

Keltner, Dacher and Robert J Robinson (1997). “Defending the status quo: Power and bias in social conflict”. In: *Personality and Social Psychology Bulletin* 23.10, pp. 1066–1077.

Klein, Mark, Hiroki Sayama, Peyman Faratin, and Yaneer Bar-Yam (2003). “The dynamics of collaborative design: insights from complex systems and negotiation research”. In: *Concurrent Engineering* 11.3, pp. 201–209.

Krippendorff, Klaus (2004). “Reliability in content analysis”. In: *Human Communication Research* 30.3, pp. 411–433.

— (2012). *Content analysis: An introduction to its methodology*. 3rd. Thousand Oaks, CA: Sage.

Lawson, Bryan (2006). *How designers think: the design process demystified*. 4th. Oxford, UK: Architectural Press.

Lessard, Donald R (2007). "Project complexity and performance". In: *Professional Development Workshop (PDW) on Projects*. Academy of Management. Philadelphia.

Lessard, Donald R and Roger Miller (2013). "International Handbook of Mega-Projects". In: ed. by Hugo Priemus and Bert van Wee. Cheltenham, UK: Edward Elgar. Chap. The shaping of large engineering projects.

Lin, Jijun, Olivier de Weck, Richard de Neufville, Bob Robinson, and David MacGowan (2009). "Designing capital-intensive systems with architectural and operational flexibility using a screening model". In: *Complex sciences*. Ed. by Jie Zhou. Springer, pp. 1935–1946.

Linsey, JS, I Tseng, K Fu, J Cagan, KL Wood, and C Schunn (2010). "A study of design fixation, its mitigation and perception in engineering design faculty". In: *Journal of Mechanical Design* 132.4, pages.

Messick, David M (1999). "Alternative logics for decision making in social settings". In: *Journal of Economic Behavior and Organization* 39.1, pp. 11–28.

Montgomery, James D (1998). "Toward a Role-Theoretic Conception of Embeddedness". In: *American Journal of Sociology* 104.1, pp. 92–125.

Ostergaard, Karen J., William R. Wetmore III, Ameya Divekar, Henry Vitali, and Joshua D. Summers (2005). "An experimental methodology for investigating communication in collaborative design review meetings". In: *CoDesign* 1.3, pp. 169–185.

Pinkley, Robin L, Terri L Griffith, and Gregory B Northcraft (1995). "'Fixed Pie' a la Mode: Information Availability, Information Processing, and the Negotiation of Suboptimal Agreements". In: *Organizational Behavior and Human Decision Processes* 62.1, pp. 101–112.

Reiter-Palmon, R, Ben Wigert, and T de de Vreede (2012). "Handbook of organizational creativity". In: ed. by M. D. Mumford. New York: Academic Press. Chap. Team creativity and innovation: The effect of group composition, social processes, and cognition, pp. 295–326.

Scott, William A (1955). "Reliability of content analysis: The case of nominal scale coding." In: *Public opinion quarterly*.

Simon, Herbert A. (1987). "Making Management Decisions: The Role of Intuition and Emotion". In: *The Academy of Management Executive (1987-1989)* 1.1, pages.

Stemler, Steve (2001). "An overview of content analysis". In: *Practical assessment, research & evaluation* 7.17, pp. 137–146.

Thompson, Leigh and Reid Hastie (1990). "Social perception in negotiation". In: *Organizational Behavior and Human Decision Processes* 47.1, pp. 98–123.

Tsay, Chia-Jung and Max H. Bazerman (2009). "A Decision-Making Perspective to Negotiation: A Review of the Past and a Look to the Future". In: *Negotiation Journal* 25.4, pp. 467–480.

Valley, Kathleen L, Joseph Moag, and Max H Bazerman (1998). "'A matter of trust': Effects of communication on the efficiency and distribution of outcomes". In: *Journal of Economic Behavior & Organization* 34.2, pp. 211–238.

Wood, Matthew, Pinzhi Chen, Katherine Fu, Jonathan Cagan, and Kenneth Kotovsky (2014). "Design Computing and Cognition". In: ed. by John S. Gero. Dordrecht: Springer. Chap. The Role of Design Team Interaction Structure on Individual and Shared Mental Models, pp. 209–226.

Zeileis, Achim, David Meyer, and Kurt Hornik (2007). "Residual-based shadings for visualizing (conditional) independence". In: *Journal of Computational and Graphical Statistics* 16.3, pp. 507–525.

Chapter 4

Subjective Understanding and Subjective Value in Negotiated Collaboration

This chapter elaborates on two subjective aspects of negotiated collaboration that are difficult to measure and often ignored in experimental studies on design. Both these latent constructs, Subjective Understanding and Subjective Value, have roots in cognitive and behavioral science. Linking these notions with the analysis of design outcomes in Chapter 3 provides a more holistic view of the nature of negotiated collaboration and its possible outcomes. Insights from the "lived" experience of individual project actors can inform the design processes of infrastructure P3s in topic areas where the institutional, contracts, and other literature does not offer much visibility.

Behavioral dynamics and their psycho-social effects on project actors merit further study because of the nature of negotiated design in infrastructure P3s. Projects are long-horizon games with high stakes, and it is unlikely that the same partners can begin and conclude a project, and then embark on a new one. In the absence of credibility from previous partnership successes, trust and rapport become important aspects of building the coalition. Subjective Value provides a framework to formally study the relationship between these relational dynamics and decision outcomes.

Subjective Understanding, the first construct, is about a designer's perception of how well the individual understands the design problem at hand. It is relevant in a process of collaborative design because preliminary understanding and any improvements in it over the course of the design process may influence how well actors can shape design choices. Their ability to understand the design problem may help or hinder the choice of a design that secures the objectives of the collaboration. An asymmetry in understanding between actors could also tip the scales in favor of the actor(s) with a more sophisticated understanding. In infrastructure P3s, a clear understanding of the project context and objectives can serve as a better foundation.

The second construct, Subjective Value, represents the psycho-social type of outcomes experienced in negotiations. It is based on an individual's perceptions and is emotive in nature. This class of negotiation outcomes has the potential to influence the quality of future design sessions with the same partners, and possibly even the conclusions a participant reaches about the results after a single design session.

The two constructs may well be associated; this chapter tests the hypothesis that improvements in Subjective Understanding over the course of the collaboration are associated with a designer's Subjective Value outcomes. It also tests whether Subjective Value is related to design outcomes, which were analyzed in depth in Chapter 3.

With respect to the construct of Subjective Understanding (at the start of the exercise) and Improvement in understanding (by the end of collaboration), the analysis in this chapter finds the following. Participants who reported an improvement in understanding by the end of the collaboration exercise attributed much of this improvement to the ability communicate with each other. The additional information received through common knowledge had the potential to confuse participants. The degree of improvement in understanding also depended on the participant's own initial perception of how well they understood the problem at the start of the exercise. Even participants who thought they initially understood it well could find that their understanding improved further. If their initial perceived understanding was high, then communication still helped but to a lower degree than for the participant's with a low perceived understanding initially.

For the other construct, collaborators on the whole experienced a large increase in Subjective Value, their psycho-social outcomes from negotiating agreement over designs. The large increase was observed across both treatment groups in the exercise, as well as across the design roles. Women in particular ascribed higher increases in Subjective Value to its relationship aspects, compared to men. These increases were associated with other aspects of the collaboration. Participants who believed that their understanding of the design issues improved significantly through collaboration also exhibited high increases in Subjective Value. In a similar manner, if collaborators agreed on design choices, they tended to report higher Subjective Value increases on average.

An important observation is that many collaborators who demonstrated very high agreement often reported very low increases in Subjective Value. Even though the collaboration process results agreement over designs, the manner in which this agreement is obtained can detract from collaborators psycho-social experience. If agreement is forced through some external mechanism, the negotiating collaborators may be more likely find the experience negative, for example. In this exercise however, there were no forcing mechanisms. This supports the rationale for considering not only the techno-economic or Objective Value outcomes of negotiated collaboration, but also the Subjective Value outcomes.

The two main constructs are latent variables. No research design or instrument can observe or measure them directly. Instead, the constructs manifest in a number of measurable or indicator variables. This chapter emphasizes all latent variables as Variable with capital first letters to distinguish the specific connotation from ordinary English usage. The variables are also often expressed in shorthand by a notional indicator like V.

The structure of the chapter is as follows. Section 4.1 describes the indicators and data collected on the topic of understanding to develop the construct of Subjective Understanding (*SubjU*). This includes two other notions of Objective Understanding (*ObjU*) and Mood that are presented first, because they inform *SubjU*. Next, Section 4.2 discusses the idea of Improvement in Subjective Understanding, and designer's perceptions as to factors that were related to improvement. The final section of the chapter delves into Subjective Value (SV) outcomes, and draws on an extensive literature in negotiation as well as the use of the Subjective Value Inventory (Curhan, Elfenbein, and Kilduff, 2009; Curhan, Elfenbein, and Xu, 2006). Section 4.4 summarizes the results and main findings of this chapter.

4.1 Assessing Understanding

Understanding is intimately related with both creativity in problem-solving as well as group cognition and collaboration. This analysis therefore explicitly assesses participant's understanding of the design task to determine the role of understanding in design outcomes as well as other perceptual outcomes. While the participants in the collaboration exercise were experienced systems engineers and managers, they may have had a variety of conceptual priors from different disciplines and domains. The study therefore recorded participant's level and variation in understanding 'pre-experiment' - before they began working on the design task. This section develops the analysis of two related measures of understanding, Objective Understanding (*ObjU*) and Subjective Understanding (*SubjU*), and an intervening variable, Mood (*M*), that indicates a collaborator's disposition during the exercise.

4.1.1 Measuring Understanding and Mood

Objective Understanding ($ObjU$) captures whether participants were able to absorb facts and structural relationships about the design problem and their role. This information is the background knowledge explicitly stated in the tutorial video and slides, and also summarized for them on a role sheet. These three different sources cater to different learning and retention styles of individuals, as well as help overcome language and attention barriers.

Subjective Understanding ($SubjU$) on the other hand captures how participants perceived whether they understood the design task and objectives. This is worth measuring because a participant's perception of understanding may relate to their confidence, motivation, anxiety, or ability to communicate. In fact, a specific hypothesis is that a participant's $SubjU$ at a point in time is positively correlated with not just their *ObjU* (their factual understanding) but also their instantaneous *Mood*. All of these taken together may affect their ability to communicate and collaborate for co-design.

At the start of the design session, the administrator simultaneously gave all participants a ten-minute tutorial on the essential elements of the infrastructure P3 co-design problem. The tutorial consisted of a pre-recorded movie clip, with embedded presentation slides and a voice recording.

The co-design problem was to deliver a high-level conceptual design of a large desalination facility, as explained in Chapters 2 and 3. The tutorial included an example of a desalination plant, and the long-term concession contract approach for procuring such facilities. The presentation slides and verbal description covered the principal-agent nature of the procurement with each party's objective functions, constraints and the design variables that affected them. The presentation also included an overview of the DesalDesign software with an introduction to the interface, problem description readouts, and key input and output indicators. By the end of the tutorial, participants thus had a full overview of the general co-design problem, and also the workings of the software tool they were about to use.

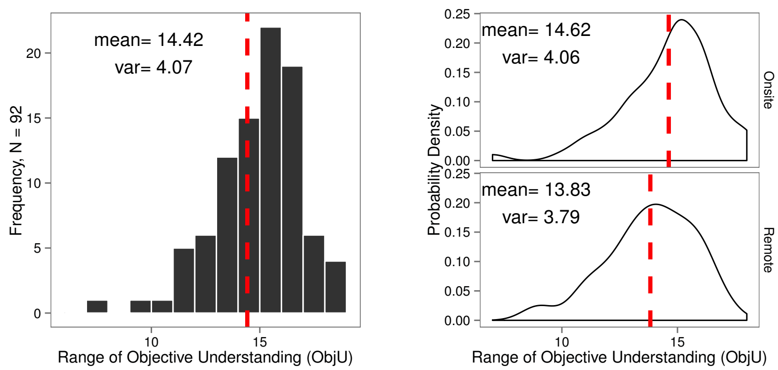
In addition to the tutorial, participants also received a one-page role sheet that summarized the information from the tutorial, in a way that emphasized their role. Role sheets for both the Firm's role and the Water Authority' role are included in Appendix I. This served as a reinforcement of the information and as an easy resource and reminder. With the recorded movie clip and printed role information, participants received the information using three media to support a number of differential learning styles.

Immediately after the tutorial, participants responded to a series of survey questions comprising the 'pre-experiment survey'. Some questions addressed factual details covered in the tutorial and printed role sheet. These were designed to capture participant's understanding of the facts of the design problem. Participants were also asked to explicitly rank how well they thought they understood the design task and objectives. The first subset of questions had 'correct' responses with binary scoring (correct: 1, incorrect: 0) and total scores could range from 0 to 20. The rest of the questions were marked on seven-point Likert scales with a 1: 'Not at all', to a 4: 'Moderately', and 7: 'Extremely'. These scores were used to populate the measures of Objective Understanding (*ObjU*) and Subjective Understanding (*SubjU*) respectively.

A small subset of questions in the same pre-experiment survey asked about different aspects of participants' disposition: how motivated, how confident, and how nervous were the participants at the start of the session? These were also scored on the same seven-point Likert scale and scores were used to develop the construct of Mood (*M*).

4.1.2 Objective Understanding (*ObjU*)

Participants answered a number of structured and open-ended questions about the co-design task, their own objective, their collaborator's objective, and both technical and contractual variables that affect different dimensions of design performance in the DesalDesign model. A scoring protocol assigned each participant points for how they answered each of these questions, and summed them to get an *ObjU* measure (scoring scale: 0 - 20). Figure 4.1a shows the distribution of *ObjU* outcomes for the participant sample, N = 92. The distribution has a slight negative skew (mean to the left of the median), implying that most participants understood the facts and problem structure well before the exercise began.



(a) Sample *ObjU*

(b) Sample *ObjU* by participant *Location*

Figure 4.1: Distributions of *ObjU*, denoting Objective Understanding in the design exercise. ObjU is negatively skewed showing a high degree of understanding. It may also depend on sample demographic attributes such as physical location during the time of the exercise.

Table 4.1: Welch's t-test comparison of Objective Understanding cannot reject the null hypothesis that there is no bias in strata, as indicated by the high p-values

	μ_{diff}	μ_1	μ_2	$T-stat$	p-value	DoF	conf.low	conf.high
Location:	0.797	14.623	13.826	1.686	0.099	38.935	−0.159	1.753
Gender:	0.626	14.880	14.254	1.198	0.239	35.936	−0.434	1.686
Degree:	0.588	14.488	13.900	0.662	0.523	10.125	−1.388	2.563
Role:	0.159	14.500	14.341	0.374	0.709	86.839	−0.686	1.004

This understanding could however differ in sub-samples of participants, and the analysis should identify biases in advance to account for them in subsequent steps. Some demographic or sample attributes could result in different distributions of *ObjU* across strata. The relevant attributes in the exercise were whether a participant was onsite or remote during the exercise (Location - Onsite/Remote), a participant's gender (Gender - Male/Female), and the individual's education level (Degree - MS/PhD) mattered. We assess whether the same tutorial administered to participants with different attributes resulted in systematically different degrees of Objective Understanding.

As an example, Figure 4.1b shows the distributions of Objective Understanding conditioned on the variable Location (Offsite / Onsite) denoting whether the participant underwent the exercise in the same room as the exercise administrator or remotely. Visual inspection of the shape of the distributions and and the mean and variance statistics warrant at least a basic test of means comparison. A Welch t-test for means comparisons with unequal variances suggests that we cannot reject the null hypothesis that the sub-samples have the same mean and were drawn from the same distribution for the Location dimension. This is good because we can now consider the data as a single sample along the dimension of Location. The conclusion is the same along the other demographic attribute dimensions of Gender and highest education level (Degree), as summarized in Table 4.1. Knowing that participants were randomly assigned to roles and experimental treatment groups, the same test was also run along both those dimensions. The Welch's t-tests suggest that the null hypothesis of no sample bias in *ObjU* cannot be rejected even in these cases. Note that this is a two-sided test, because there is no ex ante hypothesis about whether Objective Understanding is higher or lower in the stratified sub-samples along each of these dimensions.

4.1.3 Subjective Understanding (*SubjU*)

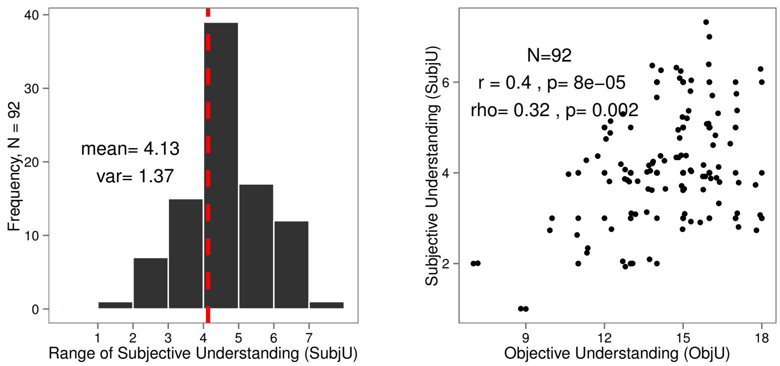
The pre-experiment survey collected data on Subjective Understanding. It asked participants to explicitly rate how well they thought they understood the design task and objectives they were about to address (scale 1: Not at all to 7: Perfectly). The distribution of the *SubjU* response variable is close to normal, as shown in Figure 4.2a. As we would expect, a participant's Subjective Understanding is positively correlated with the same individual's Objective Understanding. The relationship is statistically significant using both Pearson's r product-moment correlation (r = 0.4, p<0.001) for continuous variables as well as Spearman's rank-order relationship ρ for ordinal variables (ρ=0.32, p=0.002)(Figure 4.2b).[1]

A series of tests to detect sub-sample bias in Subjective Understanding, similar to those in Section 4.1.2, did not show any statistically significant differences in *SubjU* along the same strata (Table 4.2). We therefore do not have sufficient evidence to reject the null hypothesis that the sub-samples of participants are similar for the *SubjU* variable and drawn from the same population for the purpose of statistical hypothesis testing.

4.1.4 Mood (*M*)

Participants' disposition going into the collaboration exercise may affect the quality of their interactions. Mood (*M*) is a latent variable and difficult to measure directly, so the pre-experiment survey asked participants a number of questions related to this construct. Participants scored

[1]The rest of the analysis will continue to state both measures wherever applicable, because of differing views on when scale measures can be treated as continuous or ordinal.



(a) Sample *SubjU*

(b) Pearson's r and Spearman's ρ correlation of *SubjU* and *ObjU*

Figure 4.2: Distributions of *SubjU*, denoting Subjective Understanding in the design exercise. *SubjU* appears normally distributed and positively correlates with ObjU

Table 4.2: Welch's t-test comparison of Subjective Understanding cannot reject the null hypothesis that there is no bias in strata, as indicated by the high p-values

	μ_{diff}	μ_1	μ_2	$T - stat$	p-value	DoF	conf.low	conf.high
Location:	0.290	4.203	3.913	0.917	0.366	31.721	−0.354	0.934
Gender:	0.315	4.360	4.045	1.211	0.232	47.688	−0.208	0.839
Degree:	0.034	4.134	4.100	0.100	0.922	12.402	−0.706	0.774
Role:	0.076	4.167	4.091	0.308	0.759	86.936	−0.414	0.565
Treatment:	−0.271	3.974	4.245	−1.064	0.291	71.158	−0.779	0.237

how motivated, how nervous, and how confident they were about the upcoming exercise. These descriptors are more specific than a broad question about mood, and amenable for scoring on a scale because they can be described in degrees along a single dimension. For example, a participant's degree of motivation with respect to the exercise can be scaled from a minimum of 1: "Not at all", 4: "Moderately" to 7: "Extremely". Participants only saw these questions; they weren't primed as to what they questions may represent. These responses helped populate a measurement scale for M for use in the rest of the analysis. The specific descriptors listed above are the "items" of the scale.

Developing and using a scale for the construct of Mood (M) requires some analysis of both its validity and reliability for the purpose of a specific measurement. Broadly, validity of a tool is a statement about whether it measures what it is supposed to measure. Reliability is about the consistency of the tool's measurements across time, situations, and evaluators (Juni, 2007). Appendix K describes the approach for assessing validity and reliability of M. Table 4.3 summarizes the final results of the reliability tests, showing a reliable measurement of the M variable. We can therefore use Mood in subsequent analysis.

Table 4.3: Reliability tests for final *Mood* scale with items: *motivated* & *confident*, resulting in a higher α of around 0.65

Cronbach's α	std-α	G6(smc)	average_r	S/N	ase	mean	sd
0.644	0.647	0.478	0.478	1.829	0.163	4.359	1.108

Table 4.4: Welch's t-test comparison of Mood to identify potential bias in the two different treatment groups of the collaboration exercise. There is insufficient evidence to reject the null hypothesis that the Mood level was systematically different in the two groups

	μ_{diff}	$\mu_{\tau 1}$	$\mu_{\tau 2}$	$T-stat$	p-value	DoF	conf.low	conf.high
Mood	0.179	8.821	8.642	0.379	0.706	80.423	-0.760	1.118

As a final check for the appropriateness of the Mood scale, a Welch's t-test for sub-sample bias in the treatment groups (see Table 4.4) of the design exercise shows that the groups have comparable Mood distributions and the null hypothesis that there is no difference in means cannot be rejected. This continues to support the notion that the two treatment groups had a similar profile, before the design exercise.

4.1.5 Relationship between *SubjU*, *ObjU*, and *M*

Having described and tested the constructs of Subjective Understanding, Objective Understanding, and Mood, we can now pose the question of whether they are related. Section 4.1.3 showed that there is strong positive correlation between *SubjU* and *ObjU*. Similar tests of correlation show a weak positive relationship between *ObjU* and *M* (r = 0.22, p < 0.05; ρ = 0.20, p = 0.06). In comparison, there is a strong positive relationship between *M* and *SubjU* (r = 0.57, p < 0.001; ρ = 0.56, p < 0.001).

The correlations permit us to formulate the hypothesis that Subjective Understanding can be explained in relationship to Objective Understanding as well as Mood. This hypothesis is plausible because participants' belief about their level of understanding may be influenced by their "true" understanding of the facts, and also their instantaneous disposition. We can test this hypothesis with a standard OLS regression, and formally state it as:

H0: Subjective Understanding is independent of Objective Understanding and Mood, such that $\beta_0 = \beta_1 = \ldots = \beta_i = 0$

Table 4.5 shows the results of four different models analyzed to test this hypothesis. The first two regress *SubjU* individually on *ObjU* and *M* respectively. The third represents the two independent variables additively ($ObjU + M$) and the final also includes their multiplicative interaction term ($ObjU : M$).

Table 4.5: OLS Regression Analysis with *SubjU* as a dependent variable. Model (3), the addition of *ObjU* and *M*, gives the best fit and explains the most variation in *SubjU*.

	Dependent variable:			
	SubjU			
	(1)	(2)	(3)	(4)
μ_{SubjU}	4.130***	4.130***	4.130***	4.132***
	(0.112)	(0.101)	(0.095)	(0.098)
ObjU	0.468***		0.340***	0.337***
	(0.113)		(0.098)	(0.105)
M		0.667***	0.593***	0.592***
		(0.101)	(0.098)	(0.099)
ObjU : *M*				−0.009
				(0.110)
Observations	92	92	92	92
R^2	0.160	0.325	0.405	0.405
Adjusted R^2	0.151	0.317	0.392	0.385
Residual Std. Error	1.078 (df = 90)	0.966 (df = 90)	0.912 (df = 89)	0.917 (df = 88)
F Statistic	17.157*** (df = 1; 90)	43.326*** (df = 1; 90)	30.332*** (df = 2; 89)	19.998*** (df = 3; 88)
Note:	*p<0.1; **p<0.05; ***p<0.01			

The OLS procedure requires some data transformation so that the regression results can be interpreted appropriately. The transformation involves rescaling the independent or predictor variables so that they are centered at their mean (means shifting). Centering is helpful because an otherwise difficult to interpret intercept now takes the mean value of the dependent variable, when the independent variables are all held constant at their means. The common intercept value for all the models indicates the mean of *SubjU*, consistent with the description in Figure 4.2a.

Of the four models, Model (3) which represents *SubjU* as an additive function of *ObjU* and *M* is the best fit. It best explains the variation in SubjU (adj. $R^2 = 0.39$), has the lowest standard error of residuals, and a robust F statistic. (30.3; df 2, 89; $p<0.01$). We thus reject the null hypothesis, and state that *SubjU* can be statistically modeled as a function of *ObjU* and *M*. Objective Understanding and Mood predict the level of Subjective Understanding.

SubjU appears to be more sensitive to *M* than to *ObjU*. A unit change in the *M* score shifts *SubjU* from its mean value of $\mu_{SubjU} = 4.13$ by approximately 0.6, almost twice the effect of *ObjU*. After controlling for the effect of a participant's factual understanding of the design problem, an individual's perception of their level of understanding is highly dependent on their disposition at that moment in time.

So far the analysis has established that a participant's Subjective Understanding (*SubjU*) can be represented as a function of the individual's Objective Understanding (*ObjU*), or factual understanding, as well as their disposition at the time of the exercise as captured by Mood. Section 4.1 also showed through a suite of tests that the random assignment of participants to Role and Treatment groups did not result in bias in participants' understanding, before they began problem solving in the exercise. We therefore continue working with the metric of Subjective Understanding throughout analysis.

4.2 Assessing Improvement in Understanding

This section assesses the effects of experimental treatments during the collaboration exercise on participants' Subjective Understanding. We introduce a new variable, Improvement (*Im*), to indicate the degree of change in a participant's Subjective Understanding between the start and the end of the collaboration exercise. Recall that the participant's receive one of either Communication or Common Knowledge as experimental conditions in Problem 3, and both these conditions in Problem 4. These conditions correspond to the 'Communication first' and 'Information first' treatment groups respectively. The variable *Im* records participant's perceived improvement in understanding after experiencing the experimental conditions.

The post-exercise survey asked the participants a number of questions about whether their understanding improved after collaboration (Improvement - *Im*), whether communication with their collaborator increased their understanding (Communication factor - *Cm*), and whether seeing extra information about their collaborator's performance results confused them or detracted from understanding (Confusion factor - *Cf*). *Im, Cm* and *Cf* are thus self-reported measures. This section links the three to each other and to *SubjU*.

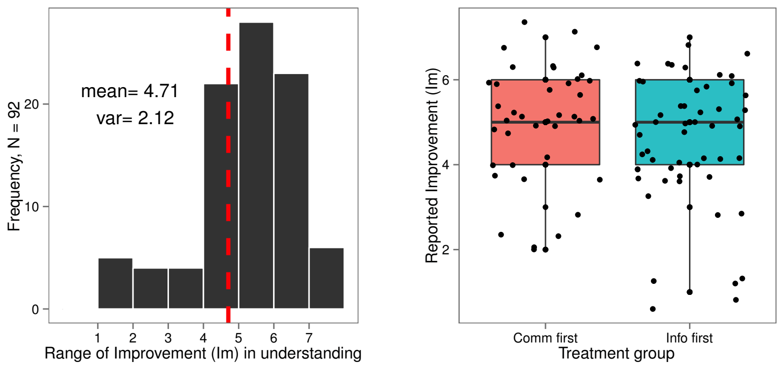
4.2.1 Improvement by Treatment Group

Participants' mental models and understanding will have evolved in both treatment groups as they courseed through the exercise, so we can expect both treatment groups to report an improvement. We test whether one treatment group reports a systematically higher *Im* score.

$H0_{IM1}$: Reported Improvement in understanding is the same across treatment groups.

Just as Subjective Understanding has an underlying distribution, so does reported Improvement in understanding. Figure 4.3a shows the probability distribution of Im, which has a negative skew. On the whole, the participants perceived that their understanding of the design exercise improved over the course of the design exercise. The distribution of Im appears comparable across the two treatment groups (Figure 4.3b), although the 'Information first' group has a slightly larger variance. An Analysis of Variance (ANOVA) test shows that the 'Communication first' group (mean = 4.97, var = 1.92) reported higher Im with a lower spread than the 'Information first' group (mean = 4.51, var = 2.22), although the difference is not statistically significant (p=0.13, see Table 4.6).[2]

[2] The 'Communication first' treatment group is the subgroup that first communicated with each other in Problem 3 of the collaboration exercise. Chapter 3 has explained the choice of labels and other treatment-related outcomes in more detail.



(a) Overall reported Improvement (Im) in understanding

(b) Im by Treatment Group

Figure 4.3: Distribution of overall Im, and Im by treatment group. Both treatment groups reported an overall Improvement in understanding

Table 4.6: ANOVA fails to reject the null hypothesis that Im in the two treatment groups is the same

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	1	4.856	4.856	2.322	0.131
Residuals	90	188.220	2.091		

4.2.2 Influence of Subjective Understanding on Improvement

The Im results can be unpacked further. The two variables Im and $SubjU$ have a small positive correlation with (r=0.3, p<0.01; ρ=0.27, p<0.01). This result suggests that a participant's belief about any improvement in understanding could depend on how well they thought they understood the design problem in the first place. This is a counter-intuitive result. One the one hand, participants who thought they understood the problem extremely well before participating in the exercise would realize that they had in fact not understood it so well after all, and consequently report a large Im. On the other hand, some participants who may have believed that they understood the problem poorly, could also realize that they understood the design task better after the exercise, and report a high Im. The number of plausible hypotheses to explain this positive correlation make it important to condition Im on $SubjU$, i.e. to control for the degree of Subjective Understanding prior to the design exercise in the assessment of Improvement.

Formally stating these propositions in the form a null hypothesis:

$H0_{IM2}$: A participant's reported Improvement in understanding post-exercise remains independent (i.e. does not increase or decrease) as a function of their pre-exercise Subjective Understanding and treatment group.

The OLS regression in Table 4.7 for Im as a function of $SubjU$ by treatment group suggests that participants in treatment group 'Communication first' had a higher Im score of more than 0.5 points at every level of $SubjU$ (p<0.1). Note that these two independent variables alone explain only about 10 % of the variation in the observations. The result is affirmed in Figure 4.4 by the different location of the distributions for the two treatment groups and decreasing variance in Im with an increase in $SubjU$.

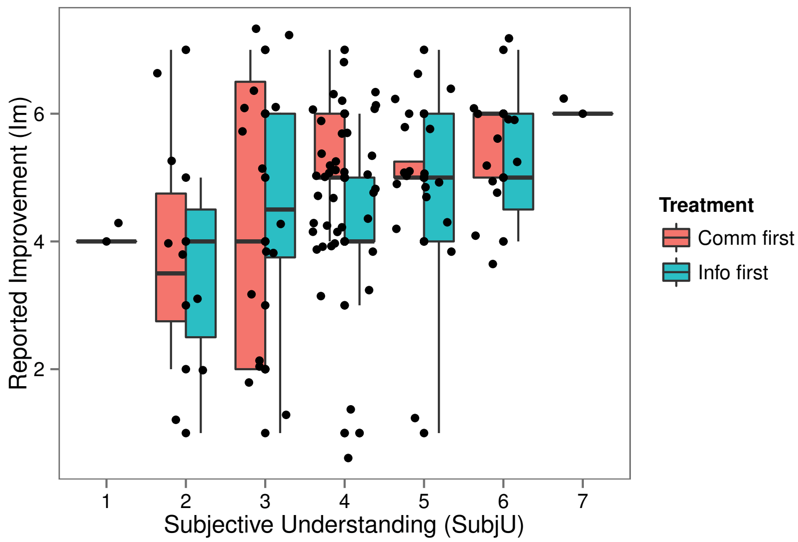


Figure 4.4: Distributions of reported Improvement (Im) with Subjective Understanding ($SubjU$), grouped by Treatment. Mean Im increases as $SubjU$ increases, although there is a large variation for low levels of $SubjU$.

Controlling for $SubjU$ only explains about 10% of the variation in Im. We can explore whether some of this variation is explained by the participants' ability to communicate with each other in collaborative design rounds.

4.2.3 Influence of Communication on Improvement

Participants were asked post-exercise to attribute how much of their improvement in understanding related to the ability to communicate, Cm, with their counterparty. Reported Im is found to correlate well with Cm (r= 0.45, p<0.001; ρ=0.35, p<0.001). We can hypothesize that more of the 'Communication first' group's improvement in understanding came from the process of discussion with their collaborator. As the Cm score increases, we also expect the Im score to increase, but differently across the two Treatment groups.

$H0_{IM3}$: The attribution of improvement to communication, Cm, is similar across the two treatment groups.

Table 4.7: Reported Improvement (Im) by Treatment group, controlling for $SubjU$. 'Communication first' group has higher reported Im on average.

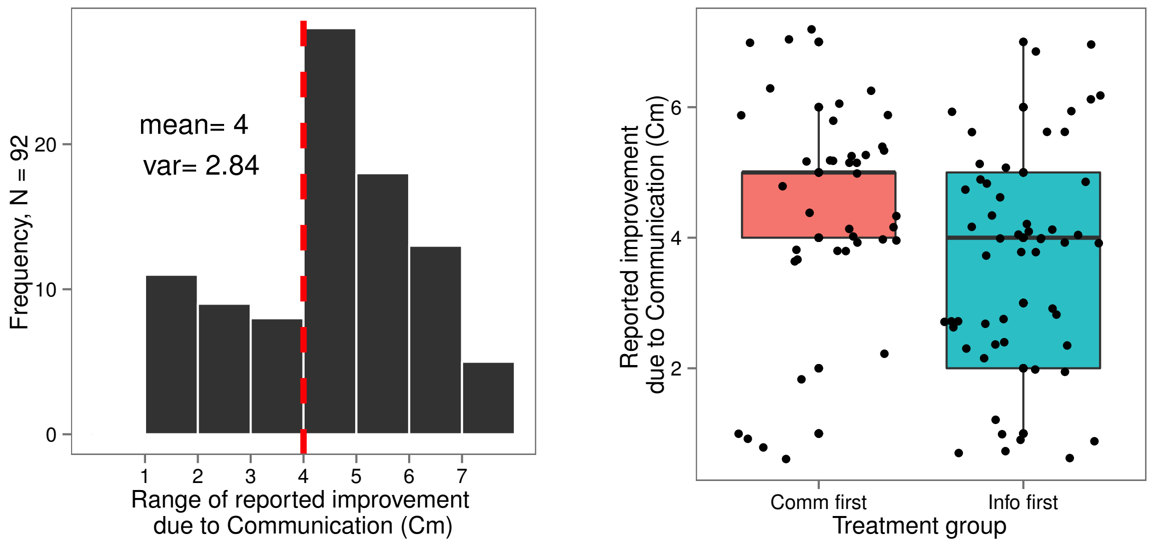
	Dependent variable:	
	Im	
	(1)	(2)
Intercept	4.707***	5.037***
	(0.146)	(0.221)
$SubjU$	0.437***	0.470***
	(0.146)	(0.145)
'Info first'		−0.574*
		(0.292)
Observations	92	92
R^2	0.090	0.128
Adjusted R^2	0.080	0.108
Residual Std. Error	1.397 (df = 90)	1.375 (df = 89)
F Statistic	8.910*** (df = 1; 90)	6.526*** (df = 2; 89)
Note:	*p<0.1; **p<0.05; ***p<0.01	

$H0_{IM4}$: The change in Im is similar across the two groups while controlling for Cm.

Table 4.8: ANOVA rejects the null hypothesis ($p<0.05$) that Cm in the two treatment groups is the same. The 'Communication first' group attributes more improvement to communication.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	1	11.394	11.394	4.158	0.044
Residuals	90	246.606	2.740		

The distribution of Cm in Figure 4.5a suggests that a large number of participants attributed improvement in understanding to the communication. However, a sizable number of participants attributed little to no improvement to the discussion process. A comparison of the distributions of Cm in the two treatment groups (Figure 4.5b) shows a marked difference. The 'Communication first' group has a higher mean with much lower variance. Specifically, the difference in means from a Welch test with unequal variance is μ_{diff} in Cm is 0. 71 ($p<0.05$, 95% ci: [0.02, 1.4]), as reinforced by the ANOVA representation in Table 4.8. Overall, these results imply that while both treatment groups reported *Improvement* in understanding, the 'Communication first' group attributed more of that improvement to communication.



(a) Overall attribution of Improvement to Communication (Cm)

(b) Cm by Treatment Group

Figure 4.5: Distribution of overall Cm, and Cm by treatment group. While both treatment groups attributed much of the Improvement to Communication, the attribution was higher in the 'Communication first' group.

When controlling for the level of reported Im in the two treatment groups, the main effect of the Treatment group becomes less pronounced. This is visually observed in Figure 4.6. Nonetheless, as Cm increases, the variance in Im decreases. At lower levels of Cm, participants could still experience high improvement which could have come through a mechanism other the communication aspect of collaboration.

We have already seen that Subjective Understanding and Improvement in understanding are linked. How does Cm interact with $SubjU$ to explain changes in Im? A first test of correlation shows that $SubjU$ and Cm are relatively uncorrelated (r=0.18, p<0.1; ρ=0.16, p=0.13). This mitigates the concern of collinearity in a regression model with both $SubjU$ and Cm as independent variables. Another set of OLS regressions is performed to evaluate models that include Cm as an independent variable. The regression results following in Table 4.9 build on the initial models specified in Table 4.7. Thus model (2) in the leftmost column from Table 4.7 is repeated for the sake of comparison. Models (3) and (4) update the previous specifications. Note that $SubjU$ and Cm are rescaled through means shifting as before.

The models that include the Cm term demonstrate significantly better fit. The amount of variation in Im explained jumps up to 32% (adj. R^2) in Model (4). This improvement is accompanied by appreciable improvements in coefficient fits as well as overall model fit.

Model (3) additively includes Cm. The effect is that the amount of variation explained by $SubjU$ decreases but continue to remain statistically significant. The control for Treatment shows that the coefficient of groups drops out of significance. The interpretation is that participants

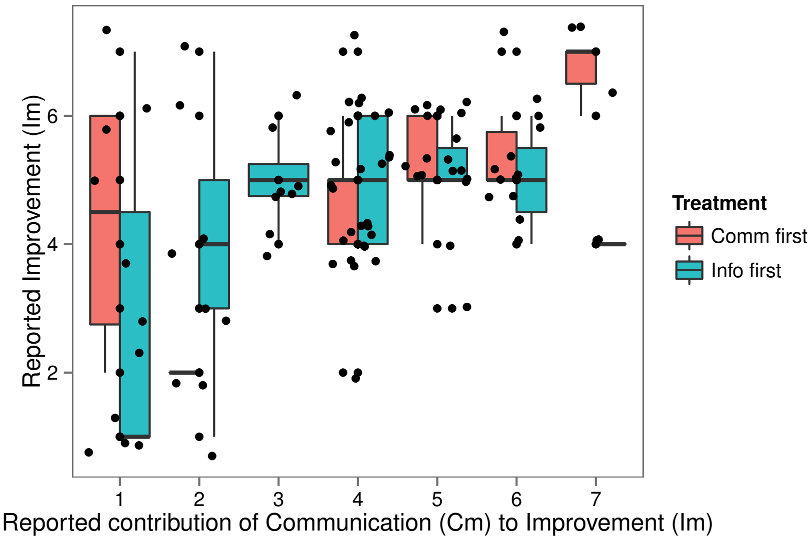


Figure 4.6: Distributions of reported Improvement (Im) with improvement attributed to Communication (Cm), grouped by Treatment. Mean Im increases as Cm increases.

experience an overall level of Im with increases in both $SubjU$ and Cm but the effect of Cm is more pronounced. The effect is reduced for the 'Information first' group, however not in a statistically significant manner.

Model (4) includes one more term: the interaction between $SubjU$ and Cm. Since the two are uncorrelated, positing an interaction effect is plausible. This model is the best fit obtained so far. The interpretation is that the slope of the lines fitted to the independent variables will change at all values of $SubjU$ and Cm except the mean levels of these rescaled variables, where the interaction term -> 0. The negative coefficient suggests a decreasing marginal contribution of these terms with an increase in independent variables.

Assessing the effect of Cm shows that there is a significant amount of unexplained variation in Im. We can look at the effect of one other contributing factor, the effect of additional information in the 'Common Knowledge' condition in the design exercise.

4.2.4 Influence of Common Knowledge on Improvement

The final question regarding Improvement in the post-exercise survey was whether participants experienced confusion when presented with the counterparty's performance results in the Common Knowledge condition. The variable Confusion (Cf) was included in the survey to assess whether the additional information in this condition detracted from the otherwise overall improvement in understanding as a consequence of completing the exercise. As expected, Cf is negatively correlated with Im (r= – 0.2, p = 0.06; ρ= –0.20, p = 0.05).

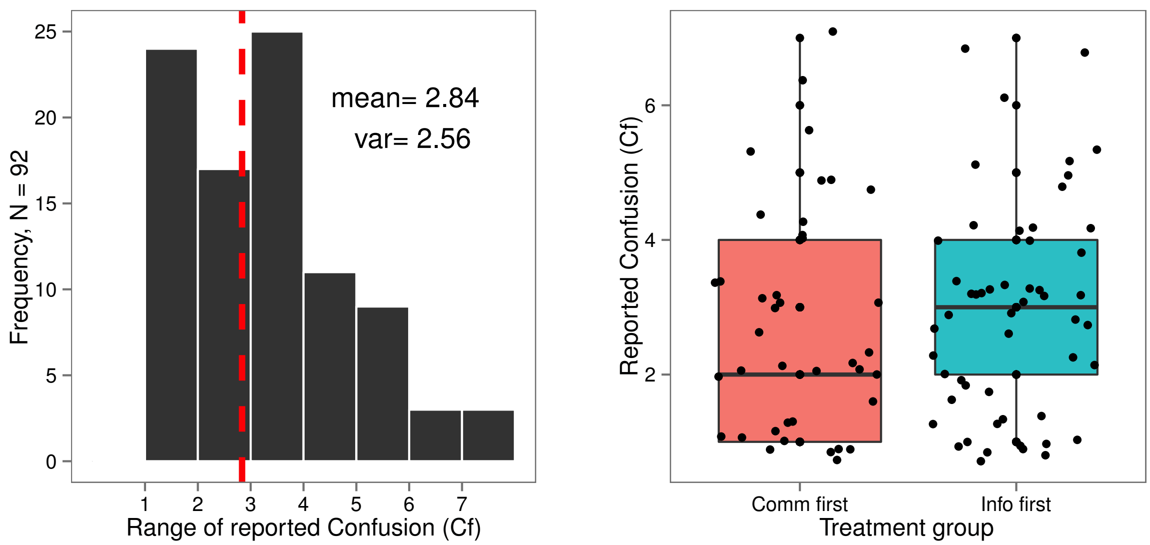
Table 4.9: Reported Improvement (*Im*) in relation to Subjective Understanding (*SubjU*), and influence of Communication (*Cm*) across both Treatment groups.

	Dependent variable:		
	Im		
	(2)	(3)	(4)
Intercept	5.037***	4.888***	4.981***
	(0.221)	(0.209)	(0.198)
SubjU	0.470***	0.357**	0.309**
	(0.145)	(0.138)	(0.130)
Cm		0.549***	0.468***
		(0.140)	(0.133)
Group 'Info first'	−0.574*	−0.315	−0.342
	(0.292)	(0.279)	(0.262)
SubjU : *Cm*			−0.441***
			(0.124)
Observations	92	92	92
R^2	0.128	0.258	0.352
Adjusted R^2	0.108	0.233	0.322
Residual Std. Error	1.375 (df = 89)	1.276 (df = 88)	1.199 (df = 87)
F Statistic	6.526*** (df = 2; 89)	10.197*** (df = 3; 88)	11.799*** (df = 4; 87)
Note:	*p<0.1; **p<0.05; ***p<0.01		

$H0_{IM5}$: The detraction from improvement in understanding due to Confusion, Cf, is similar across the two treatment groups.

$H0_{IM6}$: Reported improvement Im, is the same across the two treatment groups, while controlling for the effect of Confusion (Cf)

The distribution for Cf is right-skewed (Figure 4.7a); most participants reported low levels of confusion as a result of seeing the counterparty's information. There could be a difference in mean levels of Cf scores across the two treatment groups. In fact, an initial look at the box plots for the two groups in Figure 4.7b suggests that this might be the case. However, an ANOVA analysis (Table 4.10) shows that there isn't sufficient evidence to reject the null hypothesis that the mean level of Cf in the two treatment groups is the same.



(a) Reported Confusion (Cf) due to common knowledge

(b) Cf by Treatment Group

Figure 4.7: Distribution of Cf, and Cf by treatment group. The 'Information first' treatment group that had longer exposure to counterparty information exhibits a higher median of Cf with lower variance, but the means are comparable.

Table 4.10: ANOVA results for the mean difference in Confusion, Cf, cannot reject the null hypothesis that reported Cf is similar across the two groups.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Treatment	1	0.311	0.311	0.120	0.729
Residuals	90	232.244	2.580		

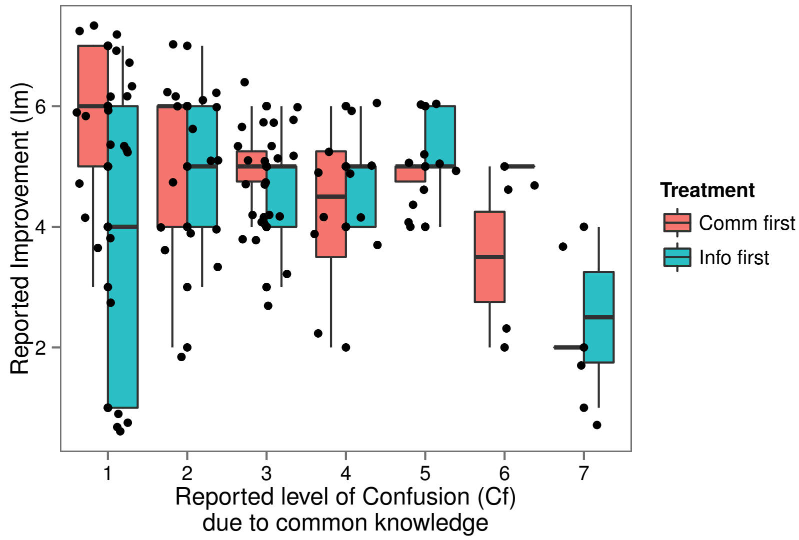


Figure 4.8: Distributions of reported Improvement (Im) with reported Confusion (Cf) due to common knowledge, grouped by Treatment. Mean Im decreases as Cf increases.

The intuition that Cm may dominate Cf can be observed in **??**, which shows the changing variance in Im in the two treatment groups while controlling for Cf. The variance in Im is typically smaller and the level of Im is higher especially at low levels of Cf in the 'Communication first' group which allowed for more communication during collaborative design rounds.

Since Cm and Cf are uncorrelated with each other, they can both be included as independent predictor variable in the OLS regrssion model the previous subsections began to develop. Table 4.11 shows some updated OLS specifications that include both the main and different interaction effects of Cf. Model (4) is reproduced from Table 4.9 for comparison. Model (5) adds Cf as a main effect only, which improves the adj. R^2 appreciably. Model (7) includes the interaction terms of $SubjU : Cf$ and $Cm : Cf$. This final term has a negligible coefficient and appears to do little to improve the fit statistics or explain much variation in Im. Model (6) is obtained by dropping the last $Cm : Cf$ term. This model is the best obtained so far in terms of goodness of fit, amount of variation explained and low standard error of the residuals.

The interpretation of Model (6) is that participants who reported an improvement in understanding by the end of the collaboration exercise attributed much of this improvement to the ability communicate with each other. The additional information received through common knowledge had the potential to confuse participants. The degree of improvement in understanding also depended on the participant's own initial perception of how well they understood the problem at the start of the exercise. Even participants who thought they initially understood it well could find that their understanding improved further. If their initial perceived understanding was high, then communication still helped but to a lower degree than for the participant's with a low perceived understanding initially.

Table 4.11: OLS regression results with Cf included as an independent as well as interaction variable. Model (6) is the best fit, and it includes the main and interaction effects of Cf.

	Dependent variable:			
	Im			
	(4)	(5)	(6)	(7)
Intercept	4.981***	4.957***	5.006***	5.006***
	(0.198)	(0.192)	(0.192)	(0.193)
$SubjU$	0.309**	0.266**	0.288**	0.287**
	(0.130)	(0.127)	(0.127)	(0.127)
Cm	0.468***	0.503***	0.497***	0.493***
	(0.133)	(0.130)	(0.129)	(0.131)
Cf		−0.315**	−0.258**	−0.263**
		(0.124)	(0.127)	(0.130)
Group 'Info first'	−0.342	−0.294	−0.331	−0.327
	(0.262)	(0.255)	(0.253)	(0.255)
$SubjU : Cm$	−0.441***	−0.458***	−0.492***	−0.492***
	(0.124)	(0.121)	(0.121)	(0.122)
$SubjU : Cf$			0.223*	0.226*
			(0.131)	(0.133)
$Cm : Cf$				−0.023
				(0.121)
Observations	92	92	92	92
R^2	0.352	0.397	0.417	0.417
Adjusted R^2	0.322	0.362	0.376	0.369
Residual Std. Error	1.199 (df = 87)	1.164 (df = 86)	1.151 (df = 85)	1.157 (df = 84)
F Statistic	11.799*** (df = 4; 87)	11.323*** (df = 5; 86)	10.128*** (df = 6; 85)	8.588*** (df = 7; 84)
Note:	*p<0.1; **p<0.05; ***p<0.01			

This chapter's analysis so far has made a case for the importance of Subjective Understanding, and unpacked a number of attributes that contributed to Improvement in understanding. This understanding helped participants in the exercise to make design choices. However, the late stages of the collaborative design exercise are inherently a process of negotiation. After exploring the tradespace to identify candidate designs, designers engaged in joint decision-making to ensure that the chosen design would meet their competing objectives. The next section examines the psycho-social nature of negotiated decision-making in design. It introduces and discusses the concept of Subjective Value (SV) outcomes in negotiated collaboration.

4.3 Assessing Subjective Value

Negotiations have two types of outcomes. The first type, economic outcomes, are the terms of the agreement struck by the negotiating parties. The bulk of the negotiations literature has focused on economic outcomes, construing them as objective or tangible terms of exchange. The second type of negotiated outcomes, social psychological outcomes, are the attitudes and perceptions of the negotiators (Thompson, 1990). They historically received little to no formal attention as the performance dimensions of negotiation studies because they are transient and fleeting, and perceived as hard to assess. We discuss recent developments and set the stage for studying the Subjective Value of negotiated collaboration.

4.3.1 Relevant literature on Subjective Value

Recent work suggests that the Subjective Value (SV) of social psychological outcomes of negotiation are just as, if not more important than the Objective Value (OV) of economic outcomes. Curhan, Elfenbein, and Xu (2006) developed the construct of SV, which they define as the "social, perceptual, and emotional consequences of a negotiation."

Behavioral science has certainly long recognized subjective issues in negotiation processes for their effects on economic outcomes, however treated these issues less as outcomes themselves. For example, Neale and Bazerman (1985) studied the effect of framing and overconfidence in simulated negotiations. Their factorial design framed outcomes in terms of gains and losses between managers and unions, however these outcomes were economic, indicating OV as defined above. The focus on OV is consistent with the trend (Raiffa, 1982; Bazerman and Lewicki, 1983; Raiffa, Richardson, and Metcalfe, 2002). Only recently have studies started to systematically consider subjectivity in outcomes, by relaxing traditional about negotiations in organizations (Walsh, Weber, and Margolis, 2003; Bendersky and McGinn, 2010).

Subjective Value in negotiated agreements for design is important for at least four reasons. First, negotiators often place high value on the degree of respect or favorable relationships, sometimes even more than the value they attribute to economic payoffs. Social psychological outcomes thus have intrinsic value. For example, when given the choice, negotiators often describe the negotiation objective with frames that signify fairness and respect even if they may secure lower monetary outcomes (Blount and Larrick, 2000). This imbalance may be conscious or unconscious. Second, individuals or entities may be sought out as good counterparts based on the strength of the relationship and credible reputation (Curhan, Elfenbein, and Xu, 2006; Curhan, Elfenbein, and Eisenkraft, 2010). The desire to deal with partners who have established rapport may serve to further enhance SV (Tinsley, O'Connor, and Sullivan, 2002). Third, securing high SV in the first round of a negotiation may lead to both higher SV and OV in subsequent rounds (Drolet and Morris, 2000; Curhan, Elfenbein, and Eisenkraft, 2010). This reinforces the intuition of the two reasons above. Finally, enhanced Subjective Value can serve as a means of commitment to honor the terms of the agreement, when outcomes are not self-enforcing or easily monitored (Curhan, Elfenbein, and Kilduff, 2009; Ferguson, Moye, and Friedman, 2008). Curhan and Brown (2011) call this the "insurance policy" function of SV. For the reasons described here, the relational view of negotiation (Gelfand et al., 2006) may take precedence over the rational view (Neale and Bazerman, 1992).

Subjective Value of negotiation thus has implications for the collaborative design processes addressed in this study. The relational phenomenon is observed in contract settings between government agencies and private firms, where a perceived lack of respect or perceived opportunism may contribute to the adversarial nature of the relationship. Many authors point to trust as a key element of negotiated decisions in this space (Smyth and Edkins, 2007; Smyth and Pryke, 2009). Relational approaches to contracting therefore emphasize a longer term view of bargaining with an emphasis on collaborative mechanisms for securing outcomes (Rahman and Kumaraswamy, 2004; Osipova, 2014; Suprapto et al., 2014).

The dual nature of value in negotiated decisions implies that neither should be considered in isolation. Curhan and Brown (2011) make the case that the very prescriptions and methods that negotiators apply to enhance *OV* may undermine *SV*, a detraction from the overall organizational objective. For this reason, the research described here tracks both the Objective Value and Subjective Value of negotiation outcomes. *OV* outcomes were analyzed at length in Chapter 3, so this section mainly elaborates on *SV* outcomes.

4.3.2 Measuring *SV* in the collaboration exercise

Subjective Value is measured with the Subjective Value Inventory (SVI), a measurement scale developed by Curhan, Elfenbein, and Xu (2006). The SVI scale is an umbrella device and has four sub-dimensions or subscales, described below (Curhan, Elfenbein, and Eisenkraft, 2010).

1. **Instrumental *SV***: this sub-scale records the subjective perception that the economic or Objective Value of outcomes in the negotiated agreement were balanced between the parties' objectives, and in line with negotiators' normative expectations of legitimacy. Negotiators' responses to four questions about satisfaction, balance, loss, and legitimacy populate the scores of this sub-scale.

2. **Self *SV***: the second sub-scale indicates the perception of feeling competent during the session and "losing face." This is relevant because some the economic outcomes of some negotiations are not immediately revealed or clear, and negotiators look to their own perceptions for closure about their performance.

3. **Process *SV***: Perceptions of fairness in process, being heard or feeling listened to while expressing arguments, and perception of the counterpart adequately considering an individual's viewpoint are captured by this sub-scale.

4. **Relationship *SV***: this sub-scale captures impressions about the positivity of the exchange between negotiators, beliefs about trust, and the extent to which counterparties perceive a good foundation for future exchanges, if they were to transact again.

These four sub-dimensions of Subjective Value taken together comprise the global SVI measure, where Global SV denotes the aggregated score for the umbrella scale. Process and Relationship SVs are combined to give a Rapport SV. The post-survey administered at the end of the collaboration exercise asked participants a series of questions that have been standardized in the Subjective Value Inventory.

Table 4.12 presents a summary of a series of reliability tests on the SVI subset of questions in the post exercise survey. The three different estimates of reliability (Cronbach's α, standardized α, and G6) suggest that Instrument (I) and Self (S) SV estimates are reliable, however they are slightly lower than the prescribed threshold of 0.7 for ordinal measurement scales. These sub-scales should therefore not be used independently. On the other hand, Process (P) and Relationship (R) are highly reliable. We can confidently combine the latter two into the Rapport SV scale ($\alpha = 0.85$). The Global SV estimate ($\alpha = 0.71$) is consequently also within the prescribed range of 0.7 to 0.9. [3]

Table 4.12: Reliability tests for SV outcomes along the sub-scales and global scale of the Subjective Value Inventory (Curhan, Elfenbein, and Xu, 2006). High α reliability estimates [0.7,0.9] imply that the aggregated Rapport and Global SV scores may be confidently used to indicate Subjective Value in further analysis.

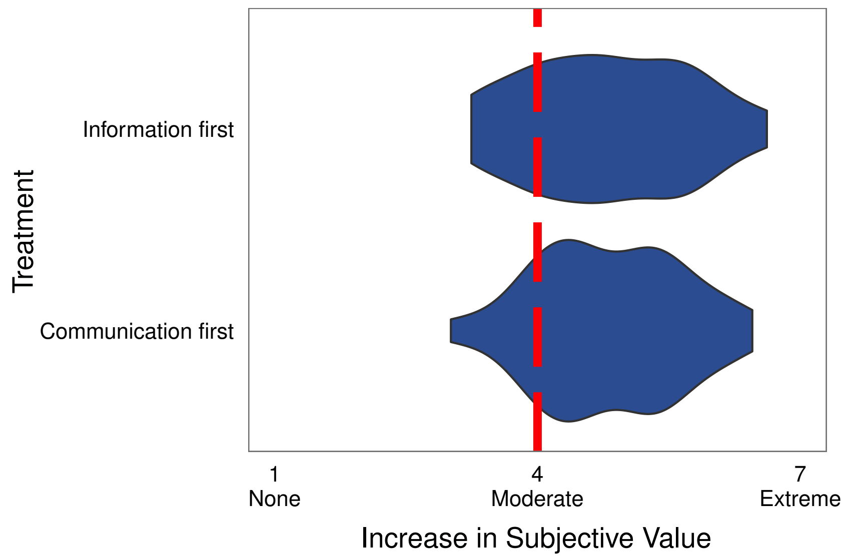
Sub-scale	Cronbach's α	Std α	G6(smc)	avg r	S/N	ase	mean	sd
Instrument (I)	0.617	0.622	0.615	0.291	1.642	0.100	4.873	1.046
Self (S)	0.640	0.687	0.690	0.305	2.199	0.087	4.871	0.780
Process (P)	0.896	0.897	0.880	0.686	8.737	0.060	4.861	1.446
Relationship (R)	0.928	0.933	0.919	0.776	13.871	0.054	4.759	1.355
Rapport SV (P+R)	0.852	0.853	0.743	0.743	5.783	0.132	4.778	1.323
Global SV (I+S+P+R)	0.710	0.701	0.700	0.370	2.346	0.085	4.809	0.872

4.3.3 Subjective Value outcomes of negotiated collaboration

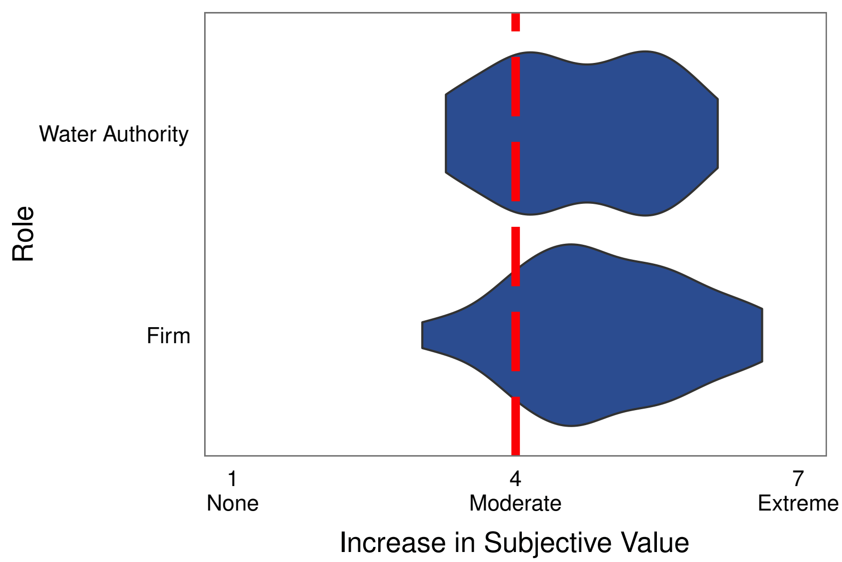
Most participants reported a large increase in Subjective Value after participating in the collaboration exercise. We can look at SV outcomes in a number of ways to substantiate this result.

Subjective Value outcomes by treatment group show that both groups ('Communication first' and 'Information first') experienced a large increase in SV. Figure 4.9a shows this in the form of a violin plot. The aggregate SVI scale for 'Increase in Subjective Value' is on the horizontal axis and ranges from 1: None to 7:Extreme. The red dashed line marks the scale mid-point. The ends of the colored areas indicate the range of the observations for each group. The relative density of observations at each level of the scale is given by the width of the shaded area at each level

[3] We would be skeptical of α estimates very close to 1, because of redundancies in measurement. In other words, any one of the "items" may be sufficient to denote the construct of interest, however this is not the case for the SV estimates here.



(a) Reported increase in *SV* by Treatment group. Both the 'Communication first' and the 'Information first' group reported a large increase in Subjective Value, shown by the large density of observations to the right of the midpoint (red-dashed line) of the scale. The difference in the means of the two groups is not statistically significant.



(b) Reported increase in *SV* by Role group. Both the Water Authority and the Firm role-players reported a large increase in Subjective Value, shown by the large density of observations to the right of the midpoint (red-dashed line) of the scale. The difference in the means of the two groups is not statistically significant.

Figure 4.9: Plots of the reported increase in Subjective Value after collaboration, by Treatment group (upper), and by Role (lower). The aggregated SVI scale ranges from 1:None to 7:Extreme. The width of the shapes shows the relative density of scores at each level of the scale.The red-dashed line marks the mid-point of the scale.

Table 4.13: Correlations between demographic attributes and SVI sub-scales. As expected, SVI sub-scales correlate positively with each other, and with the Global measure (by construction). The Relationship score is correlated with Gender. Women ascribe higher Subjective Value in terms of relational outcomes

	Gender	Age	Education	Location	Role	Treatment	Instrument (I)	Self (S)	Process (P)	Relationship (R)	Rapport *SV* (P+R)
Gender											
Age	0.28**										
Education	-0.17	-0.02									
Location	0.28*	0.14	-0.02								
Role	-0.01	-0.04	0.18	0.02							
Treatment	-0.08	0.06	-0.04	-0.04	-0.01						
Instrument (I)	0.07	-0.03	-0.11	-0.09	-0.11	0.11					
Self (S)	-0.06	0.13	0.02	-0.03	0.01	-0.05	0.21				
Process (P)	-0.16	-0.10	-0.06	-0.04	-0.08	0.12	0.27*	0.28*			
Relationship (R)	-0.22*	-0.09	0.08	-0.10	-0.07	-0.08	0.27*	0.44***	0.75***		
Rapport *SV* (P+R)	-0.20	-0.10	0.01	-0.07	-0.08	0.03	0.28**	0.38***	0.94***	0.93***	
Global *SV* (I+S+P+R)	-0.14	-0.06	-0.02	-0.09	-0.09	0.04	0.57***	0.58***	0.85***	0.88***	0.93***

of the scale. We can see that most of the shaded area is well to the right of the scale mid-point of 'Moderate' increase in SV. The difference in the means of the two groups is not statistically significant.

The conclusion from an analysis of SV by Role is very similar. Participants in both the Water Authority's and the Firm's role reported that their SV increased after collaboration. Figure 4.9b shows this in the form of another violin plot. Although the increase in SV on the whole was large, the difference in the means of the two Role groups is not statistically significant.

Elfenbein et al. (2008) find that some demographic attributes correlate with SV outcomes. I therefore also establish whether participants in my study tend to exhibit similar correlations. In particular, I test 'Gender','Age','Education', and 'Location' of participation, see Table 4.13. The four sub-scales comprising the Global SV measure are positively correlated with each other, by construction and from the reliability tests above. Another relationship of note is the negative correlation between the Relationship (R) sub-scale measure and Gender [Female=1, Male =2]. The interpretation is that women ascribe higher SV outcomes along the Relationship dimension. This observation is explored further below. SV outcomes do not co-vary much with the other demographic attributes tested here.

The relationship between Gender and Relationship SV is consistent with observations in the literature, but not sufficiently compelling based on a test of correlation alone. It is interesting enough to run a few more tests to either confirm or reject any statistical hypotheses. Two different tests of means comparison - Welch's t-test (t=2.24, $p<0.05$, μ:[0.07,1.37]) and a non-paramteric Wilcoxon rank sum test (W=985.5, $p<0.05$) - both reject the null hypothesis that gender has no effect on Relationship SV outcomes (Table 4.14). The evidence thus supports the finding that women did indeed experience higher Subjective Value along the Relationship sub-dimension, with a difference in means of slightly more than 0.7 points on the scale.

Figure 4.10 visualizes this result. The density of increase in Relationship SV is much more to the right of the scale for Women than for men. In fact, the range for Men extends almost the full length of the scale. Many women reported very high increases of 6 or 7 on the Relationship sub-dimension.

Table 4.14: Comparison of means for Relationship SV by Gender. The null hypothesis that Relationship SV does not depend on Gender is rejected ($p<0.05$)

	μ_{diff}	μ_{Female}	μ_{Male}	statistic	p.value	DoF	conf.low	conf.high
Welch's t-test	0.722	5.281	4.560	2.237	0.031	40.329	0.070	1.374
Wilcoxon rank sum test				985.5	0.029			

I also tested the dimensions of Subjective Value other than Relationship SV for correlation (Table 4.13), means differences and dependence on either experimental Role or Treatment condition. Neither the Instrument, Self and Process SV sub-scale scores, nor the Global or Rapport SV scores exhibited statistically significant results with these variables endogenous to the experiment. Appendix L contains the results of some of these tests.

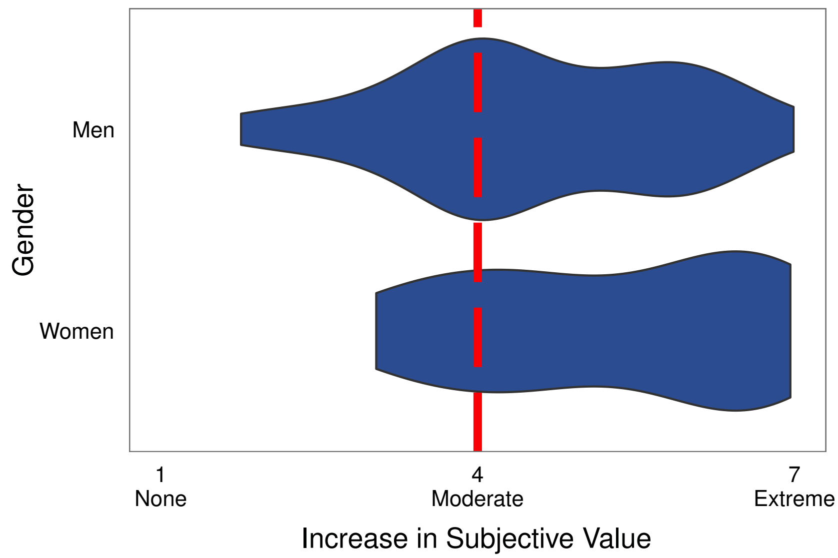


Figure 4.10: Participants' reported increase in *SV* by Gender. Women and men show different degrees of increase (pv = 0.003) in the Relationship dimension of the SVI scale. Women reported higher Relationship *SV* outcomes than men.

So far, we've assessed that collaboration led many participants to report an increase in their Subjective Value outcomes, or overall psycho-social experience of engaging in the collaboration exercise. How does *SV* relate to some other aspects of the collaboration? For example, is it associated with the participants change in understanding? Is there a relationship between Objective Value and Subjective Value outcomes in this instance of negotiated collaboration? We assess these questions next.

4.3.4 Relating *SV* to Improvement in understanding

We can now connect the idea of Subjective Value to the construct of subjective understanding that this chapter developed earlier in Section 4.1 and improvement (*Im*) in that understanding in Section 4.2.

The analysis summarized in Figure 4.11 gives a sense of the relationship between the increase in aggregate *SV* and the *Im* variable. The figure shows boxplots to for *SV* to show both the mean and the variation in outcomes, while controlling for *Im* on the horizontal axis. Except for the lowest level of *Im*, as the participants' *Im* increases, their distribution of their aggregate *SV* score shifts upward on the SVI scale. Even at the lowest *Im* of 'no improvement' in understanding, a few participant's reported a high increase in *SV*.

Based on this trend, we can formulate and test the hypothesis of a correlation between Subjective Value and Improvement in understanding. Tests of correlation do in fact show that *SV* and *Im* are positively correlated (r = 0.37, ρ = 0.41, p<0.001). Table 4.15 summarizes the results

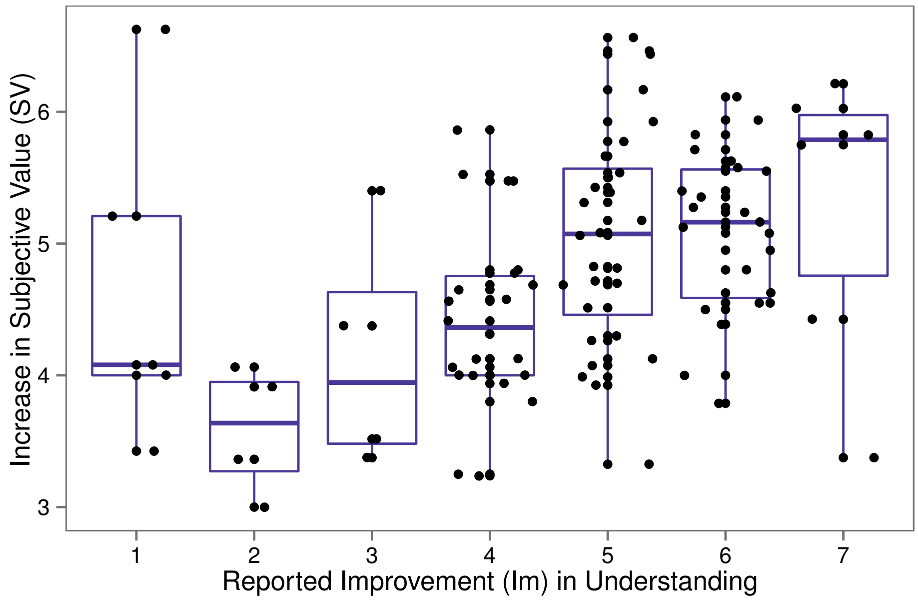


Figure 4.11: Distributions of the increase in aggregate Subjective Value (*SV)*, while controlling for the reported Improvement (*IM*) in understanding at the end of the collaboration exercise. The boxplots show that, except for the lowest level of *Im*, as *Im* across the participants increases, the distributions of their *SV* outcomes also shifts in to the upward part of the SVI scale.

Table 4.15: Tests of correlation between *SV* and *Im*. The increase in Subjective Value and Improvement in understanding are positively and significantly correlated.

	estimate	statistic	p.value	parameter	conf.low	conf.high
Pearson's r	0.371	3.785	0.0003	90	0.179	0.535
Spearman's ρ	0.409	$76,664$	0.0001			

of both Pearson's r and Spearman's ρ tests. We conclude that there is a positive relationship between how much participants felt their understanding improved after collaboration and the Subjective Value they ascribed to their experience.

4.3.5 Relating *SV* to Agreement in design choices

In Chapter 3, the analysis of Objective Value outcomes such as value outcomes and agreement in designs linked these outcomes to the treatment and role aspects of collaboration, and to the emergent behavioral archetypes. We can now link one representation of Objective Value outcomes, the degree of agreement, Agreement (*Ag*) in design choices to the aggregate *SV* outcomes. The variable *Ag* is a good proxy for *OV* outcomes because to balance value trade-offs between reliability of meeting demand, profit, and contract payments the collaborators had to agree on the independent dimensions of design. Hence we can hypothesize that if collaborators agreed more on designs, they may have experienced higher *SV* outcomes.

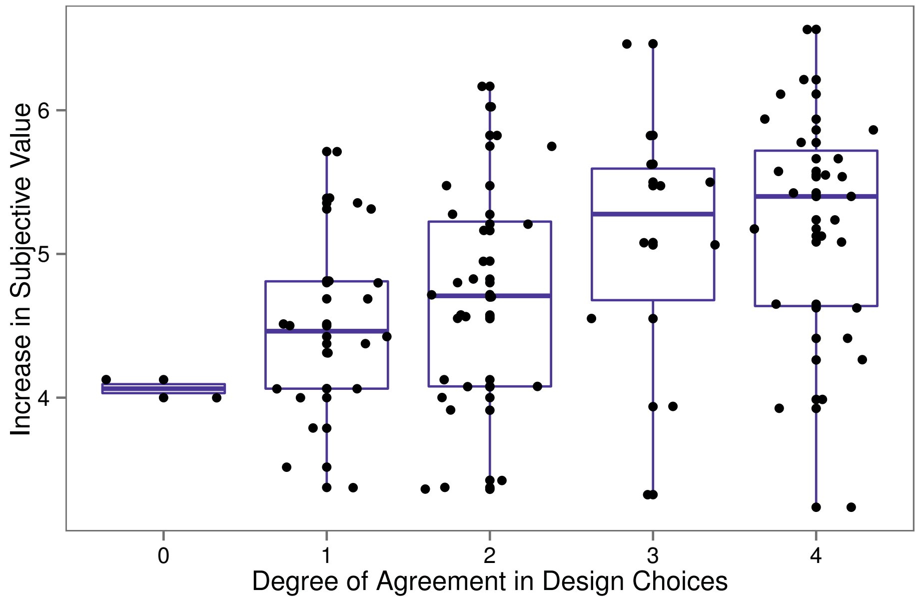


Figure 4.12: Distributions of the increase in aggregate Subjective Value (*SV*), while controlling for the degree of agreement in design choices (*Ag*) at the end of the collaboration exercise. As *Ag* across participants increases, both the mean level of *Sv* and its variance also increase. Even though participants could have a high degree of agreement they may have experienced low *SV*

.

Table 4.16: Tests of correlation between *SV* and *Ag*. The increase in Subjective Value and the degree of Agreement in designs are positively and significantly correlated.

	estimate	statistic	p.value	parameter	conf.low	conf.high
Pearson's r	0.363	3.378	0.001	75	0.152	0.543
Spearman's ρ	0.365	$48,323$	0.001			

A visual inspection of the distribution of aggregate *SV* scores by controlling for the degree of agreement *Ag* suggests a positive relationship between *SV* and *Ag*. The box plots in Figure 4.12 help to do this. As the degree of agreement across participants increases, the mean level of increase in SV rises. However, the variation in SV scores also increases. It becomes clear that collaborators who did not agree on designs reported low increases in SV as a result of collaboration. There are also many participants with both high *Ag* and *SV scores*. The resulting correlation between SV and Ag is significantly positive (r = 0.36, ρ = 0.36, p = 0.001, see Table 4.16).

An important observation is that many participants who did agree on a high number of design dimensions experienced low Subjective Value change after the exercise. This supports the idea that negotiated agreements do not always result in high Subjective Value outcomes, for example, when collaborators feel that they are forced to agree because of some external enforcing mechanism. Since the collaboration mechanism had no enforcing mechanism, the low SV scores are likely due to the negotiating dynamics in collaborating pairs interacting with their attributes (Subjective Understanding, Mood, etc.)

In summary, the *SV* assessment finds that collaborators on the whole experienced a large increase in Subjective Value, their psycho-social outcomes from negotiating agreement over designs. The large increase was observed across both treatment groups in the exercise, as well as across the design roles. Women in particular ascribed higher increases in Subjective Value to its relationship aspects, compared to men. These increases were associated with other aspects of the collaboration. Participants who believed that their understanding of the design issues improved significantly through collaboration also exhibited high increases in Subjective Value. In a similar manner, if collaborators agreed on design choices, they tended to report higher Subjective Value increases on average.

4.4 Chapter Summary

This chapter extended the analysis of outcomes from the collaboration exercise, first described in Chapter 3. While Chapter 3 focused on value and design outcomes, the analysis in this chapter focuses on two subjective constructs: Subjective Understanding and Subjective Value. These notions are often left untreated in many design and negotiation studies because they are difficult to measure and transient. A relatively recent formalization of the Subjective Value (Curhan, Elfenbein, and Xu, 2006) outcomes of negotiations provides a more robust theoretical framework for assessing these effects in negotiated collaboration. Linking these subjective notions with analysis of design outcomes in Chapter 3 provides a more holistic view of the nature of negotiated collaboration and its possible outcomes. Studying the social psychology of project actors also rounds out the understanding of dynamics over and above the insights provided by the fields of relational contracting and project organizations.

The chapter first introduced the construct of Subjective Understanding as the designers' own perception of how well they understand the design problem at hand. This is important to evaluate in collaboration exercises because a collaborator's degree of understanding can help or hinder the objective of approaching agreement on design choices. The analysis demonstrated that a participant's Subjective Understanding is predicted by not only their understanding of the facts and structure of the problem, but also by their disposition at the time of the exercise. Further, participants who reported an improvement in understanding by the end of the collaboration exercise attributed much of this improvement to the ability communicate with each other. The additional information received through common knowledge had the potential to confuse participants. The degree of improvement in understanding also depended on the participant's own initial perception of how well they understood the problem at the start of the exercise. Even participants who thought they initially understood it well could find that their understanding improved further. If their initial perceived understanding was high, then communication still helped but to a lower degree than for the participant's with a low perceived understanding initially.

The chapter then introduced the second construct, Subjective Value. This represents the psycho-social type of outcomes experienced in negotiations. It is also based on perceptions and has the potential to influence the quality of future design sessions with the same partners, and even the conclusions a participant reaches about the results after a single design session. Collaborators on the whole experienced a large increase in Subjective Value, their psycho-social outcomes from negotiating agreement over designs. The large increase was observed across both treatment groups in the exercise, as well as across the design roles. Women in particular ascribed higher increases in Subjective Value to its relationship aspects, compared to men. These increases were associated with other aspects of the collaboration. Participants who believed that their understanding of the design issues improved significantly through collaboration also exhibited high increases in Subjective Value. In a similar manner, if collaborators agreed on design choices, they tended to report higher Subjective Value increases on average.

An exception is that many collaborators who demonstrated very high agreement often reported very low increases in Subjective Value. Even though the collaboration process results agreement over designs, the manner in which this agreement is obtained can detract from collaborators psycho-social experience. If agreement is forced through some external mechanism, the negotiating collaborators may be more likely find the experience negative, for example. In this exercise however, there were no forcing mechanisms. This supports the rationale for considering not only the techno-economic or Objective Value outcomes of negotiated collaboration, but also the Subjective Value outcomes.

The insights about understanding and the social psychological outcomes of collaboration tell us more about the "lived" subjective experience of individual project actors than just the design and value outcomes from observing the co-design of a project at a distance. Retaining a focus on the subjective aspects of negotiated collaboration can create a better foundation for future interactions between collaborators, and help them better balance trade-offs to meet each others design objectives. This has important implications for P3 projects because such projects are long-lived, making it unlikely that the same partners will be able to complete multiple partnerships. As a result, trust and credibility through rapport early on in the relationship are important for shaping the project.

References

Bazerman, Max H and Roy J Lewicki (1983). *Negotiating in organizations*. Sage Beverley Hills, CA.

Bendersky, Corinne and Kathleen L. McGinn (2010). “Perspective—Open to Negotiation: Phenomenological Assumptions and Knowledge Dissemination”. In: *Organization Science* 21.3, pp. 781–797.

Blount, Sally and Richard P. Larrick (2000). “Framing the Game: Examining Frame Choice in Bargaining”. In: *Organizational Behavior and Human Decision Processes* 81.1, pp. 43–71.

Curhan, Jared R and Ashley D Brown (2011). "The Oxford handbook of positive organizational scholarship". In: ed. by Kim S Cameron and Gretchen M Spreitzer. Oxford University Press. Chap. Parallel and divergent predictors of objective and subjective value in negotiation.

Curhan, Jared R., Hillary Anger Elfenbein, and Noah Eisenkraft (2010). "The Objective Value of Subjective Value: A Multi-Round Negotiation Study". In: *Journal of Applied Social Psychology* 40.3, pp. 690–709.

Curhan, Jared R, Hillary Anger Elfenbein, and Gavin J Kilduff (2009). "Getting off on the right foot: subjective value versus economic value in predicting longitudinal job outcomes from job offer negotiations." In: *Journal of Applied Psychology* 94.2, p. 524.

Curhan, Jared R, Hillary Anger Elfenbein, and Heng Xu (2006). "What do people value when they negotiate? Mapping the domain of subjective value in negotiation." In: *Journal of personality and social psychology* 91.3, p. 493.

Drolet, Aimee L and Michael W Morris (2000). "Rapport in conflict resolution: Accounting for how face-to-face contact fosters mutual cooperation in mixed-motive conflicts". In: *Journal of Experimental Social Psychology* 36.1, pp. 26–50.

Elfenbein, Hillary Anger, Jared R Curhan, Noah Eisenkraft, Aiwa Shirako, and Lucio Baccaro (2008). "Are some negotiators better than others? Individual differences in bargaining outcomes". In: *Journal of Research in Personality* 42.6, pp. 1463–1475.

Ferguson, Merideth, Neta Moye, and Ray Friedman (2008). "The Lingering Effects of the Recruitment Experience on the Long-Term Employment Relationship". In: *Negotiation and Conflict Management Research* 1.3, pp. 246–262.

Gelfand, Michele J., Virginia Smith Major, Jana L. Raver, Lisa H. Nishii, and Karen O'Brien (2006). "Negotiating Relationally: The Dynamics of the Relational Self in Negotiations". In: *Academy of Management Review* 31.2, pp. 427–451.

Juni, Samuel (2007). "Encyclopedia of Measurement and Statistics". In: ed. by Neil J. Salkind. SAGE Publications, Inc. Chap. Reliability Theory, pp. 835–836.

Neale, Margaret A. and Max H. Bazerman (1985). "The effects of framing and negotiator overconfidence on bargaining behaviors and outcomes". In: *Academy of Management Journal* 28.1, pp. 34–49.

— (1992). "Negotiating rationally: the power and impact of the negotiator's frame". In: *The Executive* 6.3, pp. 42–51.

Osipova, E. (2014). "Establishing Cooperative Relationships and Joint Risk Management in Construction Projects: Agency Theory Perspective". In: *Journal of Management in Engineering*, p. 05014026.

Rahman, M. and M. Kumaraswamy (2004). "Potential for Implementing Relational Contracting and Joint Risk Management". In: *Journal of Management in Engineering* 20.4, pp. 178–189.

Raiffa, Howard (1982). *The art and science of negotiation*. Cambridge, Mass.: Belknap Press of Harvard University Press.

Raiffa, Howard, John Richardson, and David Metcalfe (2002). *Negotiation analysis : the science and art of collaborative decision making*. Cambridge, USA: Belknap Press of Harvard University Press.

Smyth, H. and S. Pryke (2009). *Collaborative Relationships in Construction: Developing Frameworks and Networks*. cited By 4, pp. 1–253.

Smyth, Hedley and Andrew Edkins (2007). "Relationship management in the management of PFI/PPP projects in the UK". In: *International Journal of Project Management* 25.3, pp. 232–240.

Suprapto, Mohammad, Hans L. M. Bakker, Herman G. Mooi, and Wim Moree (2014). "Sorting out the essence of owner–contractor collaboration in capital project delivery". In: *International Journal of Project Management*.

Thompson, Leigh (1990). "Negotiation behavior and outcomes: Empirical evidence and theoretical issues." In: *Psychological bulletin* 108.3, p. 515.

Tinsley, Catherine H, Kathleen M O'Connor, and Brandon A Sullivan (2002). "Tough guys finish last: The perils of a distributive reputation". In: *Organizational Behavior and Human Decision Processes* 88.2, pp. 621–642.

Walsh, James P, Klaus Weber, and Joshua D Margolis (2003). "Social issues and management: Our lost cause found". In: *Journal of Management* 29.6, pp. 859–881.

Chapter 5

Conclusions

This thesis has framed infrastructure Public-Private Partnerships (P3s) as an exercise in negotiated collaboration. I defined negotiated collaboration as a process in which project actors with competing objectives and asymmetric information co-create a solution to balance trade-offs through communication and knowledge exchange. The research described here investigated the benefits of this special type of collaboration in the design setting of infrastructure P3s.

Many countries have pursued the P3 approach with the goal of making the design of large infrastructure projects more innovative than under traditional public sector procurement. The record is mixed however; and studies of P3 projects have not been conclusive in pointing to innovative results. Does this mean that the P3 approach does not have the potential to deliver innovation in design? This research concludes otherwise, and identifies some specific mechanisms for capturing the available benefits.

Infrastructure P3s are a complex systems design problem with highly customized solutions. These projects are nested within larger infrastructure systems and a framework of institutions. They must match the evolving requirements of a physical and institutional environment. Such projects have both a technical and a contractual architecture to meet the project's high level objectives as well as accommodate risks and uncertainties. These two sub-domains of design interact to affect the value outcomes of projects.

In this setting, people and organizations deliver designs using design processes. These project actors make design decisions in each of the two sub-domains with an eye towards meeting their value objectives. Because project actors often have different value objectives they are likely to choose fundamentally different designs while designing independently. Do their design choices change when they collaborate? If so, what are the specific mechanisms that drive this change?

5.1 Main Findings and Policy Recommendations

In this thesis, I investigated the effects of negotiated collaboration in design, and conclude that collaboration systematically shifts design choices. The process of negotiated collaboration leads project actors to clarify their individual mental models of the design problem. Over the course of collaboration they develop a shared understanding of the project's value objectives. They also better understand how to link designs to expected value trade-offs. The degree to which they agree on project design choices also leaves them better off in the value they ascribe to aspects of their working relationship such as fairness of the process, and legitimacy of the approach.

How can current P3 institutions incorporate the lessons of this research? A first recommendation is that project actors should avoid premature lock-in to designs either from the contractual perspective while "doing the deal" or in the technical approach through over-specifying the project's features. They should make risks and uncertainty explicit, explore many design possibilities systematically from different value perspectives, and recognize that their choices will result in trade-offs that evolve over time. A second recommendation is that project actors should communicate early and often in the design process while there is still scope for exploration and learning about the implications of design alternatives. Any studies and knowledge they can share to support their viewpoints can help them reach a better mutual understanding of why the other actors prefer different alternatives. Transparency within the bounds of the project agreement is critical for developing the necessary trust for establishing these long-term relationships. Finally, project actors should prioritize the third P in P3s: 'partnership'. Confidence in the fairness and legitimacy of the established relationship will help the actors re-engage constructively in negotiated collaboration during the project's life as they come together to take stock and re-visit choices.

5.2 Chapter summaries and findings

5.2.1 Chapter 1: Why negotiated collaboration?

Chapter 1 first reviews the institutional arguments for infrastructure P3s as a mode of delivery. Of the two main potential benefits of P3s - additionality and innovation - the discussion quickly scopes down to the expertise-based innovation argument.

Design in infrastructure P3s holds the promise of innovation because the public sector engages the deep know-how, repertoires, and experience of private infrastructure firms. The intent is that their combined knowledge and responsibilities makes them both better off than if either project actor were to independently pursue a project. They exercise their creativity to jointly create configurations that match the project's long-term objectives. In the ideal, the collaborative relationship is generative. The jointly created design grows the size of the project pie over the traditional made-to-order or turnkey project approach.

Yet design in P3s is negotiated because the project actors may have competing objectives along different value dimensions. The public sector interest values reliability in service and quality of supply. It trades-off its payment obligations in the balance. On the other hand, private participants in projects still retain clear profit motivations. They often trade some profits away to assure reliability and quality of service. These actors have to agree on designs that will meet both their objectives.

Negotiated collaboration is thus a specific form of integrative bargaining that plays out in the context of design. Designers use their creativity and unique perspectives to first grow the size of the pie and then pursue agreement on how best to slice it.

While this approach shows great promise in the ideal and some P3 projects have been resoundingly successful, the overall record is mixed at best. The sparse literature on technical design in P3s does not conclusively point to innovation, especially for adaptive designs that can meet evolving needs. The empirical evidence suggests that designs are sequentially sub-optimized. Actors have tended to lock-in contractual terms prematurely, leaving only a narrow band within which to innovate on the technical side. This observation creates an opportunity to explore the possibilities of co-design - the integrated technical and contractual design of P3s.

Given the complex design environment, human cognitive limitations and decision-making biases are pervasive. Both individuals and organizations must seek knowledge, learn from it, and then agree on designs. Cognition and biases are therefore intertwined with the broader institutional and organizational processes for P3 design. These challenges create the opportunity to better understand how individuals understand the design objectives, develop shared mental models, and ultimately communicate to exchange salient information for design.

The chapter ends with a theoretical framework that links the ideas of value outcomes to the process of co-design and the specific mechanisms of collaboration. The framework posits that project actors can balance trade-offs in competing value objectives through co-design if they develop a shared understanding of each others objectives and the structure of the problem. A review of the relevant literature on design cognition and negotiation showed that actors enhance their understanding by jointly shaping their mental models of the design task. There are specific mechanisms in the process of negotiated collaboration such as communication (dialogue) and information sharing that help actors develop their understanding to ultimately make negotiated design choices.

5.2.2 Chapter 2: Co-design reveals value trade-offs

Chapter 2 makes a case for the importance of co-design in infrastructure P3s. The first part of the chapter used a general example to illustrate how facility size interacted with technology choice and contractual structure to influence value outcomes. There was no dominant solution, and a main observation was that co-design leads to contingent solutions.

A second important aspect of co-design was the shaping of project risk profiles, once again as a consequence of the facility's technical characteristics and also its contractual structure. Some contract structures such as take-or-pay arrangements can truncate downside risk as well as manage upside exposure.

A final aspect of the case for co-design was to show that while one project actor may be indifferent among designs because they lead to similar outcomes from that actor's point of view, these designs could have dramatically different outcomes for another project actors. Modularity in design through flexible, phased designs illustrated this effect in the general example, as a mechanism for value creation. The three ideas of contingency, risk-shaping and value co-creation and exchange are the pillars of the case for co-design.

The second part of the chapter then presented a tradespace modeling framework and details for co-design applied to a desalination P3 project. The state space component of the model creates a background environment for decision-making under uncertainty for the project actors. The design space encapsulates the technical and contractual features of the project's co-design and relates them to value outcomes. Finally, the value space juxtaposes and visualizes the value outcomes corresponding to different co-design configurations.

The main result of the co-design process is that there exists a zone of negotiated agreement in which a number of feasible designs can meet preferred value outcomes for project actors. Co-design clearly identifies these designs and shows their relative positions in the value space. Project actors can iteratively explore the zone of agreement to converge on a design that is acceptable to both. While the chapter demonstrates this with specific parameter values for a desalination P3, this approach can be valuable for the co-design of any infrastructure P3 facility, or engineering projects more broadly.

5.2.3 Chapter 3: Collaboration shifts design outcomes

Chapter 3 builds on the idea that project actors co-design to make trade-offs in different value dimensions. They work within the zone of negotiated agreement to identify designs that help them balance competing value outcomes. Whereas the tradespace model enumerated the feasible designs that are available to project actors, this chapter investigated the mechanisms by which project actors could search for and reach agreement over those designs in the process of negotiated collaboration.

The chapter first reviewed the theoretical framework for the research. The framework posits that project actors can balance competing value outcomes if they develop a shared understanding of each others objectives and the structure of the problem. A review of the relevant literature on design cognition and negotiation showed that actors enhance their understanding by jointly shaping their mental models of the design task. There are specific mechanisms in the process of negotiated collaboration such as communication (dialogue) and information sharing that help actors develop their understanding to ultimately make negotiated design choices.

The chapter then presented the design and results of an experimental collaboration exercise to test the relative effects of communication and information as separate mechanisms of collaboration. Participants played the roles of a Water Authority and a Firm that are engaged to co-design a desalination infrastructure P3. These role-players made design choices independently and collaboratively in a series of four problems. The experimental setup collected data on the participants' submitted design choices, their communication transcripts, and detailed survey responses.

An analysis of the submitted design choices found that communication dominates as an enabling mechanism for the project actors to be able to make trades in value. Communication was effective even in the absence of common knowledge between actors. In fact, common knowledge plays a supporting role in helping project actors develop their shared understanding. When project actors who have already been communicating also acquire common knowledge, the additional information either reinforces or amplifies the effect of communication on participants' choice to make trade-offs. The implication of this finding for the co-design of infrastructure P3s is that project actors should communicate early and often in the process of negotiated collaboration to understand the types of value trade-offs they will have to eventually make through design choices.

Further analysis of submitted designs and communication transcripts revealed that three types of behavioral archetypes emerged during the collaboration exercise. These archetypes are *aligning*, *anchoring*, and *sensitive.* The reliability of subjectively identifying these archetypes was established through tests of inter-rater agreement between multiple coders. Members of some archetypes tended to agree more than those of others, conditional on their treatment group. In particular, the *aligning* archetype was associated with a higher propensity to agree on more aspects of the design in later collaboration rounds. The *sensitive* archetype actually decreased its degree of agreement in some cases, counter to intuition. A possible explanation is that sensitive archetype initially traded away too much in the absence of common knowledge. The implication for the co-design of infrastructure P3s is that the structural conditions might lead to the emergence of one more of these behavioral patterns, which may make participants more or less likely to eventually agree on specific design variables.

This chapter has mostly focused on the Objective Value- type outcomes (profits, payments and reliability as objective payoffs) of the negotiated collaboration exercise by analyzing submitted design choices and the supporting communication transcripts. Subjective Value outcomes are treated in detail in the following chapter.

5.2.4 Chapter 4: Collaboration improves understanding and Subjective Value

Chapter 4 extended the analysis of outcomes from the collaboration exercise, first described in Chapter 3. While that chapter focused on value and design outcomes, the analysis in this chapter focuses on two subjective constructs: Subjective Understanding and Subjective Value. These notions are often left untreated in many design and negotiation studies because they are tough to measure and transient. A relatively recent formalization of the Subjective Value (Curhan, Elfenbein, and Xu, 2006) outcomes of negotiations provides a more robust theoretical framework for assessing these effects in negotiated collaboration. Linking these subjective notions with analysis of design outcomes in Chapter 3 provides a more holistic view of the nature of negotiated collaboration and its possible outcomes.

The chapter first introduced the construct of Subjective Understanding as the designers' own perception of how well they understand the design problem at hand. This is important to evaluate in collaboration exercises because a collaborator's degree of understanding can help or hinder the objective of approaching agreement on design choices. The analysis demonstrated that a participant's Subjective Understanding is predicted by not only their understanding of the facts and structure of the problem, but also by their disposition at the time of the exercise. Further, participants who reported an improvement in understanding by the end of the collaboration exercise attributed much of this improvement to the ability communicate with each other. The additional information received through common knowledge had the potential to confuse participants. The degree of improvement in understanding also depended on the participant's own initial perception of how well they understood the problem at the start of the exercise. Even participants who thought they initially understood it well could find that their understanding improved further. If their initial perceived understanding was high, then communication still helped but to a lower degree than for the participant's with a low perceived understanding initially.

The chapter then introduced the second construct, Subjective Value. This represents the psycho-social type of outcomes experienced in negotiations. It is also based on perceptions and has the potential to influence the quality of future design sessions with the same partners, and even the conclusions a participant reaches about the results after a single design session. Collaborators on the whole experienced a large increase in Subjective Value, their psycho-social outcomes from negotiating agreement over designs. The large increase was observed across both treatment groups in the exercise, as well as across the design roles. Women in particular ascribed higher increases in Subjective Value to its relationship aspects, compared to men. These increases were associated with other aspects of the collaboration. Participants who believed that their understanding of the design issues improved significantly through collaboration also exhibited high increases in Subjective Value. In a similar manner, if collaborators agreed on design choices, they tended to report higher Subjective Value increases on average.

An exception is that many collaborators who demonstrated very high agreement often reported very low increases in Subjective Value. Even though the collaboration process results agreement over designs, the manner in which this agreement is obtained can detract from collaborators psycho-social experience. If agreement is forced through some external mechanism, the negotiating collaborators may be more likely find the experience negative, for example. In this exercise however, there were no forcing mechanisms. This supports the rationale for considering not only the techno-economic or Objective Value outcomes of negotiated collaboration, but also the Subjective Value outcomes.

The insights about understanding and the social psychological outcomes of collaboration tell us more about the "lived" subjective experience of individual project actors than just the design and value outcomes from observing the co-design of a project at a distance. Retaining a focus on the subjective aspects of negotiated collaboration can create a better foundation for future interactions between collaborators, and help them better balance trade-offs to meet each others design objectives.

5.3 Contributions to the literature

This research contributes to three bodies of knowledge. First, it directly addresses the literature on infrastructure public-private partnerships by showing how partnering can create objective as well as psycho-social benefits for a stronger partnering relationship. In the debate on whether P3s have the potential to result in innovation, this contribution suggests that P3s do in fact present this potential. To realize it, partners must develop a mutual understanding of the project's objectives in early stages of design. The design process in P3s must become more flexible and allow for iterative technical and contractual design to take place further upstream in the project delivery process.

Second, the co-design approach speaks to the literature on systems design, via technical and contractual design. This contribution emphasizes how an integrated systems view can help designers balance trade-offs. Infrastructure projects generate value for their participants in multiple dimensions. Designers can avoid prematurely locking out benefits and use co-design to shape and secure value trade-offs. They can preserve system-level objectives such as reliability, a shared interest across actors.

Third, the experimental study on negotiated collaboration demonstrates a useful application of the Subjective Value framework in an integrated design setting. Design studies focus almost exclusively on Objective Value outcomes while very few negotiation studies assess social psychological performance effects as Subjective Value outcomes. This research suggests that both are important in collaborative design interactions, which are an example of integrative bargaining. An experimental test of the collaboration mechanisms of communication and information exchange shows the primacy of communication in helping negotiating collaborators approach agreements. The experimental setup is thus a methodological contribution to both design and negotiation literature.

5.4 Future Work

This research has spawned a number of ideas for directions in which this line of inquiry can be extended. Some of these ideas address the inherent limitations of this work, and others point to promising opportunities:

1. **Extend the collaboration sessions**: Negotiated collaborations in early stage design often occur in multiple rounds where project actors engage with each other over time. The partnership is thus punctuated by short but intense collaboration sessions, with longer intervening periods during which the actors can further prepare the project and reflect and synthesize on emerging information (Gil, Miozzo, and Massini, 2012). One inherent limitation of the structure of this study is that it restricts the observation of interactions between collaborators to a few hours. How do longer collaboration engagements affect design outcomes as well as the psycho-social perceptions of collaborators? Protracted collaboration

sessions using more detailed design tasks may also help determine the effects of communication and information sharing, especially because of the increased chance of conflict (Iorio and Taylor, 2014a).

2. **Monitor and re-evaluate over time**: Renegotiations in infrastructure P3s are a common occurrence in which project actors revisit the original terms of the bargain (Guasch, Laffont, and Straub, 2008). This work has treated collaboration as a one-shot design decision. In reality, we would expect that actors reconvene a number of times in later stages of the project (Raiffa, Richardson, and Metcalfe, 2002; Curhan, Elfenbein, and Kilduff, 2009). How well do agreement patterns and behavioral archetypes from a first-negotiated agreement predict outcomes in subsequent decision-making engagements? Looking at how the same actors engage to revisit earlier choices can inform both design as well as the negotiations literature.

3. **Study actors embedded in projects**: A common concern with studies using experiments is that the experiments cannot replicate the complexity and social pressures of real projects (Cicmil and Marshall, 2005) or the day to day experience of design (Cross, 2004). However, conducting similar studies to the one developed here with experienced project designers may elicit the same behaviors they are likely to use on projects because of the conditioning of their experiences (Lawson, 2006; Suprapto et al., 2014). How does the collaboration between professional project actors differ from collaborative design by other types of designers?

4. **Collaborate across cultures**: Different cultures design and perceive collaborative relationships differently (Comu, Unsal, and Taylor, 2010). Some are heavily consensus focused whereas others have hierarchical authority and influence structures (Iorio and Taylor, 2014b). How does the cultural context of collaboration affect infrastructure P3 design outcomes? Are some cultures systematically better at project innovations or balancing trade-offs?

5. **Collaborate through model-based bidding**: A recent trend in some project domains is to assess the credibility of design proposals by submitting not only design configurations but also the models that were used to select those designs (Haveman and Bonnema, 2015; Ahn, de Weck, and Steele, 2014). A variant of this approach is one in which the agent firm submits its designs to be evaluated by a well-understood model that the principal has made available in advance. Do these 'model exchanges' systematically affect design choices in comparison with traditional design proposals? This work has the potential to build on contracting, auctions, and systems design.

References

Ahn, Jaemyung, Olivier L de Weck, and Martin Steele (2014). "Credibility Assessment of Models and Simulations Based on NASA's Models and Simulation Standard Using the Delphi Method". In: *Systems Engineering* 17.2, pp. 237–248.

Cicmil, Svetlana and David Marshall (2005). "Insights into collaboration at the project level: complexity, social interaction and procurement mechanisms". In: *Building Research & Information* 33.6, pp. 523–535.

Comu, Semra, Hakan I Unsal, and John E Taylor (2010). "Dual impact of cultural and linguistic diversity on project network performance". In: *Journal of Management in Engineering* 27.3, pp. 179–187.

Cross, Nigel (2004). "Expertise in design: an overview". In: *Design studies* 25.5, pp. 427–441.

Curhan, Jared R, Hillary Anger Elfenbein, and Gavin J Kilduff (2009). "Getting off on the right foot: subjective value versus economic value in predicting longitudinal job outcomes from job offer negotiations." In: *Journal of Applied Psychology* 94.2, p. 524.

Curhan, Jared R, Hillary Anger Elfenbein, and Heng Xu (2006). "What do people value when they negotiate? Mapping the domain of subjective value in negotiation." In: *Journal of personality and social psychology* 91.3, p. 493.

Gil, Nuno, Marcela Miozzo, and Silvia Massini (2012). "The innovation potential of new infrastructure development: An empirical study of Heathrow airport's T5 project". In: *Research Policy* 41.2, pp. 452–466.

Guasch, J Luis, Jean-Jacques Laffont, and Stephane Straub (2008). "Renegotiation of concession contracts in Latin America: Evidence from the water and transport sectors". In: *International Journal of Industrial Organization* 26.2, pp. 421–442.

Haveman, Steven P and G Maarten Bonnema (2015). "Communication of simulation and modelling activities in early systems engineering". In: *Procedia computer science* 44, pp. 305–314.

Iorio, Josh and John E Taylor (2014a). "Boundary object efficacy: The mediating role of boundary objects on task conflict in global virtual project networks". In: *International Journal of Project Management* 32.1, pp. 7–17.

— (2014b). "The Impact of Cultural Assumptions about Language on Collaboration in Global Virtual Project Networks". In:

Lawson, Bryan (2006). *How designers think: the design process demystified*. 4th. Oxford, UK: Architectural Press.

Raiffa, Howard, John Richardson, and David Metcalfe (2002). *Negotiation analysis : the science and art of collaborative decision making*. Cambridge, USA: Belknap Press of Harvard University Press.

Suprapto, Mohammad, Hans L. M. Bakker, Herman G. Mooi, and Wim Moree (2014). "Sorting out the essence of owner–contractor collaboration in capital project delivery". In: *International Journal of Project Management*.

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Appendix A

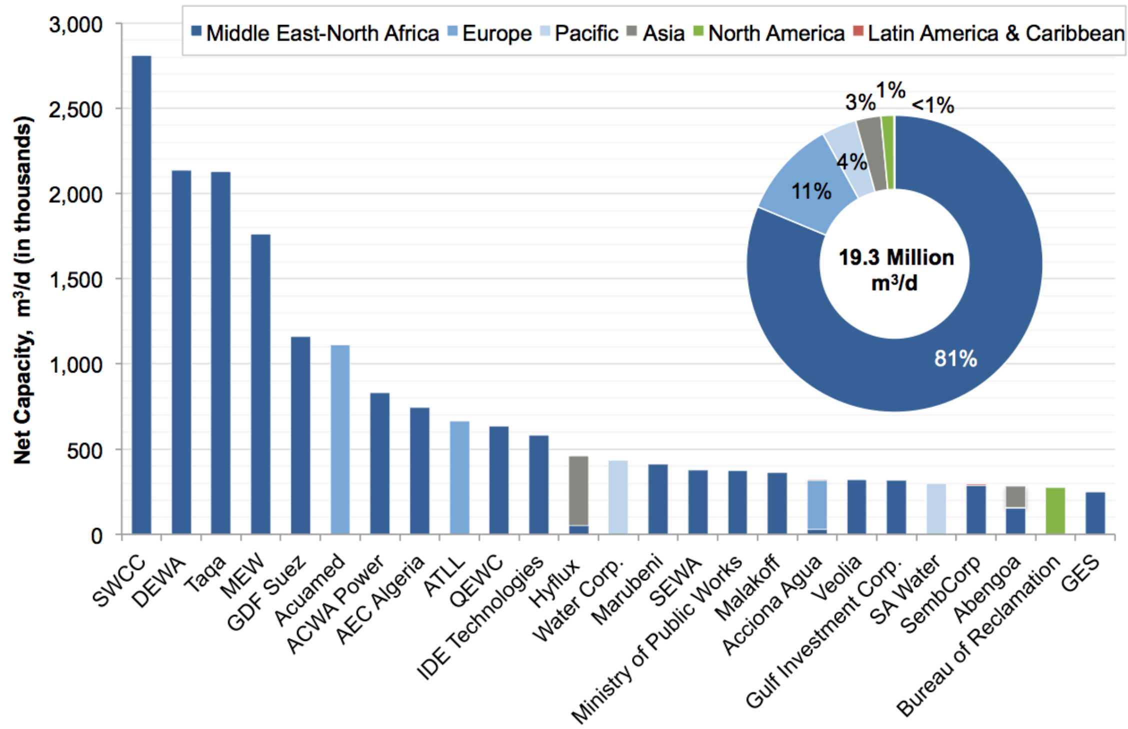
Descriptive Statistics on Saudi Arabia's Desalination Portfolio

The Kingdom of Saudi Arabia (KSA) has the largest share of the world's installed desalination capacity, and many consider it to continue as the largest desalination market. This appendix presents some statistics to place Saudi Arabia in global and regional context. It also covers some history and current issues unique to the Saudi portfolio, especially as it relates to new investment and private sector participation. Much of this discussion and associated analysis is excerpted from Sakhrani and Khiyami (2015) and some synthesis is obtained from the *Saudi Arabia Country Profile* (GWI, 2015).

Between 1980 - 2013, about 80% of global desalination capacity installations occurred in the Middle East and North Africa (MENA) region, followed by Europe (11%) (Figure A.1). In MENA countries, state-owned utility enterprises own and operate much of the installed capacity. Saudi Arabia's Saline Water Conversion Corporation (SWCC) is by far the largest owner and operator of desalination plants. Note that SWCC had a large number of installations even prior to 1980, which are not captured in this figure.

MENA countries are notable for their high reliance on desalination because of their insufficient renewable freshwater resources. The lopsided water balance is a common feature across these countries, as shown in Figure A.4.

The United Nations *World Urbanization Prospects* estimated that in 2015 approximately 25 million (over 80%) of Saudi Arabia's 30 million strong population lives in cities. By 2025, the urban population will rise to 30 million, continuing to stress the nation's water supply system (United Nations, 2014). Data from KSA's Ministry of Water and Electricity (MoWE) suggests that in 2010, total water demand was estimated at at nearly 18,000 million m^3/yr (MCM/yr). A majority share of this demand was met by non-renewable groundwater resources (Figure A.2). Desalination and treated wastewater made up less than 10% in aggregate, and their contribution is expected to grow to protect supplies of non-renewable groundwater. Notably, about 50% of municipal (domestic) demand is met by desalination (MoWE, 2012).



(a)

Companies

- Abengoa SA // Spain
- Acciona Agua // Spain
- Acuamed // Spain
- ACWA Power // Saudi Arabia
- AEC Algeria // Algeria
- ATLL (Aigües Ter Llobregat) // Spain
- Bureau of Reclamation // United States
- Chennai Metrowater // India
- DEWA (Dubai Electricity & Water Authority) // U.A.E.
- BEWA (Electricity & Water Authority) // Bahrain
- GDF Suez // France
- GDCOL (General Desalination Company of Libya) // Libya
- GES // Israel
- Gulf Investment Corp. // Saudi Arabia
- Hyflux // Singapore
- IDE Technologies // Israel
- Lagos Water Corp. // Nigeria
- Malakoff Corp. Berhad // Malaysia
- Marubeni Corp. // Japan
- Mekorot (Mekorot Israel National Water Co.) // Israel
- MEW (Ministry of Electricity & Water) // Kuwait
- Ministry of Public Works // Kuwait
- OPWP (Oman Power & Water Procurement)
- QEWC (Qatar Electricity & Water Co.) // Qatar
- QGC // Australia
- SA Water // Australia
- SDIC (State Development & Investment Corp.) // China
- Sembcorp // Singapore
- SEWA (Sharjah Electricity & Water Authority) // U.A.E.
- Shikun & Binui // Israel
- SWCC (Saline Water Conversion Company) // Saudi Arabia
- Taqa // Saudi Arabia
- Thames Water // United Kingdom
- Total SA // France
- Tuas Power // Singapore
- Veolia Water // France
- Water Corp. // Australia

(b)

Figure A.1: Global Ranking of desalination ownership (1980-2013)(Bluefield Research 2013)

Water resource	Volume (million m³/yr)	%
Non-renewable groundwater	10,421	58.2
Surface water and renewable groundwater	6,000	33.5
Desalinated water	1,082	6
Wastewater reuse	400	2.2
Total water supply	**17,903**	**100**

Figure A.2: Share of different supply sources to meet water demand in 2010. (MoWE 2012, GWI 2015)

Domestic and industrial water demand is set to triple between 2010 and 2060, according to the Ministry of Water and Electricity (MOWE) (Figure A.3). Agriculture is currently a big consumer of water, and policies are in place to reduce and then maintain the demand from this sector. A current open question is the large-scale technical and economic feasibility of using desalinated water for irrigation.

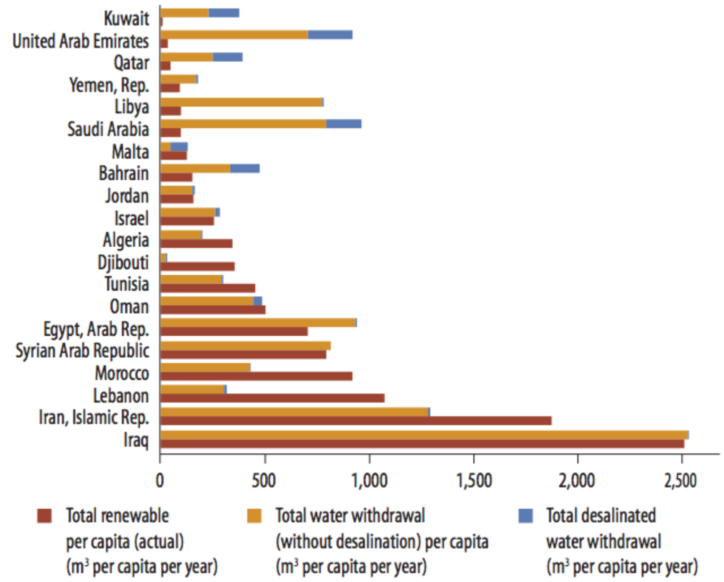
For the above mentioned reasons, Saudi Arabia remains as the top market for desalination in terms of investment value (Figure A.5).

Sector (million m³/yr)	2010	2015	2020	2030	2040	2050	2060
Domestic demand	2,063	2,609	2,881	3,512	4,281	5,219	6,361
Industrial demand	800	905	1,024	1,311	1,598	1,948	2,375
Agricultural demand	15,040	13,473	13,473	13,473	13,473	13,473	13,473
Total demand	**17,903**	**16,987**	**17,378**	**18,296**	**19,352**	**20,640**	**22,209**

Figure A.3: Sectoral demand estimates (2010-2015) and forecast (2020-2060) for water in KSA (MoWE 2012, GWI 2015)

History of Desalination in KSA

Desalination in the Kingdom of Saudi Arabia can be traced back over a century ago to the coastal city of Jeddah. Located in an arid region on the Red Sea coast Jeddah's climate is subtropical with a warm winter season and hot, humid summer months. The average rainfall is slightly below 10 cm annually.



Source: Modified from FAO AQUASTAT 2009.

Note: AQUASTAT is FAO's global information system on water and agriculture, developed by the Land and Water Division. No relevant FAO data were available for West Bank and Gaza Strip. The Saudi Arabia data were modified based on the GWI desalination database since the FAO data included only desalination figures from the Saline Water Conversion Corporation (SWCC), not the total desalination production capacity in the Kingdom. Total renewable water is based on data between 1960 and 2010; data for Djibouti are unreliable.

Figure A.4: MENA water balance supply and demand sources (World Bank 2012)

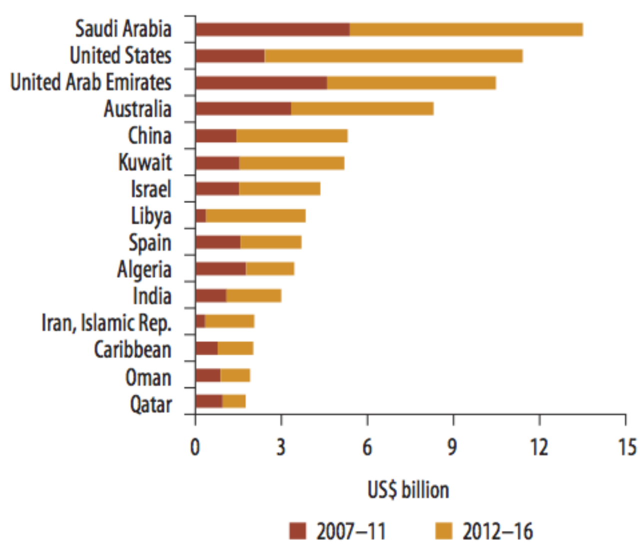


Figure A.5: Top country markets for desalination in terms of investment value (World Bank 2012)

As the point of entry to the hundreds of thousands (if not millions) of pilgrims who annually visit Makkah and an important commercial center in its own right, the city has continuously been plagued by water supply issues. Subsequently many pioneering and inventive water supply schemes were developed with Jeddah becoming the first sizable city to have its drinking water needs met via a seawater conversion plant.

This plant known as the *Kindasa*, an Arabic transliteration of "condenser", was installed in 1907. A coal actuated mechanism, its origins are unclear. Either it was salvaged from a wrecked ship (SWCC, 2012) or formally purchased from the United Kingdom (Al-Gholaikah et al., 1978). The Kindasa is believed to have provided a significant amount of Jeddah's water supplies.

The Kindasa plant remained operational until 1924, after which it was replaced by two distillation units with a capacity of 300 m^3/d. These two units were imported on the order of King Abdulaziz to provide adequate drinking water for the pilgrims to Makkah and the local people of Jeddah. Increased water demand from a growing number of pilgrims required the two distillation units to operate well above their designed capacity, causing significant operational problems. Nevertheless, they remained operation until 1950 whereby they were dismantled partly due to their inefficient operation, but also due to the development of a new water pipeline that brought water to the city from nearby wells and springs in Wadi Fatma and later on from Wadi Khulays.

The Kingdom conducted its first water resource survey in 1942. Subsequent studies highlighted that Saudi ArabiaâĂŹs fresh water sources were no longer adequate to meet its demands because of increasing industrialization and the consequent growth in population. In Jeddah alone the population quadrupled from approximately 40,000 residents in the mid-1940s to about 160,000 in the mid-1960s. Cities like Jeddah could no longer be supplied from their nearby wells and springs.

The Kingdom decided to embark on an ambitious desalination program after completing detailed studies of local and technological factors. This program was first established in 1965 via the creation of a Department for Desalination within the Ministry of Agriculture and Water. The department was subsequently elevated to the level of a Deputy Ministry in 1972. Two years later a Royal Decree established the present Saline Water Conversion Corporation (SWCC) as an independent public enterprise. The following period saw a rapid increase in the Kingdom's desalination capabilities with SWCC and Saudi Arabia representing about a fifth of world's installed desalination capacity by the start of the 21st century. Figure A.6 lists some of the large facilities that SWCC procured over the decades. These plants are some of the largest in the world.

Following 30 years of SWCC public sector leadership of the Saudi desalination industry, the Supreme Economic Council issued resolution # 5/23 defining rules and criteria for the participation of private entities in desalination projects. Subsequently, citing the Kingdoms ever increasing water requirements and its supply-demand gap, the Supreme Economic Council issued an approval for a four-stage program that would privatize and restructure SWCC starting in 2004.

This 'Executive Program for Privatization & Restructuring of SWCC' is currently underway. The first two stages involving the development of the new high level organization structure, the formulation of the privatization strategy, and the required legal approvals were completed in

Plant	Client	Plant supplier	Capacity (m^3/d)	Contract type	Technology	Contract year	Online year
Ras Al-Khair[1]	SWCC	Doosan Heavy Industries & Construction	1,035,000	EPC	MSF/RO	2010	2015
Al Jubail Phase 2 MSF (all units)	SWCC	Mitsubishi Heavy Industries/Sasakura; Hitachi Zosen; IHI Corporation	945,600	EPC	MSF	1981	1984
Shoaiba 3	SWCC	Doosan Heavy Industries & Construction	880,000	IWPP	MSF	2005	2009
Al Jubail[2]	Marafiq	Veolia SIDEM	800,000	IWPP	MED-TVC	2007	2010
Shoaiba 2	SWCC	Doosan Heavy Industries & Construction	454,000	EPC	MSF	1993	2002
Al Khobar 3	SWCC	Hitachi Zosen	280,000	EPC	MSF	1993	1997
Al Khobar 2	SWCC	Veolia SIDEM	267,000	EPC	MSF	1979	1984
Jeddah RO 3	SWCC	Doosan Heavy Industries & Construction	240,000	EPC	RO	2008	2013
Jeddah MSF 4	SWCC	Envirogenics	227,100	EPC	MSF	1977	1980
Shoaiba 1	SWCC	Mitsubishi Heavy Industries	223,000	EPC	MSF	1983	1988

[1] RO part (307,000 m^3/d) of the plant is online – MSF portion is yet to come online
[2] Plant supplies around 500,000 m^3/d for municipal purposes

Figure A.6: Very large desalination plants procured by SWCC in KSA public sector (GWI DesalData 2015)

2008. The program is now in its third phase: the Privatization and Restructuring Implementation stage, which focuses on the roll out of all restructuring and commercialization activities (SWCC, 2012).

The Kingdom aspires to continue to be a global trendsetter for the desalination sector. King Abdullah announced his initiative for solar water desalination in 2010, just a decade shy of a century following his father's order to import two distillation units for Jeddah. This initiative aims to develop the nation's own solar energy and desalination technologies and to build advanced industries that will develop the Kingdom's economy and provide it clean water and energy while protecting the environment (KACST, 2010). SWCC's Governor Dr. Abdulrahman Mohammed Al Ibrahim has stated that Saudi Arabia no longer intends for desalination to merely provide the nation with a commodity via the importation of black-box technologies. Instead, the relevant stakeholders now aspire for a sustainable industry that will integrate with the entire nation's development plans [1].

Current Institutional Landscape and Procurement in KSA

The Saline Water Conversion Corporation (SWCC) is a Saudi government corporation (state-owned enterprise) responsible for providing potable desalinated water to the Kingdom's coastal and inland cities. SWCC's stated mission is to efficiently and reliably fulfill consumers' need for

[1] Based on personal interview, conducted by A. Khiyami on June 30, 2014

desalinated water and electricity, at the lowest possible cost and highest economic return. More recently, SWCC has established new priorities of investing in its human capital and developing the local desalination industry to contribute to Saudi Arabia's overall economic growth and social development[2].

Under the current institutional landscape, SWCC falls under the jurisdiction of the Ministry of Water and Electricity (MoWE). The ministry takes overall responsibility for policies, regulations, and development relating to water and wastewater services. Through SWCC and other organizations, it not only procures but also owns and operates water infrastructure in the 13 regional directorates outside the four major cities of Riyadh, Jeddah, Medina/Mecca and Dammam/Al-Khobar.

SWCC comprises eleven distinct directorates and administrations all of which report to the SWCC Governor and Board of Directors. The General Administration for Project Implementation is responsible for the development of new projects. This group handles all preliminary actions such as the procurement of the work site and pre-commissioning meetings, as well as the preparation and signing of contracts, the coordination and supervision of construction. It also conducts follow-up visits to work sites.

SWCC outlines its future targets in five-year strategic plans formulated at a meeting of the Board of Directors. The current plan was implemented in 2012 and will end as scheduled in 2017.

For the last half-century, SWCC specialized only in the procurement and operation of desalination plants, limiting its scope to only the production of potable water. It mostly imported the technology and expertise. SWCC is now aiming for a more integrated approach of internally developing the entire value chain by broadening its scope to include the distribution, reuse, and industrial sectors.

SWCC has begun to take a long-term partnership approach for new facilities. It shies away from the "hit and run" EPC firms that will participate in a one-off fashion. It instead looks for firms that are willing to establish roots in the Kingdom and build a long-term partnership that will reap benefits in the future. For example, SWCC awarded the 2015 engineering and design contract for the very important Jeddah 4 RO plant to Black & Veatch, continuing a working relationship that was first established in 1993 (DWR, 2015).

Upon its creation SWCC inherited four plants from its predecessor at the Ministry of Agriculture and Water: the Al Wajh and Diya'a plants commissioned in 1969, the first Jeddah Plant launched in 1970, and the Al-Khubar Plant commissioned in 1973. The same year as SWCC's founding saw the opening of the Al Khafji Plant and the subsequent year saw the initiation of the Ummluj plant (SWCC, 2012). Following its establishment SWCC began to swiftly expand desalination capacity and commissioned many new plants during the subsequent decades in order to keep up with the Kingdoms rapidly increasing water demand. The world's first large seawater reverse osmosis desalination plant was commissioned by SWCC in 1978 and built in Jeddah

[2]Based on personal interview, conducted by A. Khiyami on June 30, 2014

(Al-Gholaikah et al., 1978). By the end of the 20th century SWCC produced 10.6% of its water in large RO plants, 88.5% of its production in large MSF plants, and 0.9% the remainder via small sized satellite MED, RO, and MSF plants (Hamed et al., 2002). SWCCs production represented a fifth of the world's total desalinated water supply at this time.

Following this period of rapid development SWCC began a still ongoing privatization and restructuring process in 2004. Nevertheless a decade later the company still provided 60% of the Kingdom's desalinated water with about a billion cubic meters produced in 2014 (Carey, 2014). SWCC's present day portfolio comprises of 17 working plants distributed alongside the west and east coasts as well as other independent and private production plants (SWCC, 2012). The corporation also has several plants under construction and some privately owned plants under its purview.

There are a number of large facilities in the Kingdom that are not directly owned or controlled by SWCC, but they nonetheless meet a large share of the industrial water demand for the Kingdom. Some of these are shown in Figure A.7.

Plant	Client	Plant supplier	Capacity (m^3/d)	Industry	Technology	Contract year	Online year
Rabigh IWPP	Petro Rabigh	Mitsubishi Heavy Industries	193,536	Refining/Chemicals	RO	2005	2008
Sadara, Jubail	Marafiq	Veolia	178,560	General	RO	2013	2015*
Yanbu (Marafiq) MED	Marafiq	Doosan Heavy Industries	54,552	General	MED	2011	2012
Al-Marai RO plants	Al Marai Trading Co.	Wetico	52,500	Food & Beverage	RO	2004	2004
Yanbu	Royal Commission for Jubail and Yanbu	Cadagua	50,400	General	RO	2002	2006
Al Jubail	Royal Commission for Jubail and Yanbu	AES Arabia Ltd.	37,850	General	RO	2001	2002
Al Bukariyah	Ministry of Agriculture & Water (now defunct)	US Filter (now Evoqua Water Technologies)/ VA Tech Wabag	36,000	Food & Beverage	RO	1985	1989

* Expected online later in 2015

Figure A.7: Large desalination facilities for industrial water supply (MoWE 2012, GWI 2015)

SWCC acts as an offtaker for produced water unless an integrated water and power project (IWPP) has been procured, in which case the offtaker is the Water and Electricity Company (WEC). The WEC is owned equally by the SWCC and the Saudi Electric Company. Its role has been to contract and act as offtaker for the countryâĂŹs independent water and power projects

(IWPPs). It issues the requests for proposals (RFPs) for new power and water plants, adjudicates between the different bids, and acts as counter party for the resulting water and power-purchase agreement (GWI, 2015).

SWCC supplies water to the MoWE and the National Water Corporation (NWC) at no charge (GWI, 2015). The NWC is responsible for groundwater extraction (including brackish water) and treatment and supplying water to customers in major cities, but it also has some desalination interests.

The Electricity and Co-generation Regulatory Authority (ECRA) regulates desalination assets owned by SWCC as well as IWPPs, many of which operate as co-generation facilities with co-located power plants. ECRA sets key performance indicators for desalination and encourages private sector involvement.

As a sign of evolving priorities, MoWE issued a strategy of "sustainable use of water with a focus on conservation, efficiency, equity and security" in 2013. The five specific objectives of this strategy are:

- To conserve and develop water resources for sustainability and efficiency
- To improve governance and management to the highest degree
- To provide water services to a level of developed countries whilst minimizing the fiscal burden
- To develop and introduce technological and institutional innovations
- To conserve and improve the environment

One element of the innovation strategy is to privatize some aspects of SWCC as well as use the National Water Company as a private owner and operator. Furthermore, at the Ministry level, MoWE has implemented a Strategic Transformation Plan to introduce increased private sector participation. Figure A.8 summarizes the timeline and status of this plan.

SWCC Portfolio Replacement Analysis

Many SWCC investments of the 1980s and 1990s have either exceeded the rated economic life (nominally 25 years) or about to reach this threshold. Some of these continue to operate at stable levels, although they are outdated technologies which could be replaced by more energy efficient and reliable technologies. Planners in KSA are therefore attentive to the need for replacing aging plants to maintain production capacity. This creates an investment burden for replacement in addition to proposed new investments (shown in Figure A.9) for meeting increasing demand for desalinated water. As of 2013, the Kingdom has almost 4 million m^3/d of capacity in the pipeline, shown in Figure A.9. Replacement of currently operating assets will be incremental to this pipeline. The plants that are beyond their stipulated life are shown in red in Figure A.10 for SWCC's directly held assets as well as the satellite facilities in which it has ownership or operating interests.

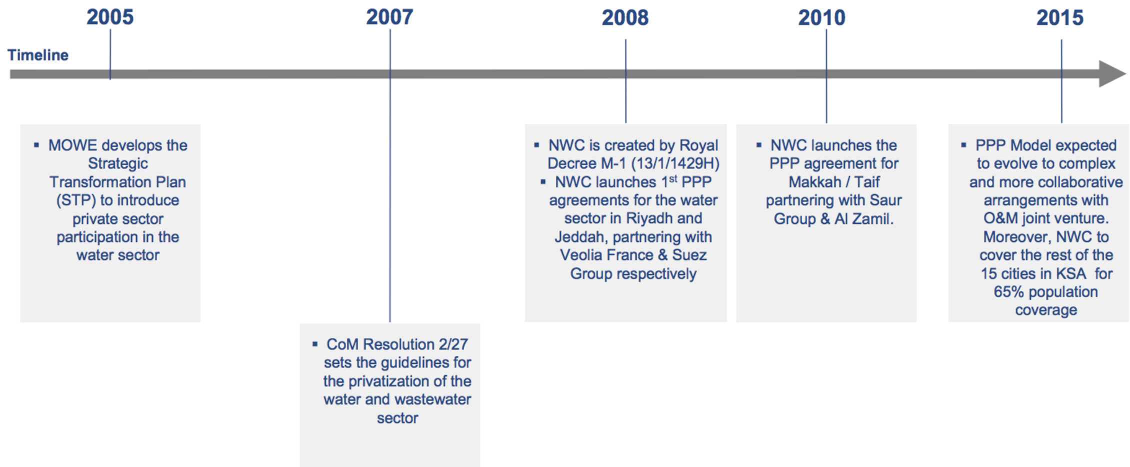


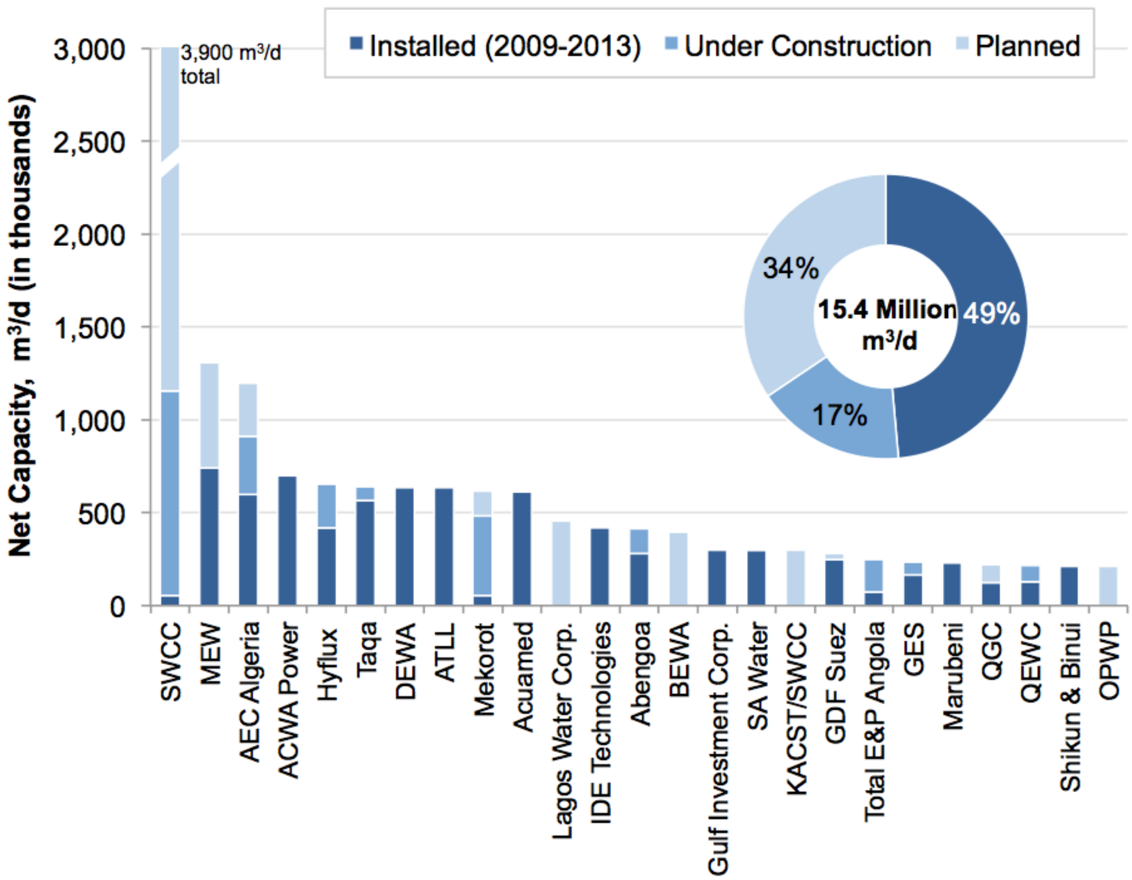
Figure A.8: Timeline of institutional privatization activities in the KSA water sector (2010 - 2015)

Policymakers in the Kingdom have a number of policy options while considering the replacement of facilities. The first is a 'do nothing' policy where projects are allowed to operate until their technical end of life, and then decommissioned or mothballed. This is an unlikely scenario, since demand for water in the Kingdom will only continue to increase. A second, more likely policy option is a business as usual case where more capacity is added to the pipeline but at new sites, with currently available technologies. A third option is a "like-for-like" replacement, where a plant at an existing site is simply replaced by the current standard of the same technology.

One possible estimate for the replacement cost of existing desalination facilities in the Kingdom using the "like-for-like" perspective is presented here. The focus is on the municipal plants owned and operated by SWCC either directly or under contract. It also includes the so called 'satellite plants' that are commissioned by SWCC as independent water producers, owned by private entities and delivering water to SWCC for municipal supply.

We first create a benchmark or reference scenario of "as is" replacements. This scenario assumes an identical build at the same realized cost in the year of award, escalated to current 2015 prices. The year 2015 is the benchmark or reference year for present value calculations. We use the US CPI index for escalation factors and assume that plant provision costs are proportional to price movements in the rest of the economy. However, this presents an outdated view of investments. So the replacement costs are updated using the cost model developed in Chapter 2 as part of the tradespace model. Thus the cost estimates are based on a statistical prediction that is empirically robust. The NPV values are the sum of the replacement cost for plants in the year of replacement, discounted to 2015. The replacement horizon is 25 years, the nominal timeline SWCC currently uses for reporting.

Figure A.11 shows a time series of replacments under the "like-for-like" scenario for the assumed 25 year replacement horizon. Again we only focus on SWCC's current portfolio of plants and some satellite facilities. So this analysis does not include new proposed investments. The



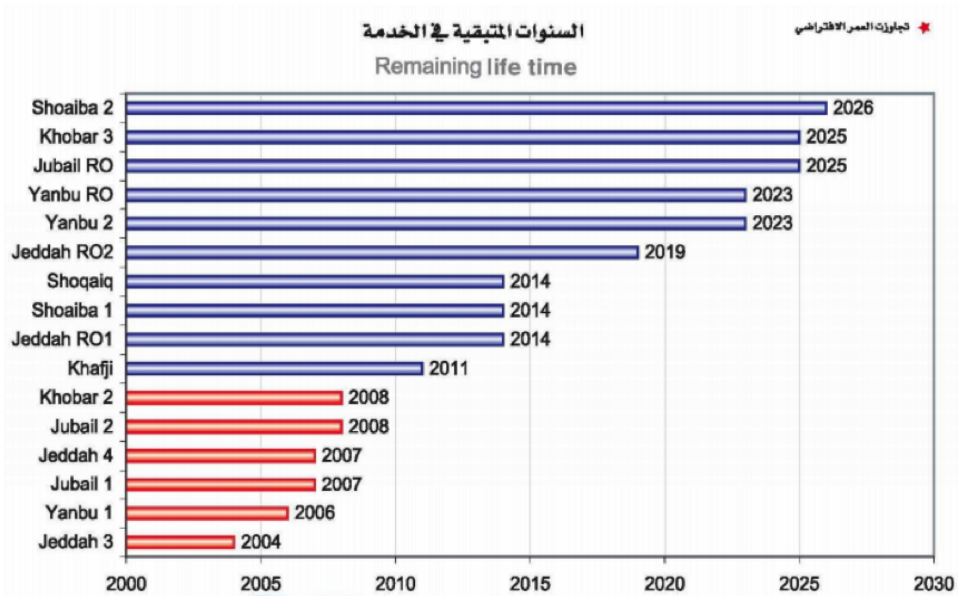
(a)

Companies

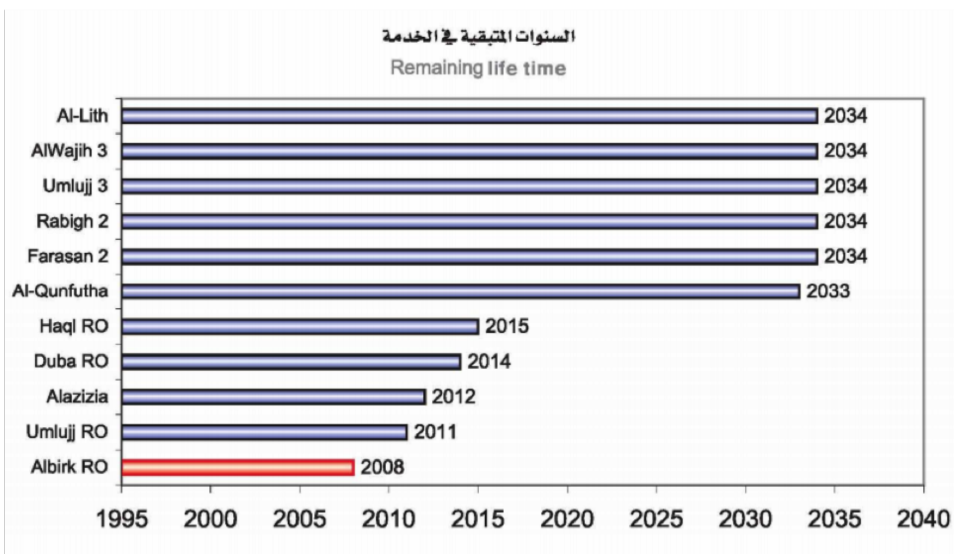
- Abengoa SA // Spain
- Acciona Agua // Spain
- Acuamed // Spain
- ACWA Power // Saudi Arabia
- AEC Algeria // Algeria
- ATLL (Aigües Ter Llobregat) // Spain
- Bureau of Reclamation // United States
- Chennai Metrowater // India
- DEWA (Dubai Electricity & Water Authority) // U.A.E.
- BEWA (Electricity & Water Authority) // Bahrain
- GDF Suez // France
- GDCOL (General Desalination Company of Libya) // Libya
- GES // Israel
- Gulf Investment Corp. // Saudi Arabia
- Hyflux // Singapore
- IDE Technologies // Israel
- Lagos Water Corp. // Nigeria
- Malakoff Corp. Berhad // Malaysia
- Marubeni Corp. // Japan
- Mekorot (Mekorot Israel National Water Co.) // Israel
- MEW (Ministry of Electricity & Water) // Kuwait
- Ministry of Public Works // Kuwait
- OPWP (Oman Power & Water Procurement)
- QEWC (Qatar Electricity & Water Co.) // Qatar
- QGC // Australia
- SA Water // Australia
- SDIC (State Development & Investment Corp.) // China
- Sembcorp // Singapore
- SEWA (Sharjah Electricity & Water Authority) // U.A.E.
- Shikun & Binui // Israel
- SWCC (Saline Water Conversion Company) // Saudi Arabia
- Taqa // Saudi Arabia
- Thames Water // United Kingdom
- Total SA // France
- Tuas Power // Singapore
- Veolia Water // France
- Water Corp. // Australia

(b)

Figure A.9: Pipeline (under construction or planned) investments in desalination facilities (2009-2013)(Bluefield Research 2013)



(a)



(b)

Figure A.10: Scheduled operating life for (a) SWCC main and (b) SWCC satellite assets (SWCC 2012). Plants beyond the end of stipulated operating life are in red.

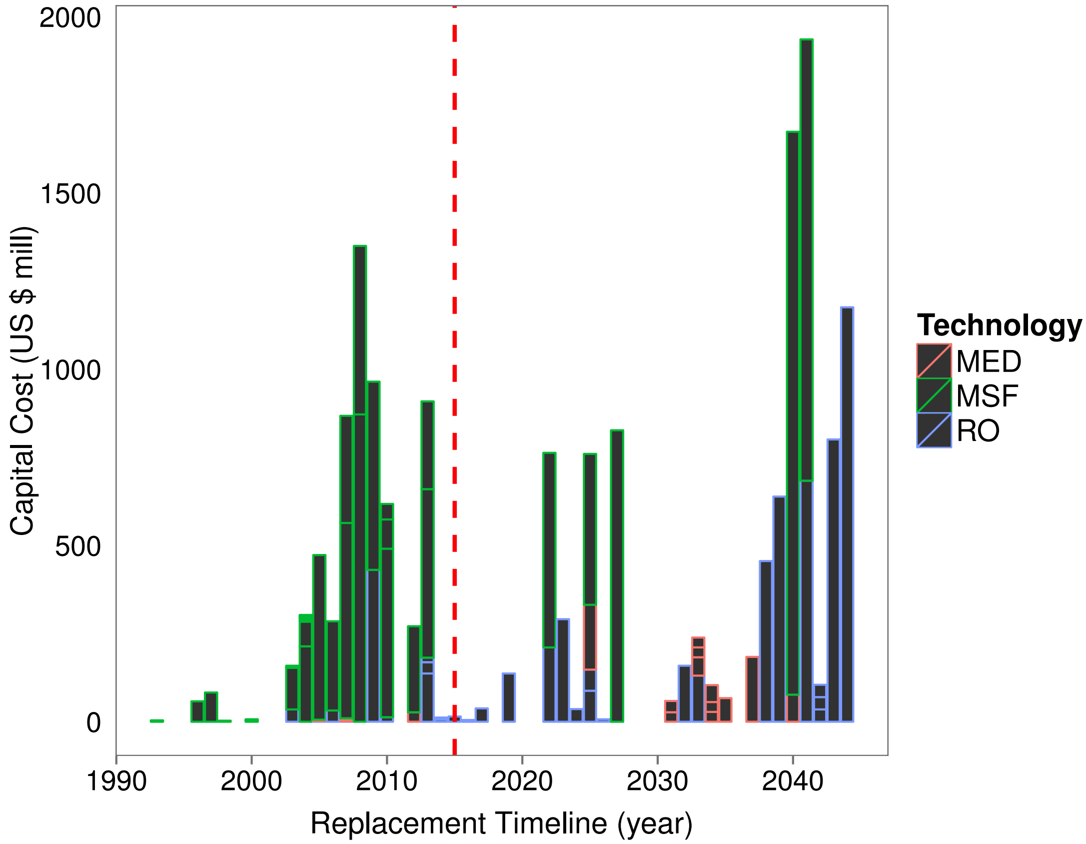


Figure A.11: Plant replacement cost time series for SWCC desalination facilities with total yearly capital cost

thin dashed red line shows the current year, 2015. The time series representation suggests that costs tend to cluster in years 2004 - 2010 when many old facilities should have been replaced, again between 2023 - 2028. Beyond 2035, most currently operating plants will reach end of life and need to be replace. There are intervening periods of little to no expenditure between 2015 âĂŞ 2024 and 2028 - 2032. Through more proactive planning, the replacement cost burden can be evened out by replacing plants slightly earlier than the nominal replacement date or building in phased options for some units to be added later.

Capital technologies evolve over time. In addition to considering a "like-for-like" replacement scenario, we could also consider current levels of costs assuming that any replacement build will employ the current state of the art instead of decades old technology. This also opens up the possibility of replacing plants with units of the same capacity and scale, but a different technology. For example, replacing an old MSF plant of 100,000 m3/d with a new RO plant of 100,000 m3 at current costs with the latest membrane technology. This provides a potentially different range of cost estimates. However due to lack of statistical data for systems level costs for current facilities, we leave this to future work.

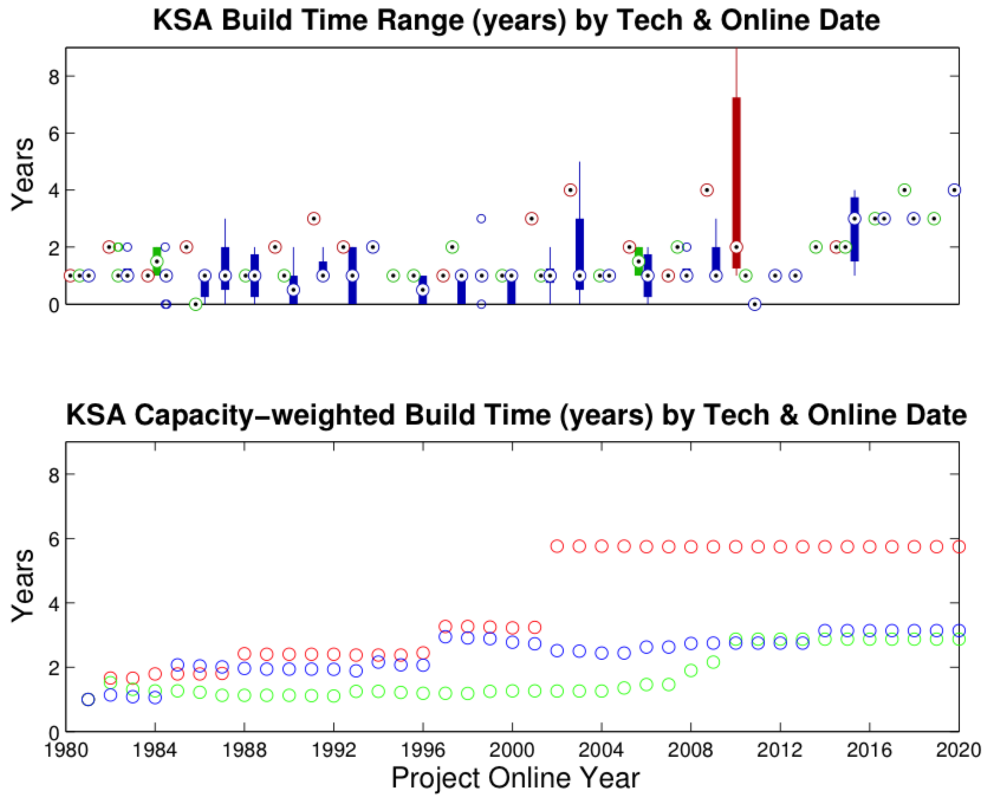


Figure A.12: Range of desalination plant build times, and capacity weighted average build time in KSA, by technology (MSF : red, MED : green, RO : blue)

Desalination costs are sensitive to delivery mode. In regressions, we find that the cost of a plant delivered using a turnkey EPC contract is different from one delivered using a long-term concession contract. Hence in future work, we could also create scenarios of costs differentiated by plant delivery mode.

In conclusion we estimate that SWCC's replacement cost burden for existing facilities is around US$ 17 billion, and occurring in peaks over the next 30 years. As a point estimate, the scenario is probably an underestimate, based on the types of assumptions we made. The obvious disclaimer here is that this is a first pass analysis based on high-level design information and published cost estimates. Truer replacement costs can only be obtained after detailed 30% or 60% engineering studies are conducted, and after negotiations with vendors. However, our estimates are sufficient for an order of magnitude understanding.

Figure A.12 shows the range of plant build time between 1980 and 2020 in the upper panel, and the capacity weighted average build time, by technology type, across the time period of the analysis. MSF plants (red bars and dots) in the Kingdom in recent years have taken the longest to deliver, at slightly below 6 years on average (normalizing for capacity). MED and RO plants are comparable and take a much shorter time to build on average at approximately 3.5 to 4 years,

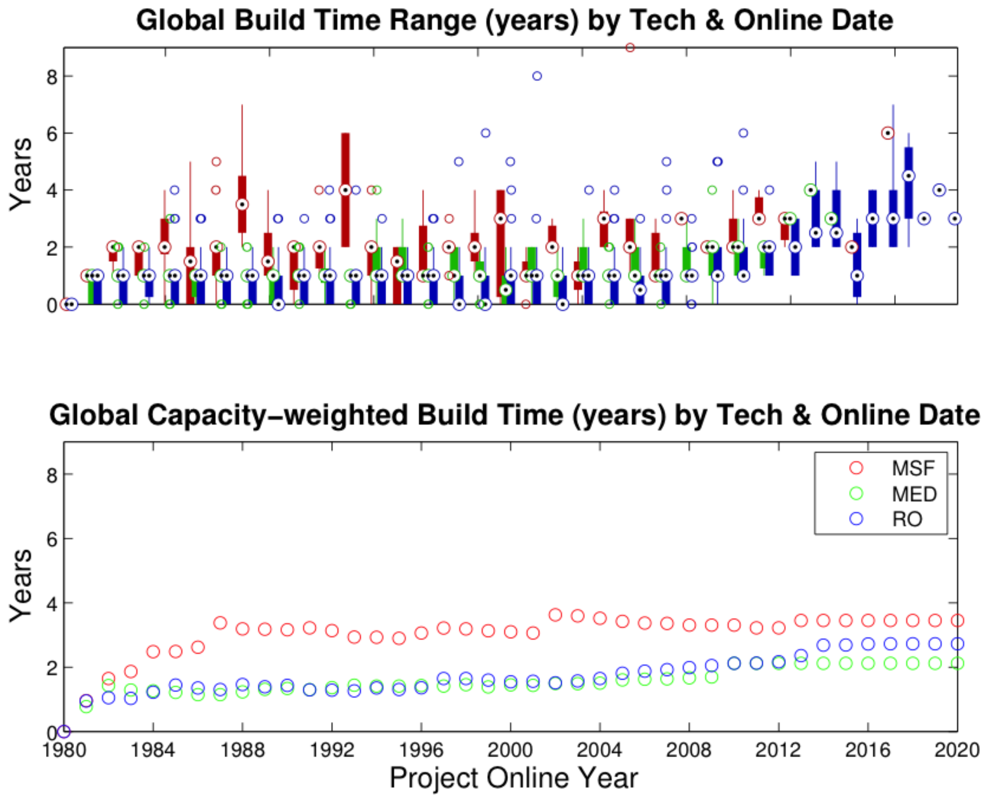


Figure A.13: Range of desalination plant build times, and capacity weighted average build time across the world, by technology (MSF : red, MED : green, RO : blue)

normalizing for capacity. Old MSF plants could therefore be replaced more quickly with RO or MED technologies because of the much lower construction lag. The justification in terms of lag time is less compelling in other parts of the world, where all technology types have been delivered between 2 to 3.5 years on average, normalizing for capacity (see Figure A.13).

References

Carey, Glen (2014). "SWCC Produced 60 pct of Saudi Arabia's Desalinated Water". In: *Bloomberg Business* June.

DWR (2015). "Black & Veatch wins consultant contract for giant Jeddah desalination project". In: *International Desalination and Water Reuse Quarterly*.

Al-Gholaikah, Abdullah, Nabil El-Ramly, Issam Jamjoom, and Ralph Seaton (1978). "The world's first large seawater reverse osmosis desalination plant, at Jeddah, Kingdom of Saudi Arabia". In: *Desalination* 27.3, pp. 215–231.

GWI (2015). *International Desalination Database*. Tech. rep. Global Water Intelligence.

Hamed, Osman A, GM Mustafa, Khalid Bamardouf, Hamed Al-Washmi, and Khalid Al-Shoail (2002). “SWCC MSF desalination plants-Current status and future prospects”. In: *Proceedings of the Sixth Saudi Engineering Conference, King Fahd University for Petroleum and Minerals, Dharan, Saudi Arabia*. Vol. 14, p. 17.

KACST (2010). “King Abdullah Intiative for Solar Water Desalination”. In:

MoWE (2012). “Annual Report”. In:

Sakhrani, Vivek and Abdulaziz Khiyami (2015). “Replacement Cost Analysis of Saudi Arabia’s Large Desalination Facilities”. In: *KACST-MIT CCES Working Paper*.

SWCC (2012). “Annual Report”. In:

United Nations (2014). “World Urbanization Prospects”. In:

Appendix B

Descriptive Statistics on Infrastructure P3s

This appendix presents summary statistics of infrastructure P3 projects from different regions of the world, domains, and stages of development. The objective is to get an overall understanding of the scope and extent of activities under the banner of infrastructure P3s over the last couple of decades.

Since systematically collected data on P3s and even traditional infrastructure procurement (TIP) is very hard to come by, we have to look across multiple sources of data. The analysis in this appendix used two main sources of data: (1) the World Bank's Private Participation in Infrastructure (PPI) (2015) database (http://ppi.worldbank.org) which contains data on over 7,000 projects, and (2) an analysis of survey data from the OECD's Government at a Glance (2013) report and related references. While the World Bank dataset covers projects in markets / countries with less developed infrastructure institutions that receive aid from donor and multilateral groups, OECD statistics cover about 30 countries that do not tend to receive development funding because of the advanced state of their infrastructure.

A main observation is that infrastructure P3s are NOT ubiquitous in all countries and sectors. This is contrary to the popular perception that many governments frequently use P3s in all infrastructure sectors. The data suggests that P3s only comprise a small share of capital spending, with public investment providing for more than 90% of infrastructure investment globally (OECD 2013).[1]

Europe has well developed P3 markets, although these are concentrated in UK, Spain, Portugal, and France. Between 1985 and 2009, approximately 650 P3 projects were delivered in the Europe at a combined total investment of about USD 300 billion. The UK contributes more than two-thirds of this by number, and about half in terms of total project value over the time period. Spain was the second largest P3 market during this time with about 10% of the projects by number and by investment value. For the same time period, only 440 P3 projects were completed in the USA and Canada at a combined total value of USD 75 billion (OECD 2013).

[1] OECD (2013) GOV/PGC/SBO(2013)2 Capital budgeting and procurement practices

The "rest of the world" data (non-OECD) from the World Bank dataset shows that about 7,500 projects were delivered using some form of private sector participation between 1990 and 2014. The time series in Figure B.1 shows that private participation in infrastructure picked up in the mid-1990s. Since then participation has oscillated. Figure B.2 identifies that the late 1990s were a period of significant private spending in infrastructure. The annual investment value of projects reaching closure then dropped in following years before stabilizing somewhat in the last ten years, reflecting macroeconomic cycles from around the world. In total, this represents USD 2,300 billion (2014 dollars) of activity between 1990 - 2014.

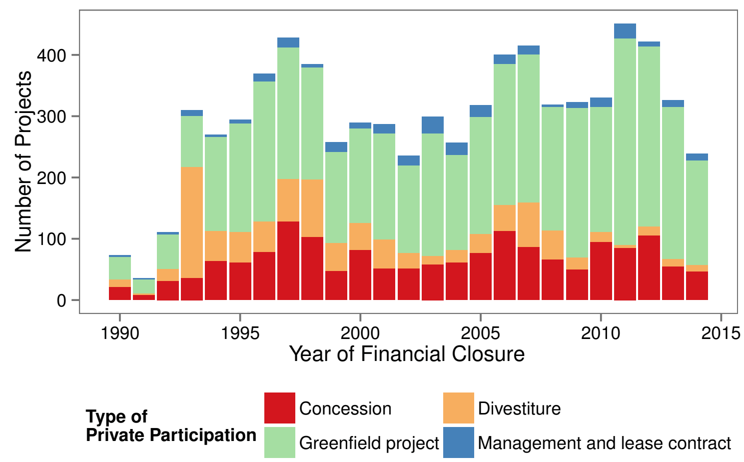


Figure B.1: Annual number of projects with private participation reaching financial closure (1990 - 2014)

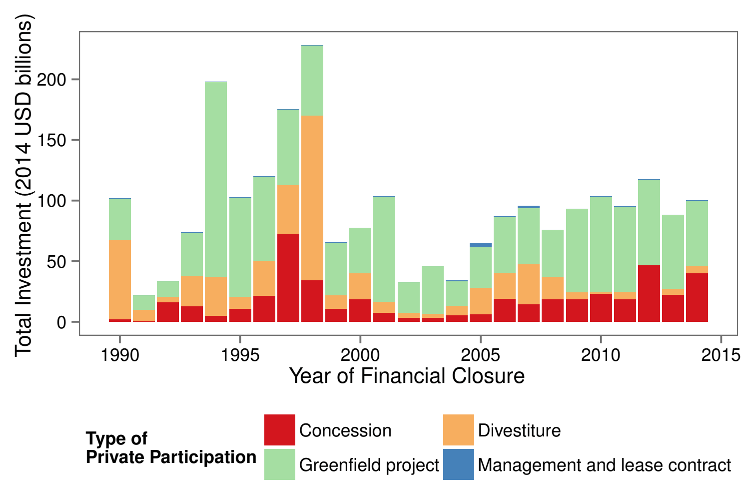


Figure B.2: Annual aggregate investment (2014 USD billions) of projects with private participation reaching financial closure (1990 - 2014)

In trying to be comprehensive, this dataset includes privatizations of existing assets ("divestitures") as well as "management and lease contracts" that bring in a private operator to run a facility after it has already been delivered. For the purposes of this thesis, the two most relevant categories of projects are "greenfield projects" and "concessions" because these involve the long-term contractual relationship which is a focus of this research. These two categories place significant agency on the private firms in terms of design, delivery, and operation of facilities over their life cycle. The rest of the analysis thus focuses on a subset of the data from the World bank data set: greenfield and concession projects only. The subset represents 5,000 projects between 1990 - 2014 at an aggregate investment of (2014) USD 1,200 billion.

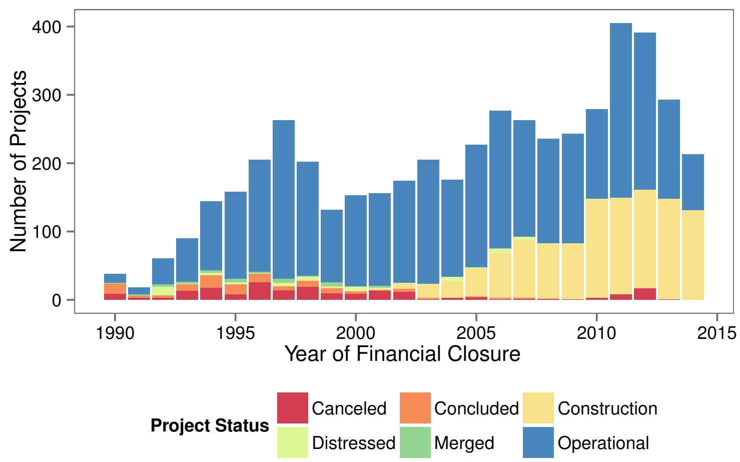


Figure B.3: Number of greenfield projects and concessions by project status (1990 - 2014)

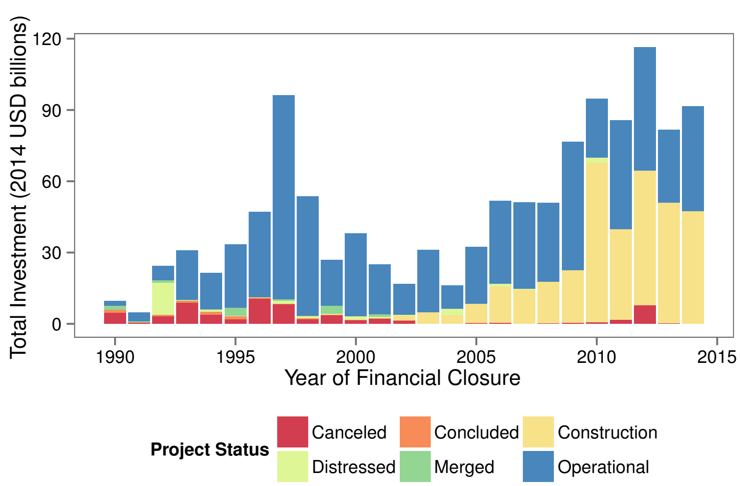


Figure B.4: Annual aggregate investment of greenfield projects and concessions by project status (1990 - 2014)

The next figure, Figure B.3, takes the subset of greenfield and concession projects and categorizes them by project status. A large majority of the projects reaching closure over the last 25 years are still operational (in blue), reflecting the long life time of P3 contract arrangements. The number of projects in the construction pipeline (yellow) decreases steadily going backwards from 2014 to about 2003. Very few projects have concluded (pink), and some projects have been merged (green) within programs or larger projects. A small fraction of cancellations stands out (red) in which many projects have been abandoned at different stages even after closure. The fraction of cancellations was larger prior to 2003, then became steadily small between 2004 - 2014.

When adjusted for aggregate investment (2014 USD billions) instead of number, the overall trends for greenfield projects and concessions remains similar, as shown in Figure B.4. A notable exception is that in the last decade a large share of projects by value remains under construction, stretching back intime until 2003. These two figures taken together suggest that although a large number of P3 projects delivered in the last 25 years are operational, much of the share of P3 projects in the last 10 years is still under different stages of construction. Long construction times for P3 suggests that project actors should also plan for longer front-end development before a project can actually be brought online to provide services and generate revenues. These dynamics affect overall project / asset value.

The extent of P3 activity has evolved at different rates in different regions of the world. Figure B.5 categorizes greenfield and concession projects by both project status and region in terms of the number of projects. Latin America and the Caribbean have shown robust activity over the last 25 years. Most of the projects are operational while a significant fraction closed in the last five years are still under construction. East Asia and the Pacific region is comparable in terms of numbers of projects, with the difference that there are many more projects in the last decade that are still under construction. Finally, there has been a recent uptick and then a fall in projects in South Asia. Sub-Saharan Africa and the Middle-East and North Africa are small PPP markets by numbers.

Latin America is by far the largest P3 market by investment value, with a majority share of projects in operating status, as shown in B.6. East Asia and Pacific regions have a stable although lower magnitude of investment, much of it under construction for project closed in recent years. South Asia has seen a big surge in investments over the last decade. Many of these projects are yet to begin operations. Once again, the Middle East and North Africa, and Sub-Saharan Africa regions are small in terms of investments.

It is also worth looking at global P3 activity by infrastructure sector. Figure B.7 shows the number of P3 projects (greenfield and concession) by region and sector. The four main sectors are energy, telecom, transport and water & sewerage. Energy dominates the set by number of projects. A major fraction of projects in Latin America and Caribbean, East Asia and Pacific, and South Asia regions are energy sector projects. Transport projects are the next most prevalent,

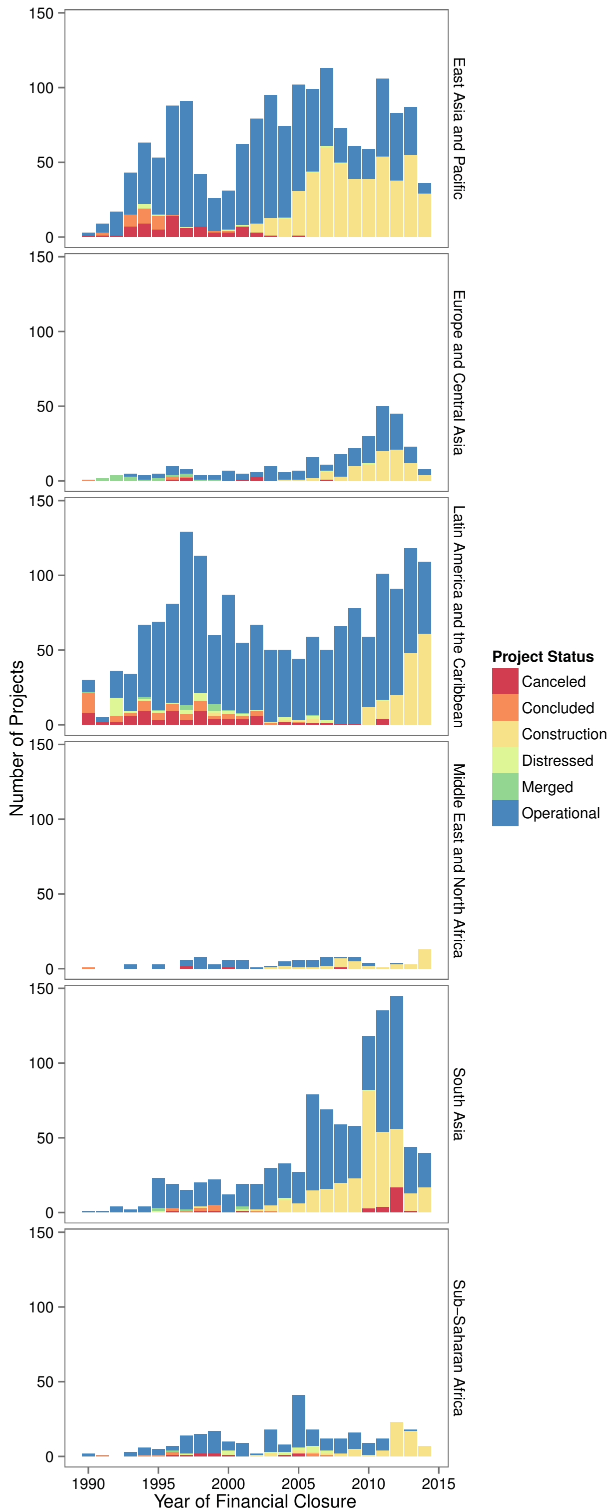


Figure B.5: Number of greenfield projects and concessions by region and project status (1990 - 2014)

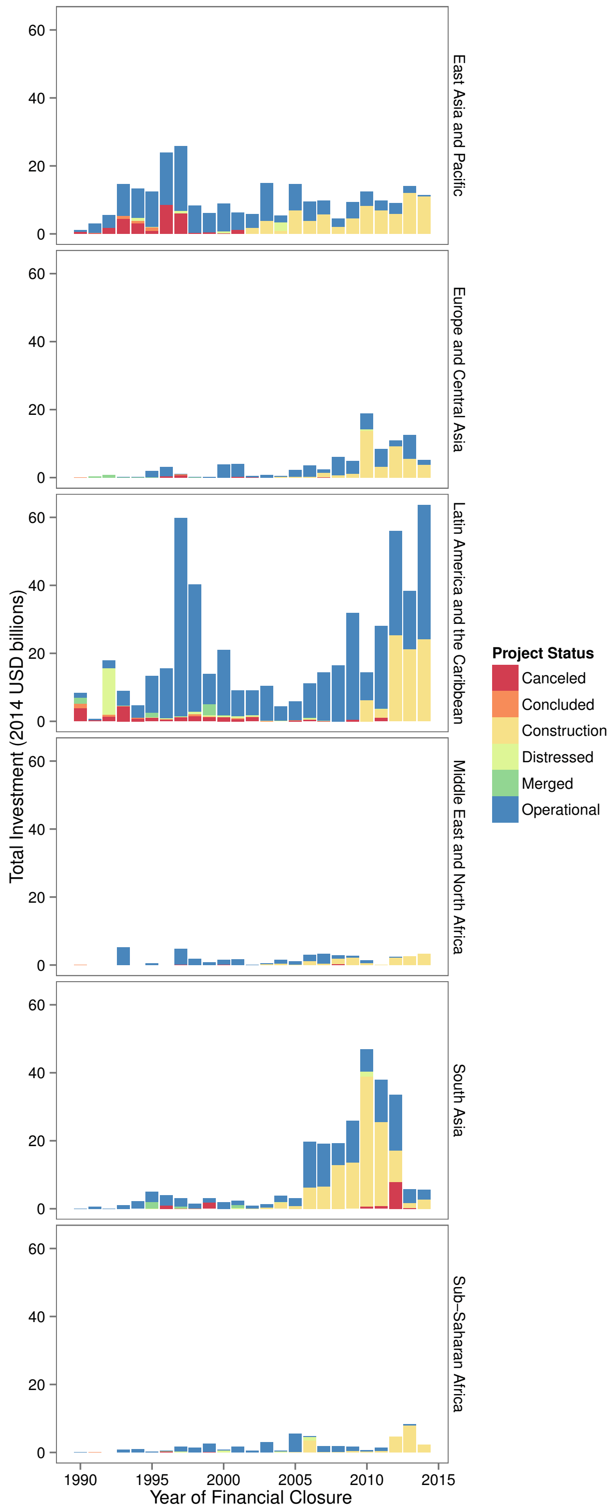


Figure B.6: Annual aggregate investment (2014 USD billions) greenfield projects and concessions by region and project status (1990 - 2014) with South Asia having a large share of projects in this sector. Telecom is the smallest sector, with very diffuse activity across regions. Most water projects are concentrated in the Latin America and Caribbean and in East Asia most recently.

Energy P3 projects are also foremost in terms of aggregate investment value, as is most noticeable in Latin America and Caribbean and South Asia regions Figure B.8. Energy is followed by transportation as the sector with the second highest investments. Both Latin America and South Asia have experienced significant recent activity in the transportation sector. The area representing water projects shrinks noticeably when using investment as a metric. This suggests that the average investment size of water P3s is quite small.

This analysis provides a sense of the distribution and investment commitments of P3 projects between 1990 - 2014 based on the World Bank's PPI dataset. We also have some understanding of the relative size of the European and North American P3 markets based on OECD statistics. These figures do not convey much about the performance of P3 projects. P3 project performance is difficult to assess because of the multi-dimensional nature of performance as well as lack of data along those dimensions.

One proxy we can use to assess the degree of success of P3s that have achieved financial closure is to look at the extent of canceled or distressed projects as a share of all projects with closure. Although a limited view of performance, this provides some understanding of sectors and regions that may be prone to performance failures.

Table B.1: Total Investment (2014 USD billions) for greenfield and concession projects achieving financial closure between 1990 - 2014, by region and sector.

(2014 USD billions)	Energy	Telecom	Transport	Water and Sewerage	Region Total
East Asia and Pacific	139.51	12.73	78.59	29.71	260.53
Europe and Central Asia	61.62	3.35	25.83	2.27	93.08
Latin America and the Caribbean	256.13	10.51	220.44	30.66	517.74
Middle East and North Africa	29.62	0.76	7.08	4.08	41.55
South Asia	145.18	4.09	97.70	0.60	247.57
Sub-Saharan Africa	25.62	2.94	19.07	0.33	47.96
Sector Total	657.68	34.38	448.70	67.66	1208.43

Table B.2: Total investment (2014 USD billions) only for projects that are canceled or distressed, by region and infrastructure sector

	Energy	Telecom	Transport	Water and sewerage	Region Total
East Asia and Pacific	5.95	6.45	8.91	11.51	32.83
Europe and Central Asia	1.46	0.41	0.15	0.01	2.02
Latin America and the Caribbean	18.60	0.42	11.36	8.97	39.36
Middle East and North Africa	0.00	0.00	0.56	0.00	0.56
South Asia	4.41	0.18	9.60	0.00	14.19
Sub-Saharan Africa	1.37	0.21	1.26	0.00	2.83
Sector Total	31.79	7.67	31.84	20.49	91.80

Table B.1 first shows the total investment for projects with closure by region and by infrastructure sector. This table collapses the data and lists the magnitude of the bar graphs in Figure B.8. It affirms the discussion earlier about the regional and sectoral variations. Table B.2 shows only

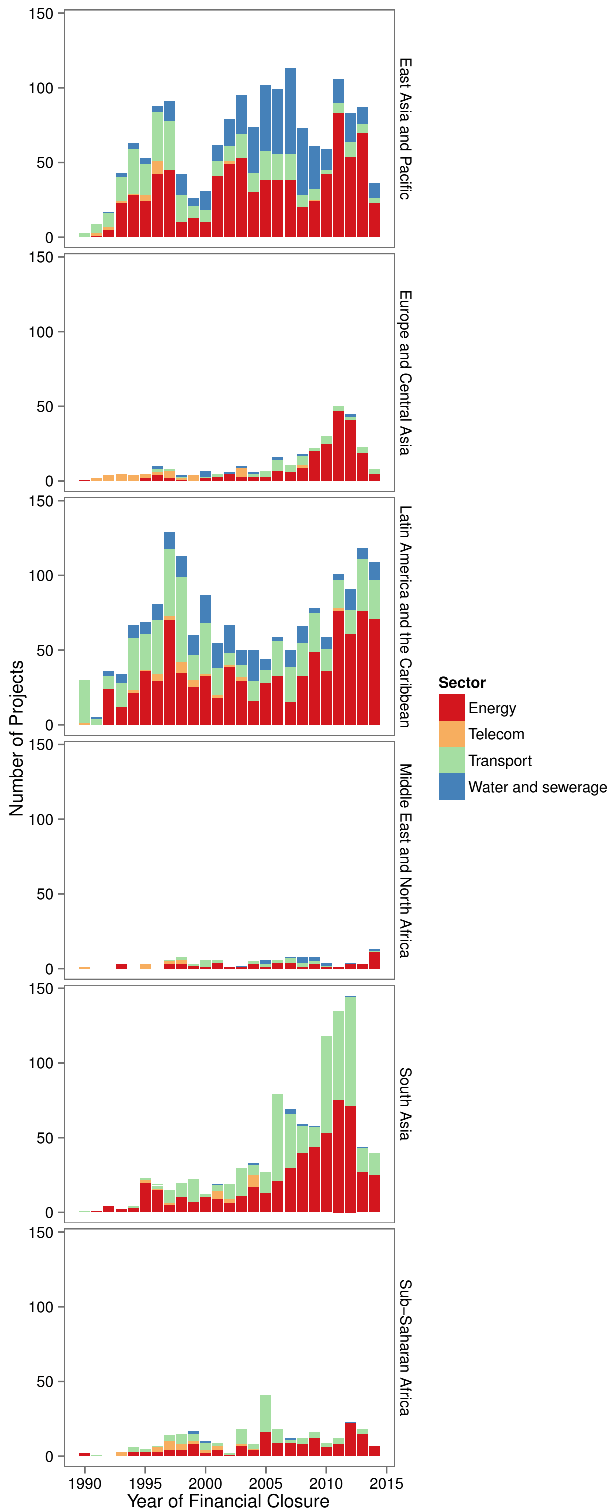


Figure B.7: Number of greenfield projects and concessions by region and infrastructure sector (1990 - 2014)

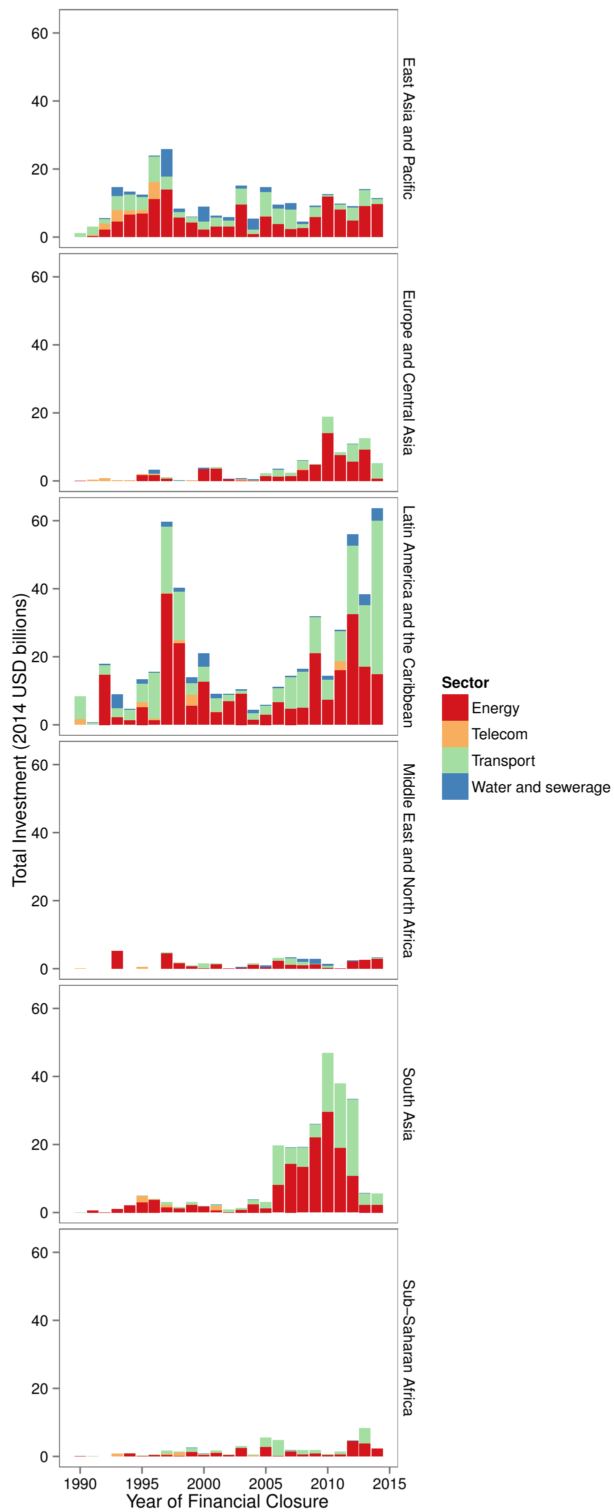


Figure B.8: Annual aggregate investment of greenfield projects and concessions by region and infrastructure sector (1990 - 2014) the investment share of projects that were canceled or distressed, also by region and infrastructure sector. Latin America and Caribbean and East Asia and Pacific are the two regions with the most distressed investments, with sizeable shares in energy, telecom, and transport. However, since the regions and sectors are disproportionate in their base magnitudes, we can look at the percentages of investments that are distressed.

The percentage shares of distressed investments are shown in Table B.3. East Asia and Pacific has the largest percentage share of distressed projects. Over 12% of its projects are distressed, with 40% of its water sector falling into this performance category. 50% of its telecom projects are also distressed. Only 7% of projects in Latin America and Caribbean are distressed, however 30% of its water projects are distressed. Overall, only 7.6% of P3 projects across these regions are distressed although most of this is driven by water (30%) and telecom (22%).

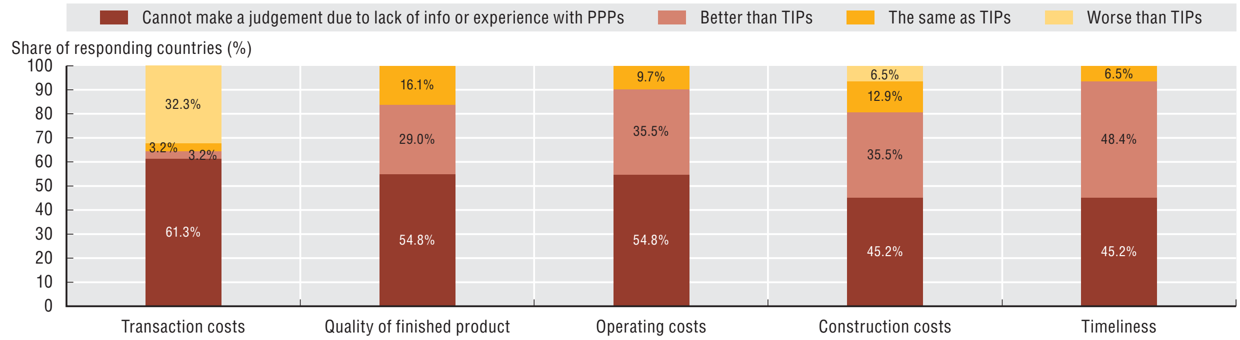
Table B.3: Percentage share of investments in P3 greenfield and concessions that are distressed.

	Energy	Telecom	Transport	Water and sewerage	Region Total
East Asia and Pacific	4.27	50.66	11.34	38.75	12.60
Europe and Central Asia	2.37	12.18	0.57	0.35	2.18
Latin America and the Caribbean	7.26	4.04	5.16	29.24	7.60
Middle East and North Africa	0.00	0.47	7.91	0.00	1.36
South Asia	3.03	4.45	9.83	0.00	5.73
Sub-Saharan Africa	5.34	7.03	6.61	0.00	5.91
Sector Total	4.83	22.32	7.10	30.28	7.60

We can thus conclude that although the fraction of "poorly" performing projects seems to be low overall, some sectors stand out with regard to their poor performance - water is notable among these since many distressed projects are found in more than one region of the world. Yet we cannot conclude much about whether P3 projects on the whole have performed better (or worse) than TIP projects based on this data alone.

Addressing this question is hard, once again because of the lack of data and disparate performance measurement approaches across countries. The OECD attempted to conduct an analysis of this issue in 2012. It surveyed government agencies associated with infrastructure procurement in over 30 countries. It's synthesis was published in the Survey on Budgeting Practices and Procedures 2012 (OECD 2013) (see Figure B.9).

The OECD concluded that a large share of respondents to the survey could not make a well-informed judgment about whether P3s were better or worse, due to lack of experience with the P3 process. Reposndents reported that P3s have higher transaction costs because of lengthier and more iterative procurement processes. On the other hand, many respondents believed that P3s perform better than or the same as TIPs in terms of the quality of the finished product, operating costs, construction costs and timeliness (on schedule). Since most of these conclusions were based on survey responses alone, the OECD reported that there is insufficient data to conclude whether P3s indeed perform better than TIPs at least in OECD countries.



Source: 2012 OECD Survey on Budgeting Practices and Procedures.

Figure B.9: Reported comparison of P3s and Traditional Infrastructure Procurements (TIPs) along different procurement performance dimensions based on a 2012 survey of OECD countries. There is insufficient data to conclude whether P3s are in fact better than TIPs along these dimensions.

	Use of relative value for money assessments	Use of absolute value for money assessments		Dedicated PPP unit reporting to Ministry of Finance	Dedicated PPP units in line ministries	No dedicated PPP unit exists in central/federal government
	For PPPs	For PPPs	For TIPs			
Australia	●	●	■			✓
Austria	x	x	❍			✓
Belgium	x	x	x			✓
Canada	●	●	❒	✓	✓	
Chile	●	●	■	✓	✓	
Czech Republic	..	..	❒	✓		
Denmark	❍	■	■		✓	
Estonia	x	x	❒			✓
Finland	❒	■	■			✓
France	❒	●	❒	✓		
Germany	●	●	●	✓	✓	
Greece	●	●	❒	..	..	..
Hungary	❒	❒	x		✓	
Iceland	..	..	..	..	..	..
Ireland	●	●	●	✓		
Israel	■	■	■	✓		
Italy	❍	❒	❒			✓
Japan	❍	●	■		✓	
Korea	■	●	■	✓	✓	
Luxembourg	❒	❒	❒			✓
Mexico	●	●	●			✓
Netherlands	■	●	■	✓	✓	
New Zealand	●	●	■	✓		
Norway	x	x	■			✓
Poland	x	●	●	✓	✓	
Portugal	●	●	●	✓		
Slovak Republic	x	x	❍			✓
Slovenia	■	●	■			✓
Spain	❒	❒	❒			✓
Sweden	❒	■	■			✓
Switzerland	❒	❍	❍			✓
Turkey	❍	●	●	✓		
United Kingdom	●	●	●	✓		
United States	❒	❒	■			✓
Russian Federation	❍	●	●	✓	✓	
OECD total						
● Yes, for all projects	10	17	7	14	9	15
■ Yes, for those above certain monetary threshold	4	4	13			
❒ Yes, ad hoc basis	8	5	8			
❍ No	4	1	3			
x Not applicable	6	5	2			

Source: 2012 OECD Survey on Budgeting Practices and Procedures.

Figure B.10: Responses to OECD survey on governance processes and dedicated P3 agencies within OECD countries.

The same OECD survey also reports on the fragmentation in governance approaches across countries (see Figure B.10). Not all countries pursuing P3 projects have dedicated agencies or clearly specified project evaluation processes (Value for Money assessment procedures). This makes cross-project and cross-country performance assessment problematic.

Appendix C

Raw Data for submitted Design Solutions

This appendix contains the design solutions submitted by each participating designer in the collaboration exercise. A total of 112 participants completed the exercise. For 111 of these cases, participants submitted complete solutions to all four rounds of the exercise. One participant submitted designs in three out of four rounds. There are therefore (112 x 4) - 1 = 447 observations in the design submissions dataset.

Note that the 447 submissions represent only a small number of iterations (attempted solutions). In all the 112 participants completed over 10,000 design iterations during the four rounds of the collaboration exercise. Since they were required to select and submit one solution per participant per round, the number of submissions represent less than 5% of the the number of iterations.

The following list explains the variables shown in the columns of the data table, Table C.1. The variable name is followed by (dimensional units), wherever applicable:

1. 'Participant ID': each participant was assigned a 'Participant ID' for data collection and records correspondence. To safeguard the identity and privacy of the participants, the data shown below is completely de-identified. This column just lists an index number that can be used for replicating the statistical analyses.

2. 'Problem Number': this column indicates the problem (or design round; one of 1, 2, 3, or 4) of the exercise for which the corresponding design was submitted.

3. 'Treatment Group': particpants were randomly assigned to one of two treatment groups in the exercise, see Chapter 3 for a detailed description. The Communication First (comm first) group pairs of collaborators were able to communicate about their designs first in the Problem 3: Individual Treatment round, followed by Information sharing in Problem 4:

Combined Treatment round. The stimuli for the other treatment group were reversed. The Information First (info first) group received Information sharing in Problem 3: Individual Treatment round, followed by Communication in Problem 4: Combined Treatment round.

4. 'Functional Role': participants were randomly assigned to one of two functional roles in the collaboration exercise, the Water Authority (WA) or the Engineering Firm (F).

5. 'Iteration'(number): this column indicates the trial number of the attempted solution to a problem, which the participant finally selected as their final submission. For example, participant 1 attempted many designs in problem 1, but he or she selected the solution in iteration 12 as the final submission for that problem. This variable thus indicates how early or late in their number of attempts did the participants discover what was to be their final solution.

6. 'Elapsed Time' (seconds): this variable denotes the time in seconds that elapsed before the participants discovered the solution which they finally submitted.

7. 'Output Capacity' (cubic meters / day, range 7,000 - 15,000): this is the first of four input variables. It represents the total potential size of the desalination facility.

8. 'Modules' (number, range 1 - 5): this is the second of four input variables. It denotes the number of phases into which the desalination facility can be phased.

9. 'Water Price' (USD / cubic meter, range: 2.25 - 2.75): this third input variable is the price per unit of water delivered that the Water Authority pays to the Firm.

10. 'Revenue Guarantee' (ENPV USD millions, 50 - 60): this fourth and final input variable is a lumpsum expected NPV minimum payment that the Water Authority agrees to pay to the Firm as part of the water purchase concession contract over its lifetime.

11. 'Profit' (ENPV USD millions): this is the first of three value dimensions (performance or output variables). It represents the NPV of the profit to the desalination facility over the life of the contract based on the chosen design solution.

12. 'Reliability' (%): the second value dimension calculates the lifecycle reliability of the chosen design solution. The lifecycle reliability is the ratio of the expected water shortage from a design to the maximum possible expected water shortage from any design (converted into economic units). For example, if the maximum possible expected water shortage is NPV USD 25 million, and the estimated expected shortage for a particular design is NPV USD 5 million, then the lifecycle reliability of that design is 1-(5/25) = 80%.

13. 'Total Payments' (ENPV USD millions): the third and final value dimension indicates the lifecycle payments made by the Water Authority to the Firm, incluse of payments associated with both the Water Price and the Revenue Guarantee considerations.

Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
1	1	comm first	WA	12	74	15000	1	2.25	50	-13.69	99.86	55.64
1	2	comm first	WA	11	41	15000	1	2.25	50	-13.69	99.86	55.64
1	3	comm first	WA	22	495	15000	5	2.50	60	7.02	99.35	61.93
1	4	comm first	WA	9	105	15000	5	2.50	60	7.02	99.35	61.93
2	1	comm first	WA	21	194	15000	1	2.25	50	-13.69	99.86	55.64
2	2	comm first	WA	3	58	15000	1	2.25	50	-13.69	99.86	55.64
2	3	comm first	WA	2	16	15000	1	2.25	50	-13.69	99.86	55.64
2	4	comm first	WA	19	197	15000	2	2.25	60	1.81	99.86	60.00
3	1	comm first	F	49	281	10000	3	2.75	60	14.32	94.80	67.41
3	2	comm first	F	18	131	10000	3	2.75	60	14.32	94.80	67.41
3	3	comm first	F	13	277	14000	4	2.25	60	5.09	99.51	60.00
3	4	comm first	F	18	298	15000	5	2.25	60	5.09	99.35	60.00
4	1	info first	F	6	90	15000	5	2.75	60	13.02	99.35	67.94
4	2	info first	F	11	105	15000	5	2.75	60	13.02	99.35	67.94
4	3	info first	F	10	116	15000	4	2.75	60	12.75	99.57	67.97
4	4	info first	F	31	580	15000	5	2.25	60	5.09	99.35	60.00
5	1	comm first	F	30	186	15000	5	2.75	50	13.02	99.35	67.94
5	2	comm first	F	12	96	15000	5	2.75	55	13.02	99.35	67.94
5	3	comm first	F	27	385	15000	5	2.50	60	7.02	99.35	61.93
5	4	comm first	F	14	226	15000	5	2.50	60	7.02	99.35	61.93
6	1	info first	WA	16	147	15000	1	2.25	50	-13.69	99.86	55.64
6	2	info first	WA	9	88	15000	1	2.25	50	-13.69	99.86	55.64
6	3	info first	WA	22	272	15000	4	2.25	50	0.39	99.57	55.61
6	4	info first	WA	29	574	15000	5	2.25	60	5.09	99.35	60.00
7	1	info first	WA	1	0	8000	1	2.25	50	3.68	79.77	53.78
7	2	info first	WA	13	48	15000	3	2.25	50	-3.04	99.72	55.62
7	3	info first	WA	25	196	15000	2	2.25	50	-2.56	99.86	55.64
7	4	info first	WA	9	217	15000	2	2.25	60	1.81	99.86	60.00
8	1	info first	F	3	64	10000	3	2.50	60	8.44	94.80	61.52
8	2	info first	F	8	108	15000	5	2.75	50	13.02	99.35	67.94
8	3	info first	F	6	533	15000	5	2.75	60	13.02	99.35	67.94
8	4	info first	F	17	571	13000	2	2.75	50	10.05	99.39	67.94
9	1	info first	WA	17	127	15000	1	2.25	50	-13.69	99.86	55.64
9	2	info first	WA	5	134	15000	1	2.25	50	-13.69	99.86	55.64
9	3	info first	WA	39	332	15000	2	2.25	50	-2.56	99.86	55.64
9	4	info first	WA	36	361	15000	5	2.25	60	5.09	99.35	60.00
10	1	info first	F	22	244	7000	4	2.75	60	8.27	31.33	60.58
10	2	info first	F	20	131	7000	4	2.75	60	8.27	31.33	60.58
10	3	info first	F	68	284	7000	5	2.25	60	8.51	0.00	60.00
10	4	info first	F	23	141	7000	5	2.25	60	8.51	0.00	60.00
11	1	info first	WA	19	270	12000	1	2.25	55	-5.61	98.73	55.95
11	2	info first	WA	4	52	12000	1	2.25	55	-5.61	98.73	55.95
11	3	info first	WA	9	183	11000	3	2.50	55	7.40	97.38	61.55
11	4	info first	WA	29	577	13000	3	2.50	50	5.14	99.37	61.77
12	1	info first	F	36	223	14000	3	2.75	50	10.17	99.65	67.97
12	2	info first	F	15	96	15000	2	2.75	60	9.81	99.86	68.00
12	3	info first	F	23	553	15000	2	2.75	50	9.81	99.86	68.00
12	4	info first	F	18	453	10000	3	2.50	50	8.19	94.80	61.28
13	1	info first	F	53	292	7000	1	2.75	60	17.12	60.80	63.68
13	2	info first	F	14	96	15000	5	2.75	60	13.02	99.35	67.94
13	3	info first	F	102	352	10000	3	2.50	50	8.19	94.80	61.28
13	4	info first	F	73	594	10000	3	2.50	50	8.19	94.80	61.28

Continued...

Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
14	1	comm first	F	10	202	13000	4	2.50	60	7.27	99.28	61.93
14	2	comm first	F	16	118	13000	4	2.75	60	13.27	99.28	67.93
14	3	comm first	F	50	507	13000	4	2.75	60	13.27	99.28	67.93
14	4	comm first	F	29	313	11000	3	2.50	50	7.40	97.38	61.55
15	1	info first	F	5	70	14000	5	2.75	60	11.61	98.66	67.84
15	2	info first	F	7	54	14000	5	2.75	55	11.61	98.66	67.84
15	3	info first	F	7	60	14000	4	2.75	55	13.05	99.51	67.96
15	4	info first	F	6	56	11000	2	2.75	60	10.00	97.38	67.71
16	1	comm first	WA	20	240	15000	1	2.25	50	-13.69	99.86	55.64
16	2	comm first	WA	5	103	15000	1	2.25	50	-13.69	99.86	55.64
16	3	comm first	WA	2	29	15000	1	2.25	50	-13.69	99.86	55.64
16	4	comm first	WA	2	23	15000	1	2.25	50	-13.69	99.86	55.64
17	1	info first	F	30	260	15000	5	2.75	60	13.02	99.35	67.94
17	2	info first	F	35	135	13000	5	2.75	60	9.71	96.80	67.57
17	3	info first	F	25	171	15000	5	2.75	55	13.02	99.35	67.94
17	4	info first	F	46	516	15000	5	2.25	60	5.09	99.35	60.00
18	1	info first	WA	6	125	15000	1	2.25	50	-13.69	99.86	55.64
18	2	info first	WA	13	108	15000	1	2.25	50	-13.69	99.86	55.64
18	3	info first	WA	25	488	10000	1	2.25	50	-0.97	94.80	55.16
18	4	info first	WA	19	494	15000	5	2.25	60	5.09	99.35	60.00
19	1	info first	F	9	180	15000	5	2.25	60	5.09	99.35	60.00
19	2	info first	F	25	139	13000	4	2.75	55	13.27	99.28	67.93
19	3	info first	F	109	537	11000	2	2.75	60	10.00	97.38	67.71
19	4	info first	F	3	38	14000	2	2.75	60	9.97	99.71	67.98
20	1	comm first	F	3	110	12000	4	2.75	60	13.09	98.56	67.84
20	2	comm first	F	16	105	7000	1	2.75	50	17.12	60.80	63.68
20	3	comm first	F	28	241	11000	3	2.75	50	13.56	97.38	67.71
21	1	comm first	WA	20	125	15000	5	2.75	55	13.02	99.35	67.94
21	2	comm first	WA	14	75	15000	5	2.25	50	0.67	99.35	55.58
21	3	comm first	WA	15	285	15000	1	2.25	50	-13.69	99.86	55.64
21	4	comm first	WA	36	582	15000	5	2.50	50	6.85	99.35	61.76
22	1	info first	F	35	293	12000	4	2.75	60	13.09	98.56	67.84
22	2	info first	F	8	55	15000	5	2.75	60	13.02	99.35	67.94
22	3	info first	F	61	516	12000	3	2.50	60	6.50	98.73	61.87
22	4	info first	F	22	535	15000	5	2.50	60	7.02	99.35	61.93
23	1	comm first	WA	1	0	8000	1	2.25	50	3.68	79.77	53.78
23	2	comm first	WA	1	0	8000	1	2.25	50	3.68	79.77	53.78
23	3	comm first	WA	13	167	15000	1	2.25	50	-13.69	99.86	55.64
23	4	comm first	WA	8	423	10000	3	2.50	50	8.19	94.80	61.28
24	1	info first	WA	6	29	15000	5	2.25	50	0.67	99.35	55.58
24	2	info first	WA	21	54	15000	5	2.25	50	0.67	99.35	55.58
24	3	info first	WA	42	220	12000	1	2.50	50	0.14	98.73	61.70
24	4	info first	WA	18	229	14000	2	2.25	50	-2.39	99.71	55.62
25	1	info first	WA	21	295	15000	1	2.50	50	-7.50	99.86	61.82
25	2	info first	WA	11	107	15000	1	2.25	50	-13.69	99.86	55.64
25	3	info first	WA	9	153	15000	5	2.25	50	0.67	99.35	55.58
25	4	info first	WA	2	65	15000	5	2.25	50	0.67	99.35	55.58
26	1	comm first	F	1	0	8000	1	2.25	50	3.68	79.77	53.78
26	2	comm first	F	1	0	8000	1	2.25	50	3.68	79.77	53.78
26	3	comm first	F	9	122	7000	1	2.50	60	13.46	60.80	60.02
26	4	comm first	F	20	469	15000	5	2.50	55	6.85	99.35	61.76
27	1	info first	WA	15	169	15000	5	2.50	50	6.85	99.35	61.76

Continued...

Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
27	2	info first	WA	2	21	15000	5	2.25	50	0.67	99.35	55.58
27	3	info first	WA	5	99	12000	3	2.25	50	0.15	98.73	55.53
27	4	info first	WA	13	265	15000	5	2.75	50	13.02	99.35	67.94
28	1	info first	F	4	16	10000	1	2.75	60	11.29	94.80	67.41
28	2	info first	F	9	54	10000	1	2.75	60	11.29	94.80	67.41
28	3	info first	F	15	114	10000	1	2.75	50	11.29	94.80	67.41
28	4	info first	F	5	255	15000	2	2.75	60	9.81	99.86	68.00
29	1	info first	WA	12	125	15000	1	2.25	50	-13.69	99.86	55.64
29	2	info first	WA	13	136	15000	1	2.25	50	-13.69	99.86	55.64
29	3	info first	WA	11	192	15000	2	2.25	50	-2.56	99.86	55.64
29	4	info first	WA	16	292	15000	5	2.25	55	1.08	99.35	56.00
30	1	info first	WA	35	293	15000	2	2.25	50	-2.56	99.86	55.64
30	2	info first	WA	31	137	15000	2	2.25	50	-2.56	99.86	55.64
30	3	info first	WA	30	187	15000	4	2.25	55	0.80	99.57	56.02
30	4	info first	WA	6	184	15000	3	2.25	50	-3.04	99.72	55.62
31	1	comm first	F	40	262	11000	3	2.75	60	13.56	97.38	67.71
31	2	comm first	F	13	54	7000	1	2.75	60	17.12	60.80	63.68
31	3	comm first	F	35	553	9000	1	2.75	55	13.60	89.72	66.83
31	4	comm first	F	68	374	9000	3	2.50	50	8.41	89.57	60.74
32	1	comm first	WA	26	182	13000	1	2.25	50	-8.59	99.39	55.59
32	2	comm first	WA	18	130	15000	1	2.25	50	-13.69	99.86	55.64
32	3	comm first	WA	2	12	15000	1	2.25	50	-13.69	99.86	55.64
32	4	comm first	WA	10	467	15000	2	2.50	50	3.63	99.86	61.82
33	1	info first	WA	25	281	15000	1	2.25	50	-13.69	99.86	55.64
33	2	info first	WA	3	20	15000	2	2.25	50	-2.56	99.86	55.64
33	3	info first	WA	20	192	15000	5	2.25	50	0.67	99.35	55.58
33	4	info first	WA	14	584	15000	2	2.25	50	-2.56	99.86	55.64
34	1	comm first	F	33	278	14000	3	2.75	60	10.17	99.65	67.97
34	2	comm first	F	11	79	14000	3	2.75	60	10.17	99.65	67.97
34	3	comm first	F	42	581	13000	4	2.50	50	7.09	99.28	61.76
34	4	comm first	F	46	566	13000	4	2.50	50	7.09	99.28	61.76
35	1	comm first	F	15	296	12000	3	2.75	55	12.49	98.73	67.87
35	2	comm first	F	3	27	10000	3	2.75	55	14.32	94.80	67.41
35	3	comm first	F	13	547	15000	4	2.50	60	6.74	99.57	61.96
35	4	comm first	F	13	161	15000	5	2.75	55	13.02	99.35	67.94
36	1	info first	F	10	141	8000	1	2.25	60	9.90	79.77	60.00
36	2	info first	F	10	75	15000	5	2.75	60	13.02	99.35	67.94
36	3	info first	F	37	333	13000	4	2.50	50	7.09	99.28	61.76
36	4	info first	F	25	588	15000	5	2.25	60	5.09	99.35	60.00
37	1	info first	WA	18	254	15000	3	2.25	50	-3.04	99.72	55.62
37	2	info first	WA	12	137	15000	1	2.25	50	-13.69	99.86	55.64
37	3	info first	WA	21	331	15000	3	2.50	50	3.14	99.72	61.80
37	4	info first	WA	7	138	15000	2	2.50	50	3.63	99.86	61.82
38	1	comm first	WA	10	202	15000	1	2.25	50	-13.69	99.86	55.64
38	2	comm first	WA	2	14	15000	1	2.25	50	-13.69	99.86	55.64
38	3	comm first	WA	10	579	13000	3	2.50	50	5.14	99.37	61.77
38	4	comm first	WA	11	467	13000	4	2.50	50	7.09	99.28	61.76
39	1	info first	WA	5	112	14000	4	2.50	60	7.04	99.51	61.95
39	2	info first	WA	5	45	12000	5	2.25	50	-3.83	92.83	54.83
39	3	info first	WA	3	56	12000	5	2.25	50	-3.83	92.83	54.83
39	4	info first	WA	11	461	13000	4	2.50	55	7.09	99.28	61.76
40	1	info first	F	8	131	14000	4	2.75	60	13.05	99.51	67.96

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Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
40	2	info first	F	11	93	10000	3	2.75	60	14.32	94.80	67.41
40	3	info first	F	43	362	9000	3	2.75	50	14.48	89.57	66.81
40	4	info first	F	40	333	10000	3	2.75	50	14.32	94.80	67.41
41	1	info first	F	44	231	13000	4	2.75	55	13.27	99.28	67.93
41	2	info first	F	15	148	14000	4	2.75	55	13.05	99.51	67.96
41	3	info first	F	20	195	12000	3	2.75	50	12.49	98.73	67.87
41	4	info first	F	10	62	10000	3	2.75	55	14.32	94.80	67.41
42	1	comm first	WA	2	8	15000	1	2.25	50	-13.69	99.86	55.64
42	2	comm first	WA	2	17	15000	1	2.25	50	-13.69	99.86	55.64
42	3	comm first	WA	8	596	15000	1	2.50	60	-7.34	99.86	61.98
42	4	comm first	WA	19	177	15000	2	2.50	60	3.79	99.86	61.98
43	1	comm first	WA	10	226	14000	3	2.25	55	-1.79	99.65	56.02
43	2	comm first	WA	10	69	15000	3	2.25	55	-2.64	99.72	56.02
43	3	comm first	WA	15	597	12000	3	2.50	50	6.32	98.73	61.70
43	4	comm first	WA	12	179	13000	4	2.50	55	7.09	99.28	61.76
44	1	comm first	WA	5	85	7000	3	2.25	50	-1.08	53.55	51.33
44	2	comm first	WA	3	40	8000	2	2.50	50	9.07	79.77	59.75
44	3	comm first	WA	13	160	15000	4	2.25	55	0.80	99.57	56.02
44	4	comm first	WA	6	177	11000	3	2.25	55	1.71	97.38	55.87
45	1	info first	F	21	111	10000	1	2.75	50	11.29	94.80	67.41
45	2	info first	F	6	38	10000	1	2.50	55	5.16	94.80	61.28
45	3	info first	F	37	493	15000	5	2.75	60	13.02	99.35	67.94
45	4	info first	F	4	281	15000	5	2.25	60	5.09	99.35	60.00
46	1	info first	WA	3	49	15000	5	2.25	55	1.08	99.35	56.00
46	2	info first	WA	3	16	15000	5	2.25	55	1.08	99.35	56.00
46	3	info first	WA	26	158	10000	5	2.50	55	2.15	77.43	59.24
46	4	info first	WA	6	295	15000	5	2.25	50	0.67	99.35	55.58
47	1	comm first	F	20	298	7000	1	2.75	50	17.12	60.80	63.68
47	2	comm first	F	29	147	13000	4	2.75	60	13.27	99.28	67.93
47	3	comm first	F	50	383	11000	3	2.75	60	13.56	97.38	67.71
47	4	comm first	F	39	570	12000	4	2.75	55	13.09	98.56	67.84
48	1	info first	F	13	68	15000	5	2.75	60	13.02	99.35	67.94
48	2	info first	F	21	116	15000	5	2.75	60	13.02	99.35	67.94
48	3	info first	F	6	61	15000	5	2.25	50	0.67	99.35	55.58
48	4	info first	F	6	284	15000	5	2.25	50	0.67	99.35	55.58
49	1	info first	F	6	141	12000	4	2.75	50	13.09	98.56	67.84
49	2	info first	F	24	135	10000	3	2.75	60	14.32	94.80	67.41
49	3	info first	F	5	132	10000	3	2.75	60	14.32	94.80	67.41
49	4	info first	F	43	279	14000	4	2.75	60	13.05	99.51	67.96
50	1	comm first	F	3	207	7000	1	2.75	50	17.12	60.80	63.68
50	2	comm first	F	10	39	7000	1	2.75	60	17.12	60.80	63.68
50	3	comm first	F	15	224	12000	3	2.25	60	4.63	98.73	60.00
50	4	comm first	F	22	152	14000	3	2.75	50	10.17	99.65	67.97
51	1	info first	F	93	209	15000	5	2.75	55	13.02	99.35	67.94
51	2	info first	F	16	122	15000	5	2.75	55	13.02	99.35	67.94
51	3	info first	F	124	388	15000	4	2.75	50	12.75	99.57	67.97
51	4	info first	F	46	499	13000	4	2.50	55	7.09	99.28	61.76
52	1	info first	WA	14	259	15000	4	2.25	55	0.80	99.57	56.02
52	2	info first	WA	34	144	15000	5	2.25	50	0.67	99.35	55.58
52	3	info first	WA	65	499	15000	1	2.25	50	-13.69	99.86	55.64
52	4	info first	WA	37	279	15000	1	2.25	50	-13.69	99.86	55.64
53	1	info first	WA	11	56	15000	2	2.25	50	-2.56	99.86	55.64

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Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
53	2	info first	WA	13	71	15000	1	2.25	50	-13.69	99.86	55.64
53	3	info first	WA	20	150	15000	2	2.25	50	-2.56	99.86	55.64
53	4	info first	WA	58	597	13000	2	2.50	60	4.05	99.39	61.94
54	1	comm first	F	6	79	12000	1	2.75	55	6.30	98.73	67.87
54	2	comm first	F	3	29	9000	1	2.75	50	13.60	89.72	66.83
54	3	comm first	F	3	29	9000	3	2.50	55	8.41	89.57	60.74
54	4	comm first	F	4	50	10000	2	2.75	50	10.98	94.80	67.41
55	1	info first	WA	10	47	13000	1	2.25	50	-8.59	99.39	55.59
55	2	info first	WA	21	65	13000	5	2.25	50	-2.58	96.80	55.28
55	3	info first	WA	20	151	11000	4	2.25	50	-0.72	96.44	55.28
55	4	info first	WA	43	346	10000	3	2.25	60	6.91	94.80	60.00
56	1	info first	WA	10	56	14000	1	2.25	50	-11.14	99.71	55.62
56	2	info first	WA	15	83	15000	1	2.25	55	-13.29	99.86	56.03
56	3	info first	WA	19	154	15000	4	2.50	50	6.57	99.57	61.79
56	4	info first	WA	53	401	15000	5	2.50	50	6.85	99.35	61.76
57	1	info first	WA	17	159	15000	1	2.25	50	-13.69	99.86	55.64
57	2	info first	WA	6	130	15000	1	2.25	60	-9.32	99.86	60.00
57	3	info first	WA	26	381	15000	1	2.25	55	-13.29	99.86	56.03
57	4	info first	WA	28	517	15000	2	2.25	60	1.81	99.86	60.00
58	1	comm first	F	4	66	8000	1	2.50	50	9.65	79.77	59.75
58	2	comm first	F	2	81	13000	5	2.75	55	9.71	96.80	67.57
58	3	comm first	F	37	519	13000	3	2.25	60	3.37	99.37	60.00
58	4	comm first	F	64	593	15000	2	2.50	60	3.79	99.86	61.98
59	1	info first	WA	36	230	15000	2	2.25	55	-2.16	99.86	56.03
59	2	info first	WA	8	70	10000	4	2.25	60	2.71	90.97	60.00
59	3	info first	WA	13	104	15000	4	2.25	55	0.80	99.57	56.02
59	4	info first	WA	8	280	14000	4	2.50	60	7.04	99.51	61.95
60	1	comm first	F	15	255	10000	3	2.50	60	8.44	94.80	61.52
60	2	comm first	F	16	146	13000	3	2.75	60	11.31	99.37	67.94
60	3	comm first	F	7	151	14000	4	2.50	50	6.87	99.51	61.78
60	4	comm first	F	7	147	14000	4	2.50	55	6.87	99.51	61.78
61	1	comm first	WA	28	168	11000	4	2.25	50	-0.72	96.44	55.28
61	2	comm first	WA	21	101	12000	1	2.25	50	-6.03	98.73	55.53
61	3	comm first	WA	4	88	11000	2	2.25	50	-2.31	97.38	55.40
61	4	comm first	WA	2	12	11000	2	2.25	50	-2.31	97.38	55.40
62	1	info first	F	18	234	15000	3	2.75	60	9.32	99.72	67.98
62	2	info first	F	10	135	15000	2	2.75	60	9.81	99.86	68.00
62	3	info first	F	22	162	14000	2	2.75	60	9.97	99.71	67.98
62	4	info first	F	4	452	15000	2	2.75	60	9.81	99.86	68.00
63	1	info first	WA	9	103	11000	2	2.25	50	-2.31	97.38	55.40
63	2	info first	WA	14	144	15000	1	2.25	50	-13.69	99.86	55.64
63	3	info first	WA	15	230	15000	2	2.25	55	-2.16	99.86	56.03
63	4	info first	WA	19	553	15000	2	2.25	60	1.81	99.86	60.00
64	1	comm first	F	38	256	11000	2	2.75	60	10.00	97.38	67.71
64	2	comm first	F	28	124	14000	2	2.75	60	9.97	99.71	67.98
64	3	comm first	F	21	486	15000	2	2.75	50	9.81	99.86	68.00
64	4	comm first	F	27	410	11000	3	2.50	60	7.60	97.38	61.75
65	1	comm first	F	49	191	15000	3	2.75	50	9.32	99.72	67.98
65	2	comm first	F	4	40	15000	3	2.75	50	9.32	99.72	67.98
65	3	comm first	F	4	264	14000	2	2.50	50	3.79	99.71	61.80
65	4	comm first	F	23	456	12000	3	2.50	50	6.32	98.73	61.70
66	1	info first	WA	28	297	15000	1	2.25	50	-13.69	99.86	55.64

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Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
66	2	info first	WA	14	127	15000	1	2.25	50	-13.69	99.86	55.64
66	3	info first	WA	35	359	15000	1	2.25	50	-13.69	99.86	55.64
66	4	info first	WA	41	562	13000	4	2.25	60	5.34	99.28	60.00
67	1	info first	F	37	152	10000	3	2.75	55	14.32	94.80	67.41
67	2	info first	F	16	54	10000	3	2.75	55	14.32	94.80	67.41
67	3	info first	F	81	415	13000	4	2.75	50	13.27	99.28	67.93
67	4	info first	F	31	390	13000	4	2.50	50	7.09	99.28	61.76
68	1	comm first	WA	2	54	15000	1	2.25	50	-13.69	99.86	55.64
68	2	comm first	WA	3	119	15000	1	2.25	50	-13.69	99.86	55.64
68	3	comm first	WA	9	594	15000	1	2.25	60	-9.32	99.86	60.00
68	4	comm first	WA	7	334	15000	2	2.25	60	1.81	99.86	60.00
69	1	comm first	F	24	226	8000	2	2.50	50	9.07	79.77	59.75
69	2	comm first	F	20	97	11000	3	2.75	50	13.56	97.38	67.71
69	3	comm first	F	42	539	15000	2	2.75	50	9.81	99.86	68.00
69	4	comm first	F	37	299	14000	2	2.75	60	9.97	99.71	67.98
70	1	info first	F	21	263	15000	4	2.75	60	12.75	99.57	67.97
70	2	info first	F	22	124	15000	4	2.75	60	12.75	99.57	67.97
70	3	info first	F	6	48	15000	2	2.75	60	9.81	99.86	68.00
70	4	info first	F	1	0	8000	1	2.25	50	3.68	79.77	53.78
71	1	comm first	F	22	254	13000	4	2.75	60	13.27	99.28	67.93
71	2	comm first	F	13	136	15000	5	2.75	60	13.02	99.35	67.94
71	3	comm first	F	13	402	14000	4	2.50	50	6.87	99.51	61.78
71	4	comm first	F	16	593	15000	5	2.50	50	6.85	99.35	61.76
72	1	comm first	WA	37	275	11000	3	2.25	50	1.25	97.38	55.40
72	2	comm first	WA	21	137	15000	1	2.25	50	-13.69	99.86	55.64
72	3	comm first	WA	17	496	15000	1	2.50	50	-7.50	99.86	61.82
72	4	comm first	WA	35	416	11000	3	2.50	50	7.40	97.38	61.55
73	1	info first	WA	11	168	15000	1	2.25	50	-13.69	99.86	55.64
73	2	info first	WA	2	19	15000	1	2.25	50	-13.69	99.86	55.64
73	3	info first	WA	17	292	15000	2	2.25	50	-2.56	99.86	55.64
73	4	info first	WA	9	580	15000	5	2.50	60	7.02	99.35	61.93
74	1	info first	WA	3	63	13000	1	2.25	50	-8.59	99.39	55.59
74	2	info first	WA	6	29	15000	2	2.25	50	-2.56	99.86	55.64
74	3	info first	WA	14	542	13000	4	2.25	55	1.33	99.28	55.99
74	4	info first	WA	17	564	15000	2	2.50	50	3.63	99.86	61.82
75	1	comm first	WA	12	209	15000	1	2.25	50	-13.69	99.86	55.64
75	2	comm first	WA	6	69	15000	1	2.25	50	-13.69	99.86	55.64
75	3	comm first	WA	2	16	15000	1	2.25	50	-13.69	99.86	55.64
75	4	comm first	WA	15	467	8000	1	2.50	55	9.65	79.77	59.75
76	1	info first	F	14	293	11000	1	2.75	50	8.82	97.38	67.71
76	2	info first	F	12	123	15000	5	2.75	50	13.02	99.35	67.94
76	3	info first	F	24	419	15000	2	2.75	50	9.81	99.86	68.00
76	4	info first	F	22	398	15000	5	2.50	50	6.85	99.35	61.76
77	1	info first	WA	6	25	12000	4	2.75	60	13.09	98.56	67.84
77	2	info first	WA	2	11	14000	5	2.75	55	11.61	98.66	67.84
77	3	info first	WA	1	0	8000	1	2.25	50	3.68	79.77	53.78
77	4	info first	WA	12	63	15000	5	2.25	55	1.08	99.35	56.00
78	1	comm first	F	30	246	9000	2	2.75	50	12.97	89.72	66.83
78	2	comm first	F	8	55	10000	1	2.75	50	11.29	94.80	67.41
78	3	comm first	F	27	243	14000	3	2.75	60	10.17	99.65	67.97
78	4	comm first	F	17	171	13000	2	2.75	50	10.05	99.39	67.94
79	1	comm first	WA	20	185	11000	1	2.25	55	-3.02	97.38	55.87

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Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
79	2	comm first	WA	13	137	10000	5	2.25	50	-3.77	77.43	53.32
79	3	comm first	WA	17	547	14000	4	2.50	50	6.87	99.51	61.78
79	4	comm first	WA	35	566	15000	5	2.25	60	5.09	99.35	60.00
80	1	comm first	F	2	23	14000	4	2.75	50	13.05	99.51	67.96
80	2	comm first	F	6	32	14000	4	2.75	50	13.05	99.51	67.96
80	3	comm first	F	19	171	14000	4	2.75	50	13.05	99.51	67.96
80	4	comm first	F	7	45	13000	4	2.75	50	13.27	99.28	67.93
81	1	info first	F	26	176	11000	3	2.75	55	13.56	97.38	67.71
81	2	info first	F	12	113	13000	4	2.75	50	13.27	99.28	67.93
81	3	info first	F	17	196	10000	3	2.75	50	14.32	94.80	67.41
81	4	info first	F	5	170	11000	3	2.75	55	13.56	97.38	67.71
82	1	comm first	WA	4	45	13000	1	2.25	50	-8.59	99.39	55.59
82	2	comm first	WA	11	51	15000	5	2.25	55	1.08	99.35	56.00
82	3	comm first	WA	22	596	15000	1	2.25	50	-13.69	99.86	55.64
82	4	comm first	WA	3	41	15000	1	2.25	50	-13.69	99.86	55.64
83	1	comm first	F	13	69	9000	1	2.75	50	13.60	89.72	66.83
83	2	comm first	F	22	114	14000	4	2.75	50	13.05	99.51	67.96
83	3	comm first	F	59	562	15000	2	2.50	50	3.63	99.86	61.82
83	4	comm first	F	4	45	15000	4	2.50	50	6.57	99.57	61.79
84	1	comm first	WA	17	243	15000	1	2.25	55	-13.29	99.86	56.03
84	2	comm first	WA	2	37	15000	1	2.25	55	-13.29	99.86	56.03
84	3	comm first	WA	8	338	15000	2	2.25	55	-2.16	99.86	56.03
84	4	comm first	WA	8	386	15000	3	2.25	55	-2.64	99.72	56.02
85	1	comm first	F	2	74	8000	1	2.25	50	3.68	79.77	53.78
85	2	comm first	F	8	107	15000	5	2.50	50	6.85	99.35	61.76
85	3	comm first	F	2	229	14000	5	2.75	60	11.61	98.66	67.84
85	4	comm first	F	13	556	15000	3	2.25	55	-2.64	99.72	56.02
86	1	info first	F	35	260	10000	3	2.75	50	14.32	94.80	67.41
86	2	info first	F	14	146	14000	4	2.75	50	13.05	99.51	67.96
86	3	info first	F	16	204	13000	4	2.75	60	13.27	99.28	67.93
86	4	info first	F	9	318	14000	4	2.75	55	13.05	99.51	67.96
87	1	info first	WA	2	52	12000	4	2.50	50	6.92	98.56	61.67
87	2	info first	WA	4	65	10000	2	2.50	50	4.85	94.80	61.28
87	3	info first	WA	4	46	12000	2	2.50	50	3.94	98.73	61.70
87	4	info first	WA	2	74	14000	2	2.75	50	9.97	99.71	67.98
88	1	comm first	F	5	182	14000	4	2.75	60	13.05	99.51	67.96
88	2	comm first	F	18	126	15000	5	2.75	50	13.02	99.35	67.94
88	3	comm first	F	29	572	12000	4	2.25	60	5.25	98.56	60.00
88	4	comm first	F	24	499	11000	3	2.25	60	5.85	97.38	60.00
89	1	comm first	WA	5	178	12000	3	2.25	50	0.15	98.73	55.53
89	2	comm first	WA	9	63	13000	4	2.25	50	0.92	99.28	55.58
89	3	comm first	WA	10	148	13000	4	2.25	50	0.92	99.28	55.58
89	4	comm first	WA	20	447	15000	5	2.50	55	6.85	99.35	61.76
90	1	comm first	WA	15	286	15000	1	2.25	50	-13.69	99.86	55.64
90	2	comm first	WA	15	144	15000	1	2.25	50	-13.69	99.86	55.64
90	3	comm first	WA	5	77	15000	2	2.25	50	-2.56	99.86	55.64
90	4	comm first	WA	13	573	15000	3	2.25	55	-2.64	99.72	56.02
91	1	comm first	WA	17	150	14000	5	2.25	50	-0.73	98.66	55.50
91	2	comm first	WA	5	51	15000	5	2.25	50	0.67	99.35	55.58
91	3	comm first	WA	19	527	12000	4	2.25	60	5.25	98.56	60.00
91	4	comm first	WA	18	483	11000	3	2.25	60	5.85	97.38	60.00
92	1	info first	F	38	200	15000	4	2.75	50	12.75	99.57	67.97

Continued...

Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
92	2	info first	F	27	142	11000	3	2.75	50	13.56	97.38	67.71
92	3	info first	F	18	164	11000	3	2.75	60	13.56	97.38	67.71
92	4	info first	F	11	406	13000	3	2.75	60	11.31	99.37	67.94
93	1	comm first	F	9	189	8000	2	2.75	50	15.04	79.77	65.73
93	2	comm first	F	5	40	10000	2	2.75	50	10.98	94.80	67.41
93	3	comm first	F	28	505	10000	3	2.75	50	14.32	94.80	67.41
93	4	comm first	F	41	382	12000	2	2.75	50	10.11	98.73	67.87
94	1	comm first	F	4	74	15000	5	2.75	60	13.02	99.35	67.94
94	2	comm first	F	19	138	14000	4	2.75	60	13.05	99.51	67.96
94	3	comm first	F	45	552	13000	4	2.75	60	13.27	99.28	67.93
94	4	comm first	F	6	71	13000	4	2.75	60	13.27	99.28	67.93
95	1	comm first	WA	9	237	15000	1	2.25	50	-13.69	99.86	55.64
95	2	comm first	WA	17	142	15000	1	2.25	50	-13.69	99.86	55.64
95	3	comm first	WA	41	498	15000	1	2.25	50	-13.69	99.86	55.64
95	4	comm first	WA	31	520	15000	4	2.25	60	4.78	99.57	60.00
96	1	info first	F	37	202	15000	5	2.75	60	13.02	99.35	67.94
96	2	info first	F	17	88	15000	5	2.75	60	13.02	99.35	67.94
96	3	info first	F	32	219	15000	5	2.75	60	13.02	99.35	67.94
96	4	info first	F	68	506	9000	3	2.75	60	14.48	89.57	66.81
97	1	info first	F	9	169	10000	3	2.50	55	8.19	94.80	61.28
97	2	info first	F	3	19	11000	4	2.25	60	4.00	96.44	60.00
97	3	info first	F	22	354	14000	3	2.75	50	10.17	99.65	67.97
97	4	info first	F	24	545	13000	4	2.25	60	5.34	99.28	60.00
98	1	comm first	F	2	11	11000	3	2.75	50	13.56	97.38	67.71
98	2	comm first	F	13	83	11000	3	2.75	50	13.56	97.38	67.71
98	3	comm first	F	9	541	13000	3	2.75	50	11.31	99.37	67.94
98	4	comm first	F	32	448	13000	2	2.75	50	10.05	99.39	67.94
99	1	info first	F	32	281	13000	4	2.75	60	13.27	99.28	67.93
99	2	info first	F	5	62	15000	5	2.75	60	13.02	99.35	67.94
99	3	info first	F	21	311	15000	5	2.75	60	13.02	99.35	67.94
99	4	info first	F	18	373	15000	5	2.25	60	5.09	99.35	60.00
100	1	comm first	F	35	292	15000	4	2.75	50	12.75	99.57	67.97
100	2	comm first	F	17	138	15000	2	2.75	60	9.81	99.86	68.00
100	3	comm first	F	48	538	15000	2	2.75	50	9.81	99.86	68.00
100	4	comm first	F	2	34	15000	2	2.75	50	9.81	99.86	68.00
101	1	comm first	WA	3	40	15000	1	2.25	50	-13.69	99.86	55.64
101	2	comm first	WA	21	125	15000	1	2.25	55	-13.29	99.86	56.03
101	3	comm first	WA	41	289	15000	2	2.25	50	-2.56	99.86	55.64
101	4	comm first	WA	30	249	15000	2	2.25	50	-2.56	99.86	55.64
102	1	comm first	WA	11	104	15000	1	2.25	50	-13.69	99.86	55.64
102	2	comm first	WA	23	85	14000	1	2.25	55	-10.74	99.71	56.02
102	3	comm first	WA	48	351	15000	1	2.25	50	-13.69	99.86	55.64
102	4	comm first	WA	3	14	15000	5	2.25	50	0.67	99.35	55.58
103	1	info first	WA	10	152	15000	1	2.25	50	-13.69	99.86	55.64
103	2	info first	WA	16	131	15000	1	2.25	50	-13.69	99.86	55.64
103	3	info first	WA	29	375	15000	5	2.25	50	0.67	99.35	55.58
103	4	info first	WA	4	461	15000	5	2.25	60	5.09	99.35	60.00
104	1	comm first	F	5	76	15000	4	2.25	60	4.78	99.57	60.00
104	2	comm first	F	4	32	15000	5	2.75	50	13.02	99.35	67.94
104	3	comm first	F	2	27	15000	5	2.75	50	13.02	99.35	67.94
104	4	comm first	F	3	34	15000	4	2.75	50	12.75	99.57	67.97
105	1	comm first	WA	44	267	11000	4	2.25	55	-0.22	96.44	55.78

Continued...

Table C.1: Design solutions submitted by 112 participants, 447 observations

Participant ID	Problem Number	Treatment Group	Functional Role	Iteration	Elapsed Time	Output Capacity	Modules	Water Price	Revenue Guarantee	Profit	Reliability	Total Payments
105	2	comm first	WA	12	109	13000	5	2.25	55	-2.06	96.80	55.80
105	3	comm first	WA	27	381	13000	3	2.25	50	-1.04	99.37	55.59
105	4	comm first	WA	14	577	15000	2	2.75	50	9.81	99.86	68.00
106	1	comm first	WA	16	239	15000	2	2.25	50	-2.56	99.86	55.64
106	2	comm first	WA	8	114	15000	2	2.25	50	-2.56	99.86	55.64
106	3	comm first	WA	12	589	13000	3	2.25	60	3.37	99.37	60.00
106	4	comm first	WA	21	593	15000	2	2.50	60	3.79	99.86	61.98
107	1	comm first	WA	13	207	15000	1	2.25	50	-13.69	99.86	55.64
107	2	comm first	WA	2	17	15000	1	2.25	50	-13.69	99.86	55.64
107	3	comm first	WA	16	513	15000	1	2.25	60	-9.32	99.86	60.00
107	4	comm first	WA	25	528	15000	2	2.75	60	9.81	99.86	68.00
108	1	info first	F	4	141	12000	3	2.50	50	6.32	98.73	61.70
108	2	info first	F	7	79	14000	4	2.75	50	13.05	99.51	67.96
108	3	info first	F	22	341	15000	5	2.75	50	13.02	99.35	67.94
108	4	info first	F	9	484	15000	4	2.75	50	12.75	99.57	67.97
109	1	info first	WA	19	286	15000	4	2.25	55	0.80	99.57	56.02
109	2	info first	WA	12	85	15000	2	2.25	55	-2.16	99.86	56.03
109	3	info first	WA	33	244	15000	1	2.25	55	-13.29	99.86	56.03
109	4	info first	WA	14	587	15000	5	2.25	60	5.09	99.35	60.00
110	1	info first	WA	18	228	15000	1	2.25	50	-13.69	99.86	55.64
110	2	info first	WA	7	46	15000	1	2.25	50	-13.69	99.86	55.64
110	3	info first	WA	19	272	15000	1	2.25	55	-13.29	99.86	56.03
110	4	info first	WA	2	48	15000	1	2.25	50	-13.69	99.86	55.64
111	1	info first	F	4	234	10000	3	2.75	50	14.32	94.80	67.41
111	2	info first	F	8	72	12000	4	2.50	50	6.92	98.56	61.67
111	3	info first	F	21	207	9000	3	2.75	60	14.48	89.57	66.81
111	4	info first	F	19	375	10000	3	2.75	50	14.32	94.80	67.41
112	1	info first	WA	17	144	12000	1	2.25	55	-5.61	98.73	55.95
112	2	info first	WA	6	100	12000	2	2.25	50	-2.23	98.73	55.53
112	3	info first	WA	11	269	13000	3	2.25	55	-0.63	99.37	56.00
112	4	info first	WA	15	571	12000	3	2.25	55	0.58	98.73	55.95

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Appendix D

Calculating uncertainty bounds for within-subjects measurements

The issue of calculating and displaying uncertainty bounds is more complex for within-subjects experimental designs than for designs in which all factors are between-subjects. The issue applies to bounds such as confidence intervals as well as standard errors of parameter values. The complexity arises because in within-subject designs, each subject is observed more than once under different experimental conditions, hence the name "repeated measures" designs. Measurements of samples under different experimental conditions can no longer be treated as independent, because the sample of observed units is common to conditions. Instead, we expect repeated measurements on each unit of analysis (the subject) in the sample to be correlated. This feature of within-subject designs requires some additional procedures for representing uncertainty, so as to enable statistical inferences from the visual representations.

An appropriate visual representation of uncertainty in measurements is important because many audiences often "eye ball" the summary information in graphs to reach conclusions about the outcomes of the experiment. For example, some researchers conclude that the differences across the means of measurements for two conditions shown side by side are not statistically significant if the confidence intervals around the mean overlap. In some cases, the conclusion is accurate and the same as the result a formal hypothesis test for differences in means would give. In other cases, the overlap can be misleading and lead to an erroneous conclusion. For this reason, many researchers in behavioral and statistical work have developed both formal procedures as well as heuristics for representing uncertainty in a manner that is more consistent with the results one could expect from hypothesis tests. Here the focus is on procedures for within-subjects experimental designs.

There are two types of variation in the collaborative design exercise, the main topic of Chapter 3. The first is the effect of uncertainty or risk factors in the value outcomes of designs. The second type of variation is differences in the design choices of participants as experimental subjects. This second type is the only variation that is actually "observed" as a consequence of the experiment, for the following reason.

In the collaboration exercise, participants make design choices in relation to expected value outcomes. For example, a participant playing the role of the water authority attempts to select designs that simultaneously meet its two objectives of (i) high reliability of meeting uncertain water demand (i.e. low water shortages), and (ii) low contract payments. Value outcomes are probabilistic for the corresponding metrics for both these dimensions because the design tradespace model uses Monte Carlo simulation to explicitly simulate uncertainty in both water demand and energy prices for a large number of paths. However, the water authority participant only sees the expected value of the outcomes of a design choice, in terms of reliability and contract payments. This was done to sidestep issues associated with an individual's perception of risk. Similarly, a participant playing the role of the firm sees the effect of design choices as the expected values of profit and reliability, which are its specific value dimensions. All participants in the experiment thus submitted design choices that gave their preferred *expected value* outcomes. These expected value outcomes (reliability, profit, payments) are the observations (i.e. measurements).

Variation in observations arises because of (a) random effects due to participant attributes in the sample, and (b) possible effects of experimental conditions. The random variation (a) is observed among participants even under identical experimental conditions. Some participants may learn more quickly than others and may therefore start out with high value outcomes. Others may lag during an initial measurement. Thus in a repeated measures setting, we expect to see the random effect of a participant's attributes propagate across the multiple measurements. This may confound the variation of interest in (b) experimental effect, which we really want to closely observe as this is what the experimental exercise intends to capture. The within-subjects analysis procedures describe here thus strip out the nuisance random effect in the *observed* expected value outcomes, and leave in the variation we want to test for statistical significance due to experimental stimuli.

The issue of correlation in measurements

This section explains how adopting the assumptions of between-subjects comparisons (no repeated measures) in within-subjects (repeated measures) analyses overestimates the error in the latter due to correlation in repeated measurements. [1] To understand why, we begin with a simple case of the mean of a single sample as a parameter of interest.

The equation for the confidence interval (CI) of a single mean with an empirical, unknown population variance is based on the t distribution. The assumption is that the data are sampled from a population with normally distributed, independent errors. For a sample of size n, the two-sided CI with a 100(1-α)% confidence is

$$\hat{\mu} \pm t_{n-1,1-\alpha/2} \times \hat{\sigma}_{\hat{\mu}} \tag{D.1}$$

[1] For a more elaborate explanation of the issues, see Baguley (2012).

where $\hat{\mu}$ is the sample mean, $t_{n-1,1-\alpha/2}$ is the critical value of the t distribution corresponding to sample size n and chosen significance level α, and $\hat{\sigma}_{\hat{\mu}}$ is the sample standard deviation given by $\hat{\sigma}_{\hat{\mu}} = \hat{\sigma}/\sqrt{n}$. For a 95% CI, the critical value of $t_{n-1,0.975}$ approaches $z_{0.975}$ for large values of n.

The basic approach in Eq D.1 extends to a comparison of means using ANOVA. The following equation gives the CI for the difference of means in a case of two samples with independent means, sampled from a normal distribution with unknown variance.

$$(\hat{\mu}_1 - \hat{\mu}_2) \pm t_{n_1+n_2-2,1-\alpha/2} \times \hat{\sigma}_{\hat{\mu}_1-\hat{\mu}_2} \tag{D.2}$$

where n_1 and n_2 are the two sample sizes and $\hat{\sigma}_{\hat{\mu}_1-\hat{\mu}_2}$ is the standard error of the difference. This standard error is typically estimated as a pooled standard deviation $\hat{\sigma}_{\hat{\mu}_1-\hat{\mu}_2} = \hat{\sigma}_{pooled}\sqrt{1/n_1 + 1/n_2}$.

The variance of a difference in two variables X_1 and X_2 is given by

$$\sigma^2_{X_1-X_2} = \sigma^2_1 + \sigma^2_2 - 2\sigma_{X_1,X_2} \tag{D.3}$$

The covariance term σ_{X_1,X_2} that appears has important implications. When the groups are independent, the covariance is zero. The (population) standard deviation of the difference reduces to $\sqrt{\sigma^2_1 + \sigma^2_2}$. Under the assumption of equal population variances $\sigma_1 = \sigma_2 = \sigma$ for the two variables, the standard deviation of the difference further reduces to $\sqrt{2}\sigma$. Thus under the assumptions of independence and homogeneity of variance, the standard deviation of a difference in variables is $\sqrt{2}$ (or 41%) larger than either of the individual standard deviations.

In a within-subjects case, the assumption of independence in errors between the two samples being compared no longer applies. Most often, we would expect a positive correlation because the sample remains the same (Baguley, 2012). The covariance term in Eq D.3 is now positive, indicating that the standard error will be smaller than a between-subjects design. The two cases will have similar standard errors only if the correlation between measures is close to zero.

Adjusting ANOVA for within-subjects measurements

Loftus and Masson (1994) were the first to propose a solution to calculating and plotting graphical summaries of correlated measurements in within-subjects designs. Their proposed calculation for a within-subjects CI mimics a between-subjects CI for ANOVA, along the lines of Eqs D.1 and D.2 above. They suggest using the pooled error term of the within-subjects F statistic, which adapts Eq D.1 by calculating a $\hat{\sigma}_{pooled}$ after discarding individual differences. The calculation is based on the MS_{error} term of the F test using the form $\sqrt{MS_{error}/n}$. CIs plotted using this approach are in broad use and popularly called Loftus-Masson intervals.

A primary criticism of Loftus-Masson intervals is that the calculation assumes sphericity - that the variances of differences between pairs of repeated samples are homogeneous. This assumption is not always realistic however and others have suggested alternatives. Notable among these is Cousineau (2005), whose approach is simpler and does not require the sphericity assumption.

Cousineau (2005)'s approach first requires normalizing the data using *participant-mean centering* to remove random variation of a subject's repeated measures. In this process, the mean of each participant's observations is subtracted from the raw score for each observation. To preserve the level mean for each level of the experimental factor, the grand mean of all observations is added back to each of the raw scores. This process is summarized in Eq D.4 for a one-way within-subjects design. The single experimental factor has J levels and there are i subjects who provide repeated measures X_{ij} in each of the $j=1,...,J$ levels.

$$X_{ij}^{norm} = X_{ij} - \hat{\mu}_i + \hat{\mu}_{grand} \tag{D.4}$$

Then, the CIs are calculated for each level of a factor using the normalized data X_{ij}^{norm}, in the same way as standard CIs for individuals means (Eq D.1). Since the error terms are not pooled, this approach does not rely on the sphericity assumption.

Morey (2008) later identified a flaw in Cousineau's approach and provided a correction. The issue is that the normalization approach produces intervals that are too narrow because the participant-mean centering process introduces a positive covariance between normalized scores, thereby biasing the estimates. Morey's correction introduces a rescaling adjustment to the interval calculation, which is a modification of Eq D.1. The interval calculation with the rescaled adjustment is given by:

$$\hat{\mu} \pm t_{n-1,1-\alpha/2} \times \sqrt{\frac{J}{J-1}} \hat{\sigma}_{\hat{\mu}} \tag{D.5}$$

Note that the adjustment factor is a function of the number of levels J in the one-way experimental factor. Intervals calculated using the adjusted normalization approach are popularly called Cousineau-Morey intervals.

The analysis of results ultimately presents the summary statistics in terms of the Cousineau-Morey intervals. The next section shows some preliminary diagnostics of the collaboration exercise data, leading up to the representations shown in the main results in Chapter 3.

Applying the within-subjects adjustments to data from the collaboration exercise

This section steps through an analysis of a subset of the raw data in which a number of steps discussed above have been applied to produce the adjusted uncertainty bounds for the within-subjects design.

The first graph is simply a scatter plot of the raw data, as shown in Figure D.4. In this plot, the expected value outcomes of design submissions for both roles are plotted using the Expected Profit value metric on the vertical axis. This representation gives a sense of the full spread of the data, as seen from the Firm's value dimension.[2] Each problem, shown on the horizontal axis, has four columns of shapes corresponding to the two roles and the two treatment groups.

[2] A similar representation can be constructed using the Water Authority's value dimension of Expected Contract Payments.

Observations for Firm role players tend to cluster in the upper half, whereas observations for Water Authority role players cluster in the bottom half although they have a larger spread. This plot shows the full range of observations in the four groups (two treatments, and two roles).

The next representation, Figure D.2, adds a layer in red that denotes the mean of each of the four groups for every problem, along with whiskers marking the range. The expected value metric of Expected Profits is the same. This example is just to transition from the full scatter to a summary version with the mean and range. The scatter points are then removed in Figure D.3. The chart is now less cluttered than before and it conveys similar information to the first figure Figure D.1.

Then, the first chart with a summary statistic for the variance of observation is shown in Figure D.4. In addition to the mean and whiskers for the range (in red), the graph superimposes the 95% confidence interval for the mean in black. The flat bars at the end of the vertical segments mark the upper and lower bouns of the confidence interval respectively. In this depiction, the formula in Eq D.1 is applied, assuming independence in the sub-samples for each of the four group for every problem (16 sub-samples). We can see that the 95%CI for the mean is much narrower than the full range of observations. The calculated values for each of the CIs shown in this figure are also summarized in Table D.1 showing the different summary statistics for variance of observations as well as the lower CI bound (CILB) and upper CI bound (CIUB).

D.5 compares the single sample CIs which assume independence among the 16 sub-samples to the adjusted Cousineau-Morey (C-M) within-subject CIs given by Eq D.5. We can see that the C-M version of the 95% confidence intervals are slightly narrower than the independent sample CIs. This can also be inferred by comparing the calculated values for C-M intervals in Table D.2 with those in Table D.1.

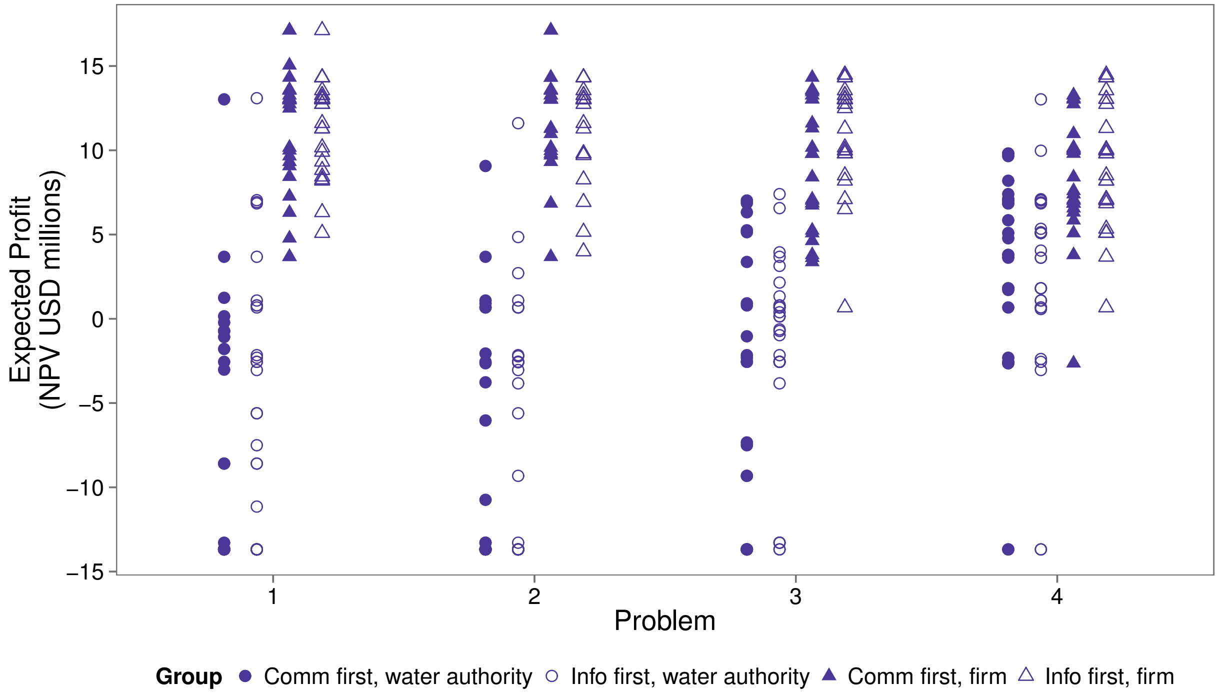

Figure D.1: A scatter plot showing the full range of observations in the four subgroups of two role and two treatment combinations over the course of four problems in the collaboration exercise.

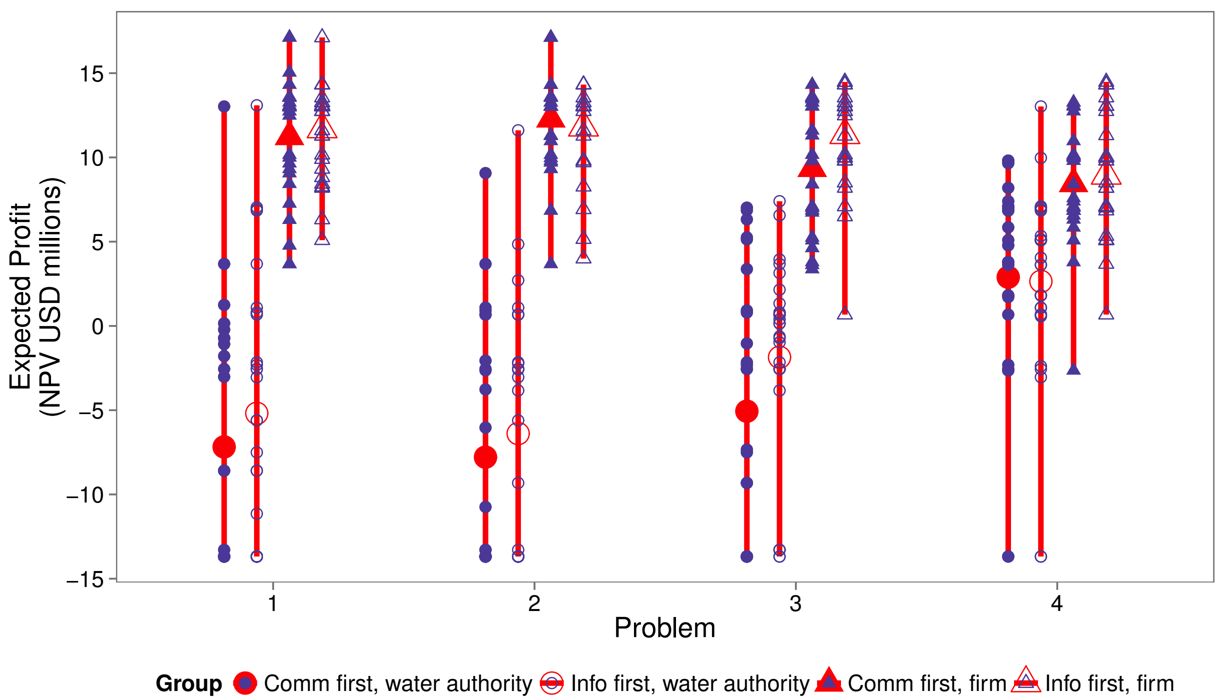

Figure D.2: The same scatter plot as above with a supplemental layer marking the mean of each sub-group and whiskers showing the range.

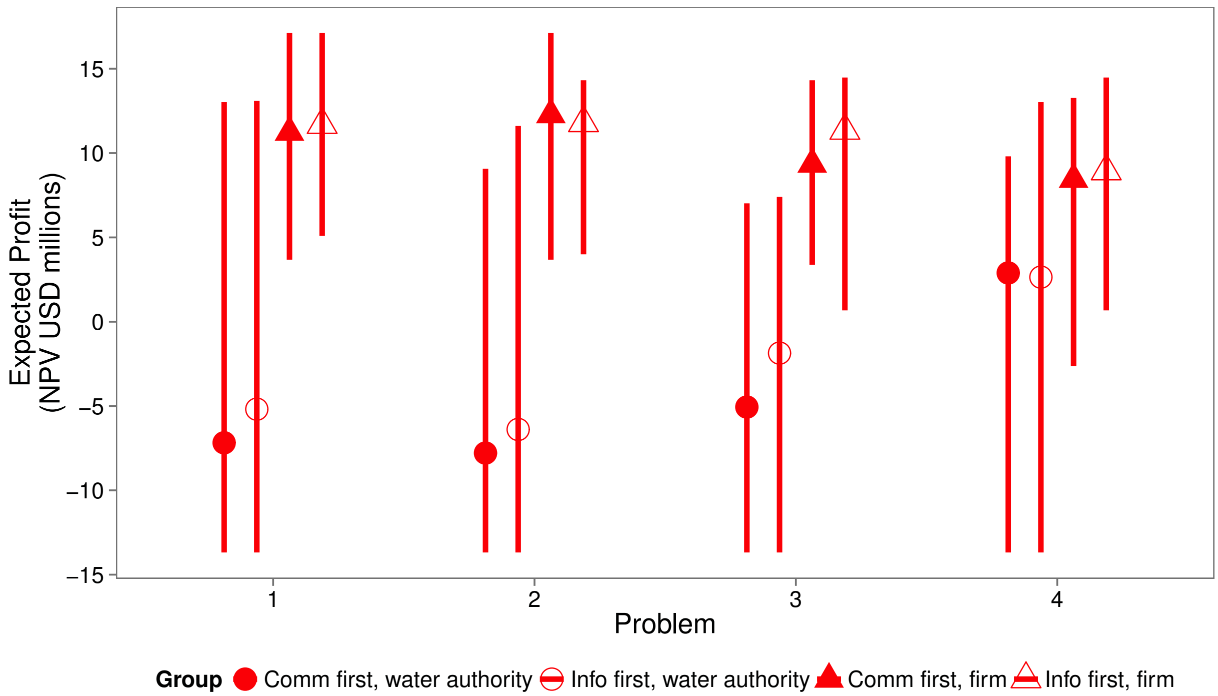

Figure D.3: A summary version of the two plots above, showing only the sub-group means and ranges.

Table D.1: Summary of calculations for uncertainty bounds assuming independence

Group	Problem	n	μ_{Profit}	sd	se	ci	CILB	CIUB
Comm first, Water Authority	1	26	-7.181	7.581	1.487	3.062	-10.243	-4.119
Comm first, Water Authority	2	26	-7.788	7.227	1.417	2.919	-10.708	-4.869
Comm first, Water Authority	3	26	-5.061	7.825	1.535	3.161	-8.221	-1.900
Comm first, Water Authority	4	26	2.892	6.226	1.221	2.515	0.378	5.407
Info first, Water Authority	1	30	-5.186	7.925	1.447	2.959	-8.145	-2.227
Info first, Water Authority	2	30	-6.389	7.300	1.333	2.726	-9.115	-3.663
Info first, Water Authority	3	30	-1.861	5.873	1.072	2.193	-4.054	0.332
Info first, Water Authority	4	30	2.644	5.693	1.039	2.126	0.518	4.769
Comm first,Firm	1	27	11.237	3.692	0.711	1.461	9.776	12.697
Comm first,Firm	2	27	12.281	2.961	0.570	1.171	11.109	13.452
Comm first,Firm	3	27	9.347	3.671	0.706	1.452	7.895	10.799
Comm first,Firm	4	26	8.447	3.538	0.694	1.429	7.018	9.876
Info first, Firm	1	29	11.680	2.688	0.499	1.022	10.658	12.702
Info first, Firm	2	29	11.784	2.679	0.497	1.019	10.765	12.803
Info first, Firm	3	29	11.334	3.049	0.566	1.160	10.174	12.494
Info first, Firm	4	29	8.927	3.765	0.699	1.432	7.495	10.359

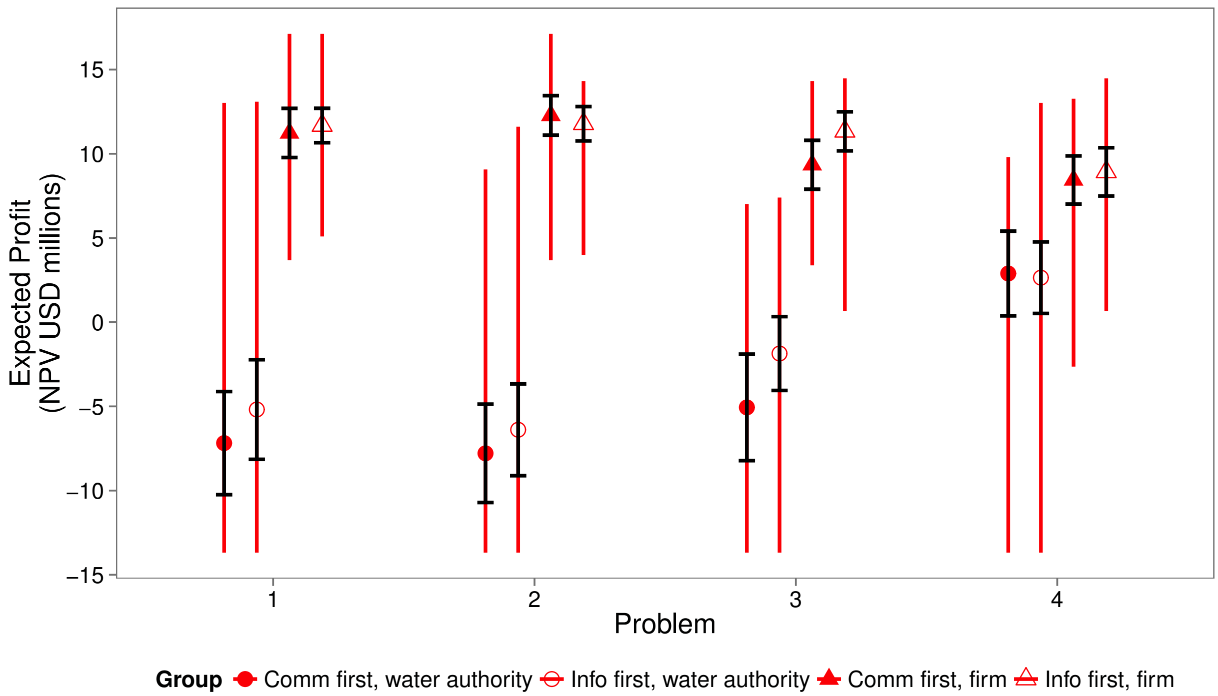

Figure D.4: Including a summary statistic for variance in terms of 95% confidence intervals, shown in black. This version of CIs assumes that the sub-samples in each of the sub-groups is independent. This applies the equation for CIs presented in Eq D.1.

Table D.2: Summary of calculations for Cousineau-Morey uncertainty bounds after adjusting for within-subject variation and correlations

Group	Problem	n	μ_{Profit}	sd	se	ci	CILB	CIUB
Comm first, Water Authority	1	26	-7.181	5.252	1.030	2.121	-9.302	-5.059
Comm first, Water Authority	2	26	-7.788	5.344	1.048	2.158	-9.947	-5.630
Comm first, Water Authority	3	26	-5.061	7.110	1.394	2.872	-7.932	-2.189
Comm first, Water Authority	4	26	2.892	6.244	1.225	2.522	0.370	5.414
Info first, Water Authority	1	30	-5.186	5.676	1.036	2.119	-7.305	-3.067
Info first, Water Authority	2	30	-6.389	5.477	1.000	2.045	-8.434	-4.344
Info first, Water Authority	3	30	-1.861	5.539	1.011	2.068	-3.929	0.207
Info first, Water Authority	4	30	2.644	6.157	1.124	2.299	0.345	4.943
Comm first,Firm	1	27	11.237	3.168	0.610	1.253	9.984	12.490
Comm first,Firm	2	27	12.281	2.335	0.449	0.924	11.357	13.204
Comm first,Firm	3	27	9.347	3.781	0.728	1.496	7.851	10.843
Comm first,Firm	4	26	8.447	2.380	0.467	0.961	7.486	9.408
Info first, Firm	1	29	11.680	2.792	0.518	1.062	10.618	12.742
Info first, Firm	2	29	11.784	2.726	0.506	1.037	10.747	12.821
Info first, Firm	3	29	11.334	2.415	0.448	0.918	10.416	12.253
Info first, Firm	4	29	8.927	2.887	0.536	1.098	7.829	10.025

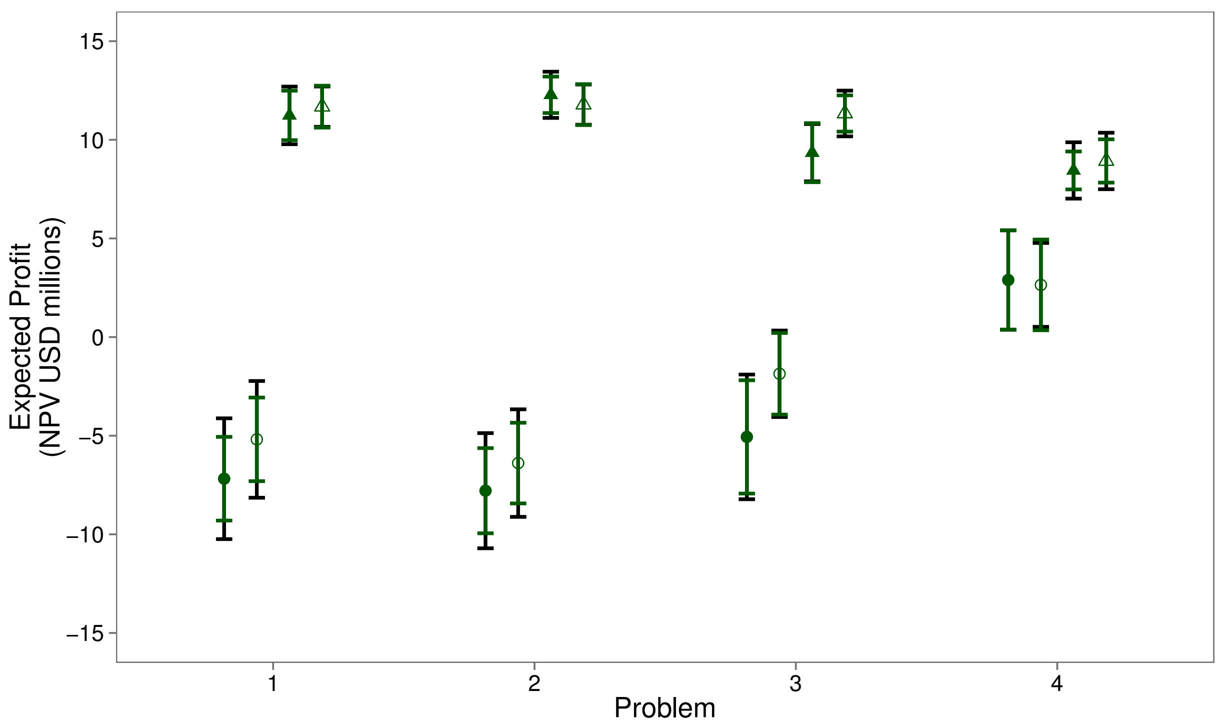

Figure D.5: Dropping the unrealistic assumption of independence, this chart overlays the Cousineau-Morey 95% CI which adjusts for within-subject variation. The width of the C-M CIs is slightly smaller than the independent CIs.

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Appendix E

Statistical tests for value outcomes analysis

Table E.1: t-tests of mean differences in profit outcomes for the Firm (F) in P1, P2

	estimate	statistic	p.value	parameter	conf.low	conf.high
Comm first	1.044	1.778	0.087	26	−0.163	2.250
Info first	0.104	0.170	0.866	28	−1.149	1.357

Table E.2: t-tests of mean differences in payment outcomes for the Water Authority (WA) in P1, P2

	estimate	statistic	p.value	parameter	conf.low	conf.high
Comm first	−0.177	−0.298	0.768	25	−1.401	1.047
Info first	−0.338	−0.781	0.441	29	−1.222	0.547

Table E.3: t-tests of mean differences in reliability outcomes for both F and WA in P1, P2

	estimate	statistic	p.value	parameter	conf.low	conf.high
F, Comm first	1.585	0.554	0.584	26	−4.296	7.465
WA, Comm first	0.504	0.385	0.703	25	−2.191	3.199
F, Info first	2.284	1.504	0.144	28	−0.827	5.396
WA, Info first	0.049	0.061	0.952	29	−1.592	1.689

Table E.4: t-tests of mean differences in profit outcomes for the Firm (F) in P2, P3

	estimate	statistic	p.value	parameter	conf.low	conf.high
Comm first	−2.933	−3.195	0.004	26	−4.820	−1.046
Info first	−0.450	−0.604	0.550	28	−1.976	1.075

Table E.5: t-tests of mean differences in payment outcomes for the Water Authority (WA) in P2, P3

	estimate	statistic	p.value	parameter	conf.low	conf.high
Comm first	2.050	3.340	0.003	25	0.786	3.314
Info first	0.221	0.334	0.740	29	−1.130	1.572

Table E.6: t-tests of mean differences in reliability outcomes for both F and WA in P2, P3

	estimate	statistic	p.value	parameter	conf.low	conf.high
F, Comm first	3.834	1.659	0.109	26	−0.915	8.583
WA, Comm first	2.374	1.766	0.090	25	−0.394	5.142
F, Info first	−1.449	−1.214	0.235	28	−3.894	0.996
WA, Info first	−1.282	−1.243	0.224	29	−3.393	0.828

Table E.7: t-tests of mean differences in profit outcomes for the Firm (F) in P3, P4

	estimate	statistic	p.value	parameter	conf.low	conf.high
Comm first	−0.739	−0.929	0.362	25	−2.376	0.899
Info first	−2.407	−4.260	0.0002	28	−3.564	−1.250

Table E.8: t-tests of mean differences in payment outcomes for the Water Authority (WA) in P3, P4

	estimate	statistic	p.value	parameter	conf.low	conf.high
Comm first	2.213	3.265	0.003	25	0.817	3.610
Info first	2.854	4.261	0.0002	29	1.484	4.224

Table E.9: t-tests of mean differences in reliability outcomes for both F and WA in P3, P4

	estimate	statistic	p.value	parameter	conf.low	conf.high
F, Comm first	1.687	1.110	0.278	25	−1.444	4.817
WA, Comm first	−1.214	−1.522	0.141	25	−2.857	0.429
F, Info first	−0.485	−0.534	0.598	28	−2.347	1.376
WA, Info first	1.769	1.776	0.086	29	−0.268	3.805

Appendix F

Behavioral archetype analysis: plots

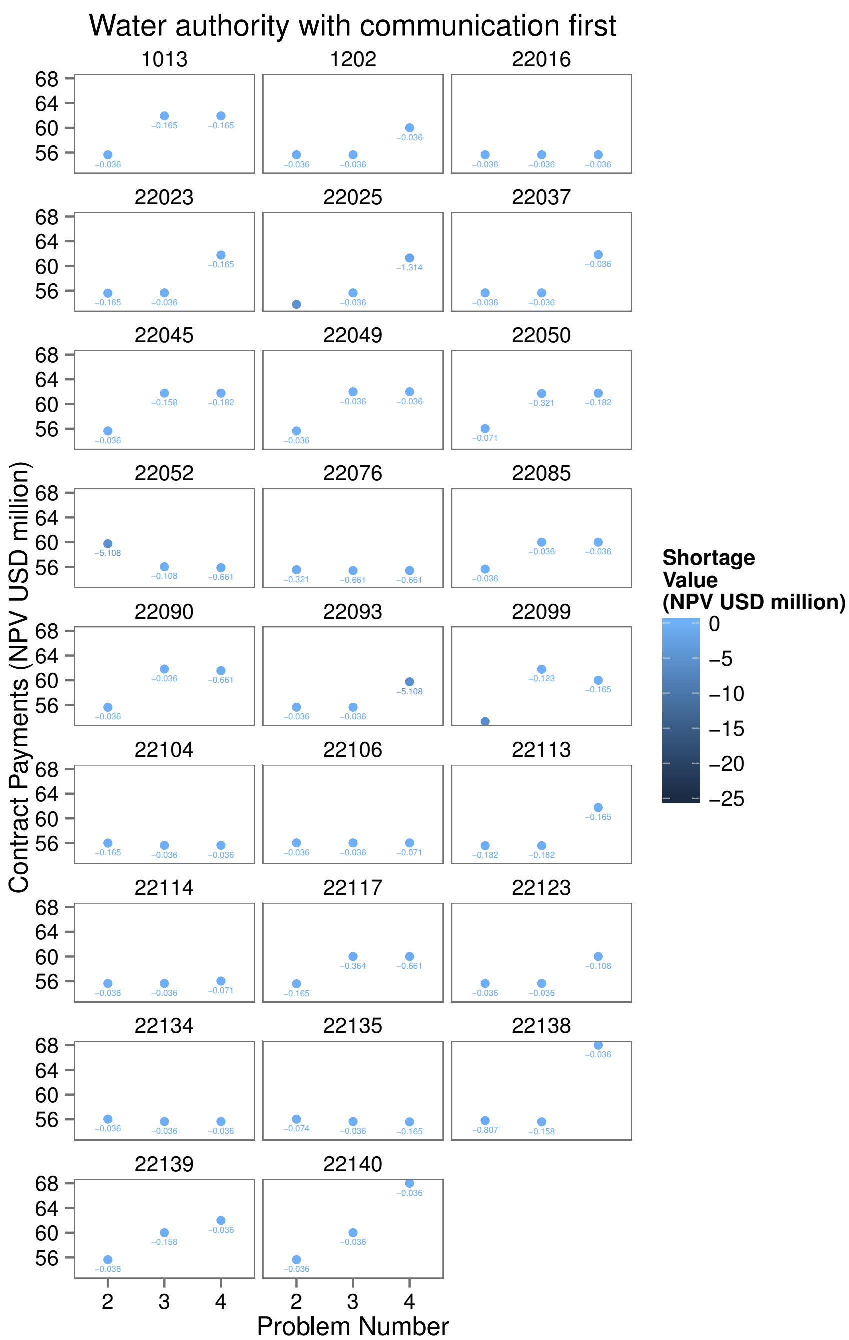

Figure F.1: Design submissions for Water Authority role players who were in the 'Communication first' treatment group

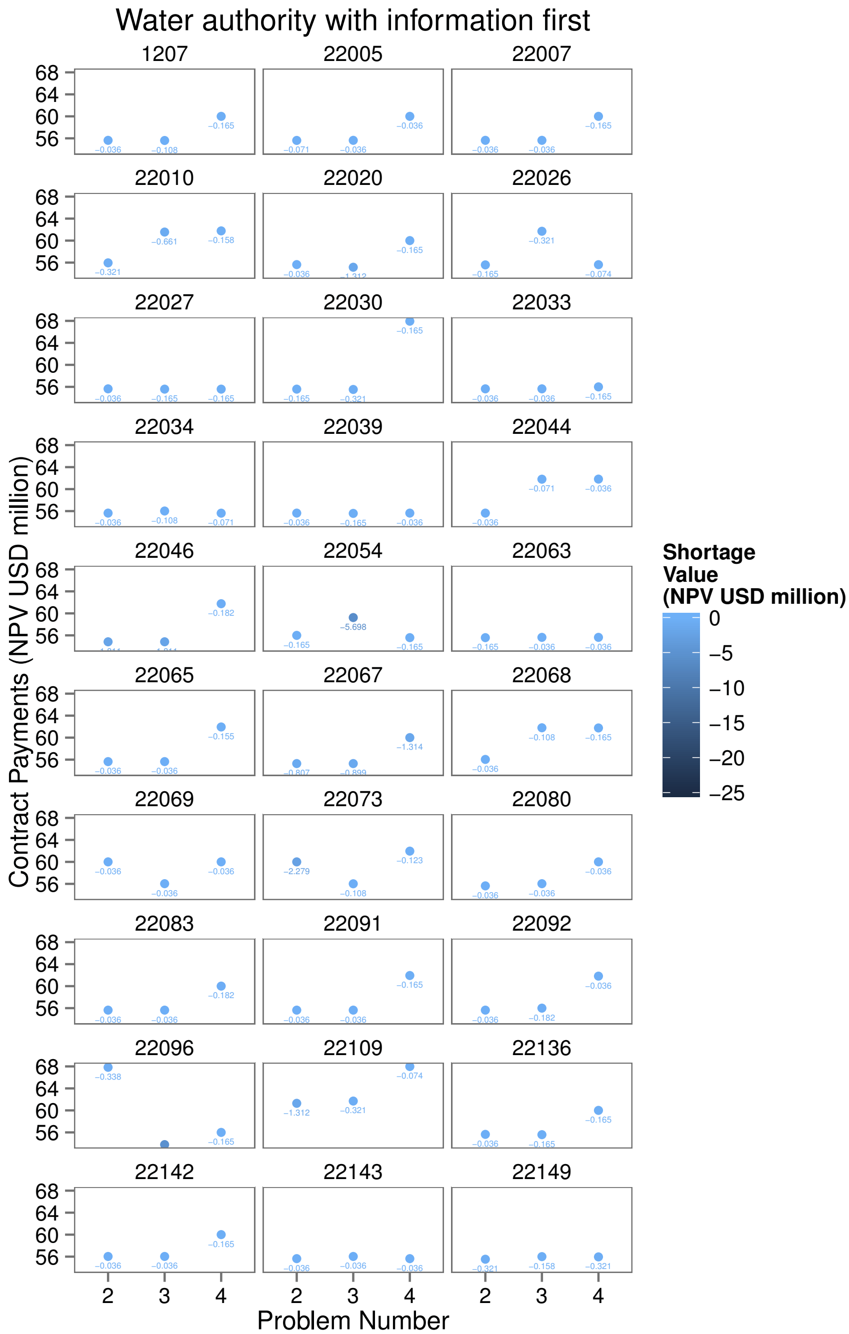

Figure F.2: Design submissions for Water Authority role players who were in the 'Information first' treatment group

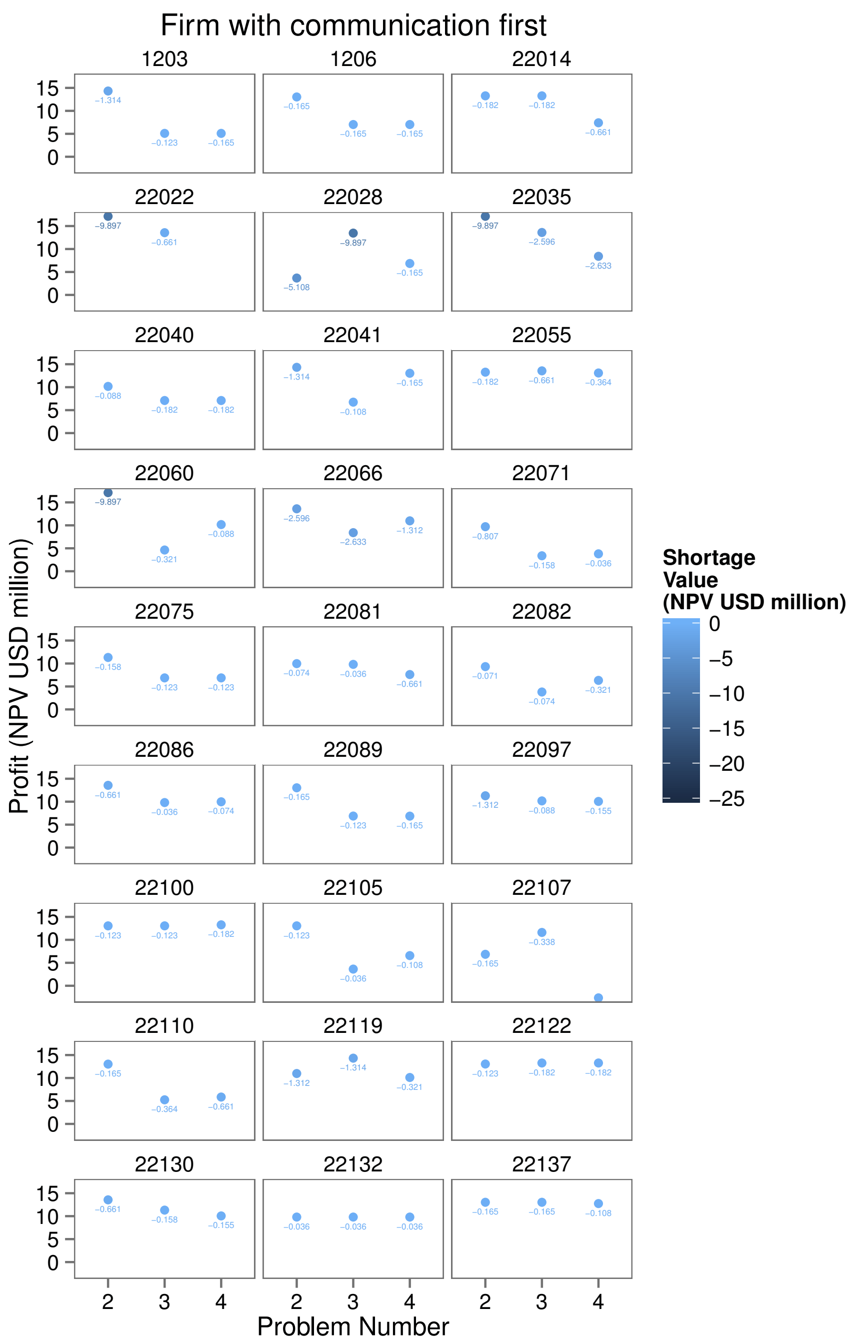

Figure F.3: Design submissions for Firm role players who were in the 'Communication first' treatment group

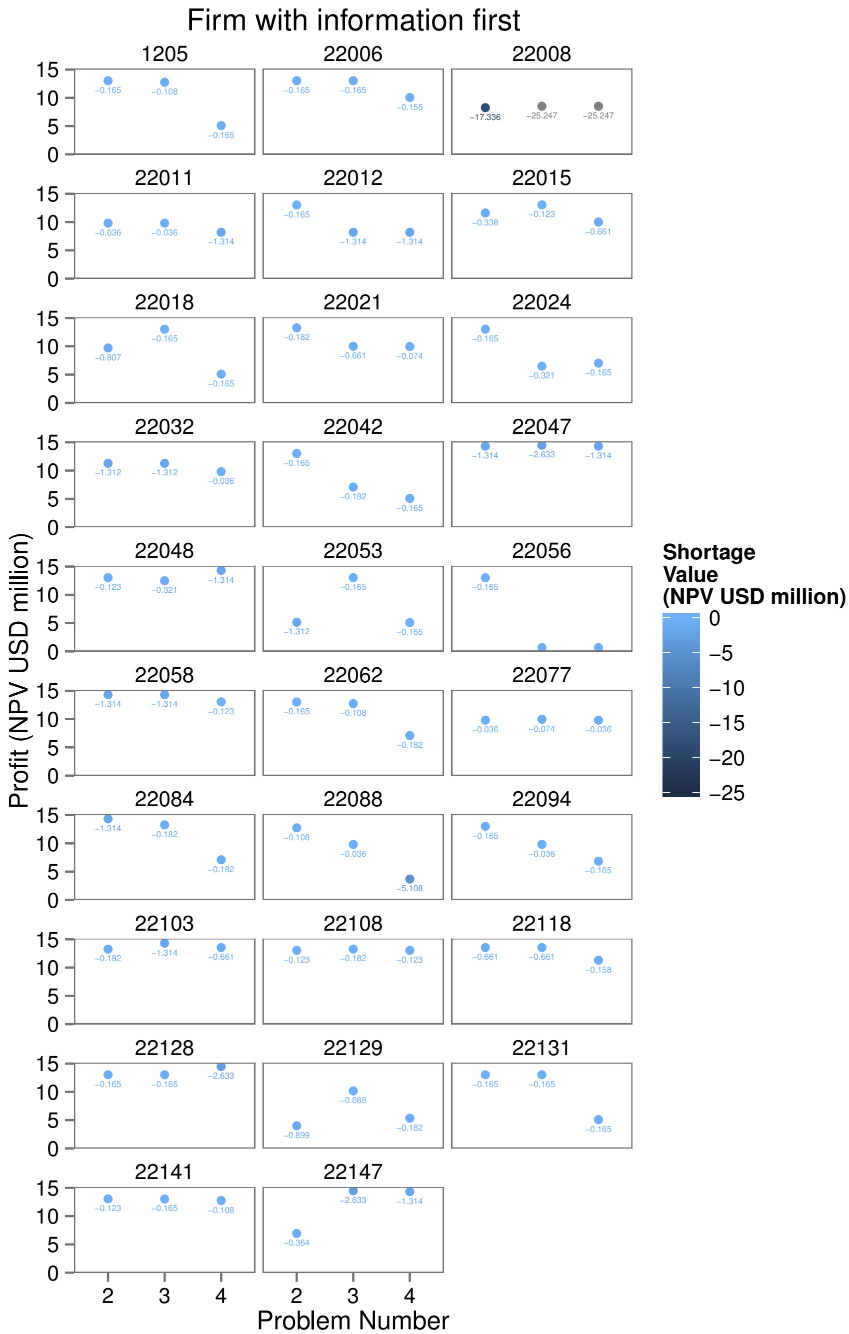

Figure F.4: Design submissions for Firm role players who were in the 'Information first' treatment group

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Appendix G

Scoring reliability analysis for behavioral archetypes

Interpreting archetypes from plots of design submissions is a subjective task. The primary coder's (me) scoring can reflect a bias, often unconscious, in matching patterns. The effect of any bias is a possibly erroneous report of what the data represents. The validity of the claims can come into question if the analysis does not sufficiently reflect the "truth" of the observed phenomenon. To account for the bias, and to mitigate interpretation errors, researchers making subjective interpretations can seek a second or third opinion through an inter-coder agreement exercise.

An inter-coder agreement exercise tests the reliability of subjective coding (Stemler, 2001). For the analysis to be *valid*, the data must be *reliable*. Artstein and Poesio (2008) state that data in subjective coding analysis are reliable if the coders can be shown to agree on the categories assigned to the items, i.e. the coded observational units. If different coders are consistent in how they match items to categories, then they can be assumed to have a similar understanding of the coding guidelines and what to look for in the data. We can then expect them to code data reliably (Krippendorff, 2004).

To test inter-coder agreement, I asked two other coders to classify observations into the three archetypes of *anchoring*, *aligning*, and *sensitive*. This gave a total of three coders, including myself, between whom we could compare archetype codes.

There are a number of techniques to assess the reliability of data from inter-coder agreement scores (Krippendorff, 2012). Percentage agreement A, the S coefficient which assumes a uniform underlying distribution (Bennett, Alpert, and Goldstein, 1954), Scott's coefficient π with the non-uniform, but single underlying distribution assumption (Scott, 1955), and Cohen's κ and its variants (Cohen et al., 1960; Cohen, 1968).

Of these, percentage agreement is the simplest form. Percentage agreement scores work well when there are dimensions with a small number of categories. Since there are only three emergent patterns in the design experiment, all along the single dimension of "archetypes", percentage agreement is an acceptable technique for measuring inter-coder reliability.

The specific form of percentage inter-coder agreement is as follows. Let a_i denote the item agreement value for all observations i in the set I of experimental pattern observations. Set the item agreement score:

$$a_i = \begin{cases} 1, & \text{if coders assign an item to same category} \\ 0, & \text{if coders assign an item to different categories} \end{cases}$$

Then the observed agreement A_o between two coders is the mean of the a_i item agreement scores:

$$A_o = \frac{1}{i} \sum a_i \tag{G.1}$$

where A_o can be expressed as a percentage.

The inter-coder reliability analysis first applied Eq (G.1) to coded observations between coders 1 and 2, and then coders 1 and 3. Both pairs of coders, (1 and 2) and (1 and 3) agreed on the pattern assignments for $A_o^{12} = A_o^{13}$ = 88% of the observations, showing a high degree of reliability between coders. Agreement was also calculated for all three coders simultaneously as a stricter measure of reliability. The agreement score decreased slightly to A_o^{123} = 86%, which is still highly reliable. Table G.1 summarizes the results of the reliability analysis. It shows the number of item agreements and disagreements [$a_i = 1; a_i = 0$] by participant role of the recorded observation. It also shows the total percentage agreement A_o for the pairs of coders and then the agreement for all three coders.

While the simple percentage agreement A_o is a good starting measure, it has some important flaws. It does not account for the fact that coders may agree on an assignment by chance. For a simple coding scheme of two categories and two coders, pure chance can result in 50% agreement. For three categories and two coders, the possibility of chance agreement drops but it is still high at a third of the total items. Further, simple percentage agreement also doesn't correct for the underlying distribution of the items among categories. When one category is much more common than the other, there will inherently be a higher percentage agreement for the more common agreement. These factors can bias reliability, and the other measures S, π, and κ were designed to correct for these flaws.

Chance correction for reliability requires us to calculate the expected agreement A_e due to chance, which takes a value [0, 1]. Then the difference $1 - A_e$ is the maximum agreement that can be obtained over and above pure chance. In general, the adjusted reliability statistic is given by the ratio (Artstein and Poesio, 2008):

$$\text{statistic} = \frac{A_o - A_e}{1 - A_e} \tag{G.2}$$

where the numerator $A_o - A_e$ is the observed agreement beyond chance, and the ratio describes how much possible agreement beyond chance was actually observed. The calculation of A_e in Eq (G.2) depends on the choice and assumptions of the test statistic. The calculations for S, π, κ are stated and applied below.

The raw classification scores for each coder's assignment to categories are helpful for exposition. These are summarized in Table G.2. Each archetype represent a category (shown on the left). The number of items assigned to a pattern are shown in the columns 2- 4, marked 'Coder ...'. The other columns represent sub-total and total assignments to these archetypes. These are used below in computing the values for the different reliability statistics:

- The S statistic assumes that all categories are equally likely (Bennett, Alpert, and Goldstein, 1954). For the case with a pair of coders $c = 2$, coding into $k = 3$ categories,

$$A_e^S = \sum_{k \in K} \frac{1}{k} \cdot \frac{1}{k} = k \cdot \left(\frac{1}{k}\right)^2 = \frac{1}{k} = \frac{1}{3} = 0.333$$

  When there are three coders,

$$A_e^S = \sum_{k \in K} \frac{1}{k} \cdot \frac{1}{k} \cdot \frac{1}{k} = k \cdot \left(\frac{1}{k}\right)^3 = \frac{1}{k^2} = \frac{1}{9} = 0.111$$

- The π statistic assumes that there is single underlying distribution of categories among the items (Scott, 1955). Since we do not know what this prior distribution is, we can get the best estimate of after the fact by using the observed proportion, $\hat{P}(k) = \frac{n_k}{c \cdot i}$, of items assigned to a category k by c coders where i is the number of items.

$$A_e^\pi = \sum_{k \in K} \hat{P}(k) \cdot \hat{P}(k) = \sum_{k \in K} \left(\frac{n_k}{c \cdot i}\right)^2 = \frac{1}{(ci)^2} \sum_{k \in K} n_k^2$$

  First, we calculate the A_e adjustment using coder pairs, i.e. $c = 2$. From Table G.2, $A_e^\pi = \frac{1}{4 \cdot 92^2} \cdot (43^2 + 83^2 + 58^2) = 0.357$ for the coder pair 1 and 2. Similarly, $A_e^\pi = \frac{1}{4 \cdot 92^2} \cdot (47^2 + 82^2 + 55^2) = 0.353$ for the coder pair 1 and 3.

  Then, in the case of all three coders taken simultaneously, $c = 3$ and $A_e^\pi = \frac{1}{9 \cdot 92^2} \cdot (66^2 + 121^2 + 89^2) = 0.353$. This version of the statistic is called the multi-*pi* statistic (Fleiss, 1971).

- The final statistic, Cohen's κ, also accounts for individual coder bias. It assumes that the prior distribution for each coder is different (Cohen et al., 1960). Thus the observed probability of assigning items to categories must be estimated separately for each coder. In the case of two coders:

$$A_e^\kappa = \sum_{k \in K} \hat{P}(k|c_1) \cdot \hat{P}(k|c_2) = \sum_{k \in K} \frac{n_{c_1 k}}{i} \cdot \frac{n_{c_2 k}}{i} = \frac{1}{i^2} \sum_{k \in K} n_{c_1 k} n_{c_2 k}$$

  Looking up values from Table G.2 for the coder pair 1 and 2, $A_e^\kappa = \frac{1}{92^2} \cdot (24 \cdot 19 + 44 \cdot 39 + 24 \cdot 34) = 0.353$. Similarly, for the pair 1 and 3, $A_e^\kappa = \frac{1}{92^2} \cdot (24 \cdot 23 + 44 \cdot 38 + 24 \cdot 31) = 0.351$

> Deriving the expected agreement for the multi-κ statistic for more than two coders is a more complicated proposition, as described in Davies and Fleiss (1982). Multi-κ was calculated using statistical software in this analysis.

We can see that the expected agreement in the case of both pairs of coders and a set of three coders depends on the choice of reliability statistic and ranges from 0.333 - 0.357. The inter-coder reliability assessment is updated using Eq (G.2). Table G.3 summarizes the values of expected agreement and the corresponding updated reliability statistics. Note that these values of A_e are specific to the case of three categories for the three archetypes identified here.

The reliability statistics presented in Table G.3 suggest that there was a high degree of agreement between multiple coders. The matching of observations to archetypes is therefore concluded to be reliable (0.78 - 0.85) based on this series of tests.

Table G.1: Inter-coder agreement results for reliability using simple percentage agreement

Role	Agree or Disagree? [$a_i = 1; a_i = 0$]		
	Coders 1 and 2	Coders 1 and 3	Coders 1, 2, and 3
Water Authority	42 ; 4	43 ; 3	42 ; 4
Engineering Firm	39 ; 7	38 ; 8	37 ; 9
Total	81 ; 11	81 ; 11	79 ; 13
Percentage Agreement, A_o	A_o^{12} = 88%	A_o^{13} = 88%	A_o^{123} = 86%

Table G.2: Raw classification scores for each coder

Canonical Pattern	Coder 1	Coder 2	Coder 3	Category Total$_{12}$	Category Total$_{13}$	Category Total$_{123}$
Anchoring	24	19	23	43	47	66
Aligning	44	39	38	83	82	121
Sensitive	24	34	31	58	55	89
Total Observations	92	92	92	184	184	276

Table G.3: Chance-corrected inter-coder agreement results for reliability

$$\text{Statistic} = \frac{A_o - A_e}{1 - A_e}$$

Expected Agreement	Coders 1 and 2	Coders 1 and 3	Coders 1, 2, and 3
A_e^S	0.333	0.333	0.111
A_e^π	0.357	0.353	0.353
A_e^κ	0.353	0.351	-

Statistic	Coders 1 and 2	Coders 1 and 3	Coders 1, 2, and 3
S	0.82	0.82	0.84
π	0.81	0.81	0.78
κ	0.81	0.82	0.85*

* calculated in software; the rest were calculated by hand using the derivations above

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Appendix H

Relating archetypes to negotiated agreement

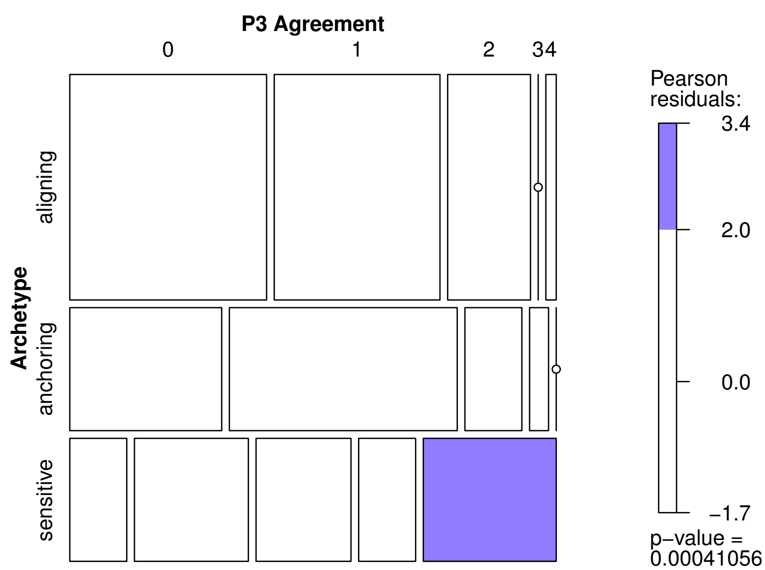

Figure H.1: Mosaic plot for agreement in Problem 3

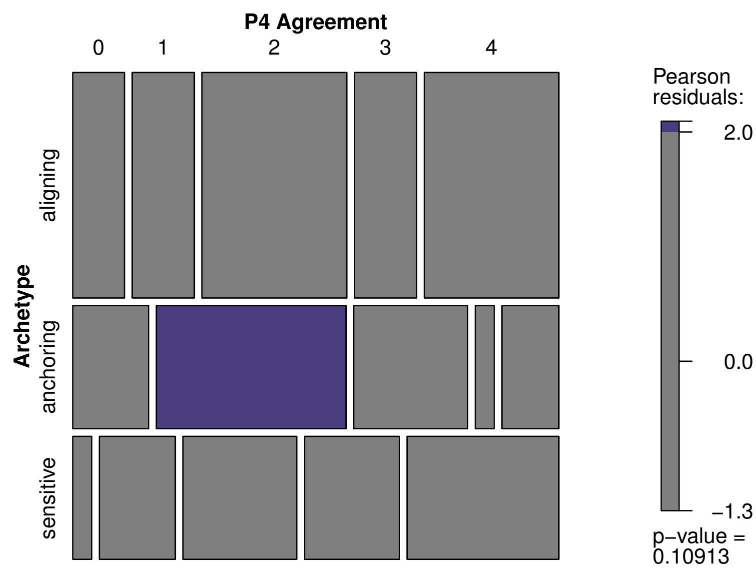

Figure H.2: Mosaic plot for agreement in Problem 4

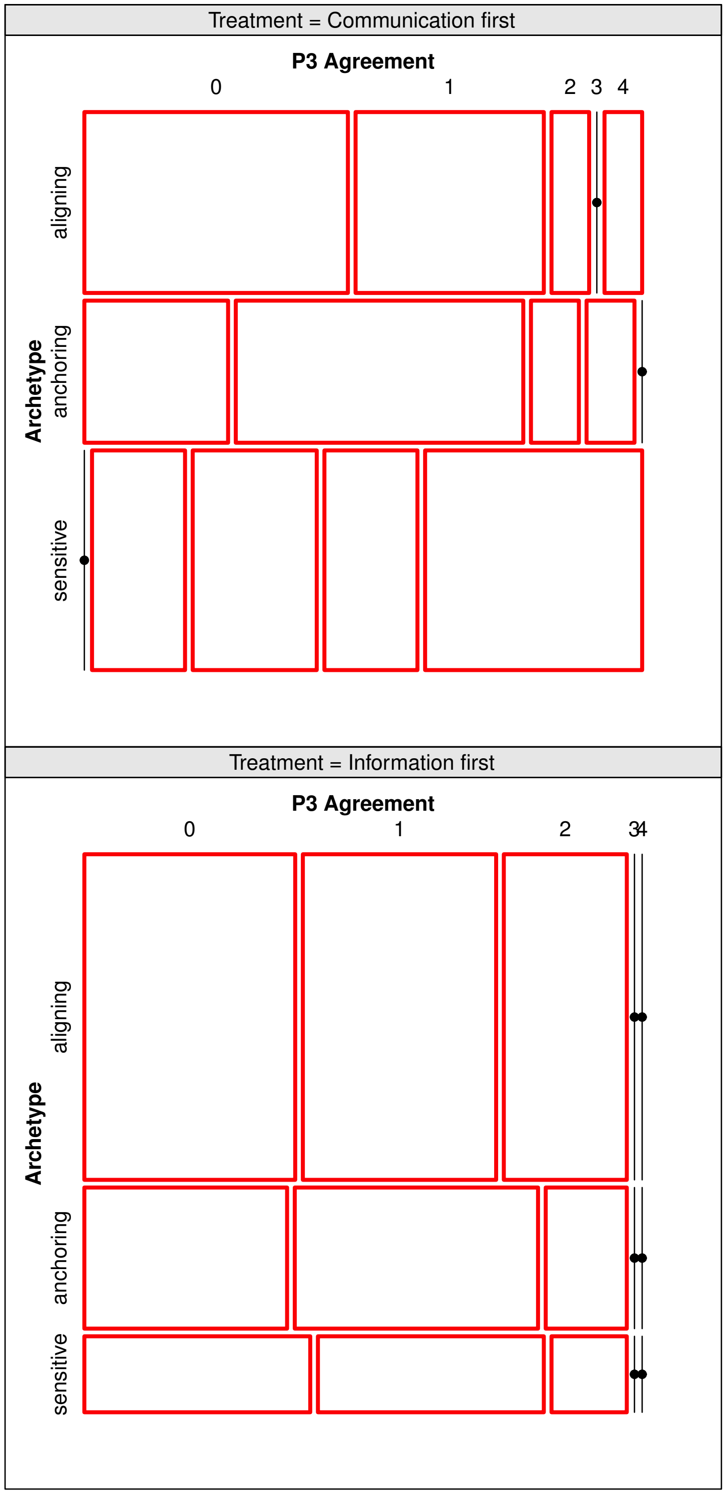

Figure H.3: Mosaic plot for agreement in Problem 3, conditioned by Treatment

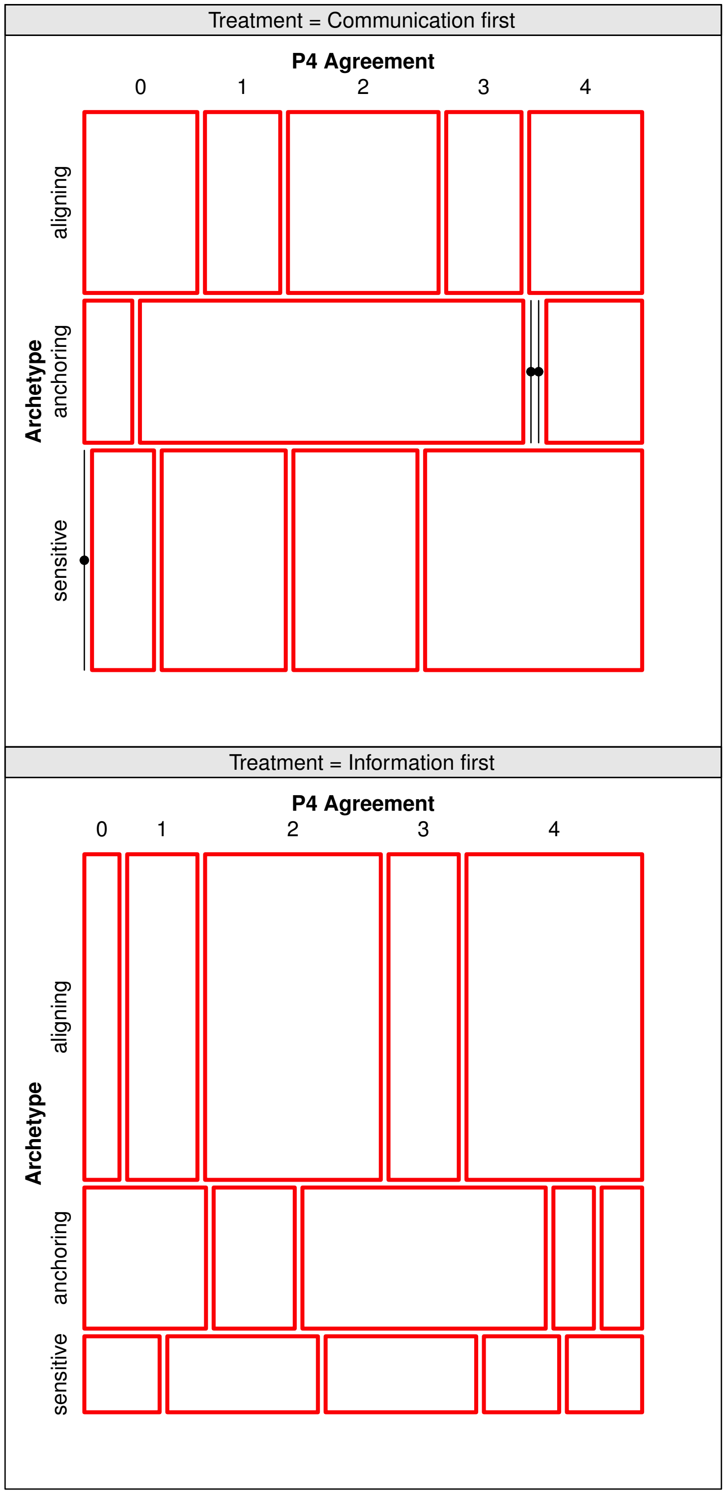

Figure H.4: Mosaic plot for agreement in Problem 4, conditioned by Treatment

Appendix I

Role Sheets for Design Exercise

ROLE SHEET for DesalDesign Exercise, version **CDCK-FV**

Your Role: **ENGINEERING FIRM**

As the ENGINEERING FIRM, you are the primary industry expert able to build and operate desalination plants to supply water. You are *very* sensitive to profits, and your shareholders have a strong interest in achieving a profit in Present Value (PV) terms of US$ 10 million. This is your profit level. However, they understand the price and demand risks in this industry and will consider profit levels as low as approximately US$ 5 million. In the contract with the Water Authority,

Your main objective is to: Increase the profit level to US$ 10 million, with a lower bound of approx. US$ 5 million

Remember that your income is based on the contract payments you receive from the authority. What you receive depends on the revenues to you as well as any subsidy the Authority pays you.

PV (Contract Payments) = PV (Firm Income)
= PV (Revenues + Subsidy)

Revenues to you depend on uncertain water demand in units of cubic meters/day (m^3 /d) and Water Price in dollars per cubic meter ($/$m^3$). Neither you nor the Authority has control over uncertain water demand.

The Minimum Income Guarantee (MIG) feature of the contract is like an insurance policy for you. If the revenues fall below this MIG threshold, the Authority will have to pay you a subsidy to bring your income back to the MIG level.

You can try to accomplish your main objective by finding a suitable combination of the contractual design inputs.

You are concerned that the lost social value of water shortages (US$ mill) will not only reduce your revenues, but also lower your reputation in this partnership as well as in future opportunities. Therefore,

Your supporting objective is to: Minimize the value of water shortages (US$ million)

You can try to accomplish this by finding a suitable combination of the technical design inputs.

To summarize, find the combination of both technical and contractual design inputs that you feel best accomplishes your objectives as stated here.

Figure I.1: A role sheet describing the Firm's role in the collaboration exercise.

ROLE SHEET for DesalDesign Exercise, version **CDCK-PV**

Your Role: **WATER AUTHORITY**

As the WATER AUTHORITY, you are the primary utility agency in charge of ensuring a reliable supply of water. You are *very* sensitive to water shortages, and have a strong preference that the lost social value of water shortages in Present Value (PV) terms is US$ 0 million, or very close to it. In the contract with the Engineering Firm,

Your main objective is to: Reduce the value of water shortages to near US$ 0 mill (zero)

You can try to accomplish this by finding a suitable combination of the technical design inputs.

This high level of reliability comes at a cost to society. The main trade-off you face is the lifetime contractual payments that must be made to the Firm, discounted over the life of the contract, i.e. in Present Value (PV) terms of US$ millions.

PV (Contract Payments) = PV (Firm Income)
= PV (Revenues + Subsidy)

Revenues to the Firm depend on uncertain water demand in units of cubic meters/day (m^3 /d) and Water Price in dollars per cubic meter ($/$m^3$). Neither you nor the Firm has control over uncertain water demand.

The Minimum Income Guarantee (MIG) feature of the contract is like an insurance policy for the Firm. If the revenues to the Firm fall below this MIG threshold, you will have to pay a subsidy to the firm to bring its income back to the MIG level.

You are concerned about overpaying for water. You want to maintain the contract payments in PV terms to approximately US$ 55 million. However, you recognize that some designs may cost more and are open to payments of up to approximately US$ 60 million. Thus,

Your supporting objective is to: Reduce contract payments to approx. US$ 55 million, with an upper bound of US$ 60 million

You can try to accomplish this by finding a suitable combination of the contractual design inputs.

To summarize, find the combination of both technical and contractual design inputs that you feel best accomplishes your objectives as stated here.

Figure I.2: A role sheet describing the Water Authority's role in the collaboration exercise.

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Appendix J

Pre-Experiment and Post-Experiment Surveys

DesalDesign Exercise Pre-Survey

Welcome to the DesalDesign Exercise!

This survey is to be taken AFTER THE TUTORIAL, and BEFORE you begin any problems. Please exit if you believe you are in the wrong survey.

Please read and select 'Proceed' to show you have noted this information.

I understand that:

- my Participant ID and role playing Dialog Name are for coding and record-keeping purposes only. Only the study adminstrator has access to them.

- My data and responses will be cleaned for identifying information and will be made anonymous before analysis

- Any published analyses will only cite this data in the aggregate across sub-groups or the full group of participants

- I can ask to look at my data, or have it withheld from analysis

- I can contact the study administrator with any questions or concerns at any time regarding my participation in the exercise.

I have read and understand this information.

DesalDesign Exercise Pre-Survey

General Questions

* 1. What is your Participant ID?

* 2. What version of the exercise were you assigned? This is the second half of your Dialog Name, the letters after the numbers...

- ◯ **CKCD-FV**
- ◯ **CKCD-PV**
- ◯ **CDCK-FV**
- ◯ **CDCK-PV**

* 3. Your task in this exercise is to design a:

[ ]

DesalDesign Exercise Pre-Survey

* 4. You are playing the role of the:

- ◯ **Water Authority, a public utility agency**
- ◯ **Engineering Firm, a private company**

* 5. Your main objective is to maximize profit

- ◯ Agree, that's my objective
- ◯ Disagree, that's my partner's objective

* 6. Your main objective is to minimize water shortages

- ◯ Agree, that's my objective
- ◯ Disagree, that's my partner's objective

* 7. Which of these design inputs do you think will affect water shortages? Select all that may apply.

- ☐ Technology
- ☐ Total Plant Capacity (cubic meters / day, m3/d)
- ☐ Number of units / modules
- ☐ Water Price (dollars /cubic meter, $/m3)
- ☐ Minimum Income Guarantee ($ millions)

* 8. Which of these design inputs do you think will affect the contractual payments the water authority pays? Select all that may apply.

- [ ] Technology
- [ ] Total Plant Capacity (cubic meters / day, m3/d)
- [ ] Number of units / modules
- [ ] Water Price (dollars /cubic meter, $/m3)
- [ ] Minimum Income Guarantee ($ millions)

* 9. Which of these design inputs do you think will affect the contractual income the firm receives? Select all that may apply.

- [ ] Technology
- [ ] Total Plant Capacity (cubic meters / day, m3/d)
- [ ] Number of units / modules
- [ ] Water Price (dollars /cubic meter, $/m3)
- [ ] Minimum Income Guarantee ($ millions)

* 10. The water authority's contract payments are equal to the firm's contract income

- ○ True
- ○ False

DesalDesign Exercise Pre-Survey

For each question, please select a postition on the scale that most accurately reflects your opinion. Some of the questions are similar to each other; this is to ensure the reliability of the questionnaire.

* 11. How motivated are you to participate in this exercise?

Not at all			Moderately			Extremely
○	○	○	○	○	○	○

* 12. How well do you think you understand the design problem?

Not at all			Moderately			Perfectly
○	○	○	○	○	○	○

3

* 13. Do you feel nervous about this exercise?

Not at all			Moderately nervous			Extremely nervous
○	○	○	○	○	○	○

* 14. How confident are you that you will accomplish your design objective?

Not at all			Moderately			Perfectly
○	○	○	○	○	○	○

DesalDesign Exercise Post-Survey

Thank you for participating!

This survey is the last step of the exercise.

Please read and select 'Proceed' to show you have noted this information.

I understand that:

- my Participant ID and role playing Dialog Name are for coding and record-keeping purposes only. Only the study adminstrator has access to them.

- My data and responses will be cleaned for identifying information and will be made anonymous before analysis

- Any published analyses will only cite this data in the aggregate across sub-groups or the full group of participants

- I can ask to look at my data, or have it withheld from analysis

- I can contact the study administrator with any questions or concerns at any time regarding my participation in the exercise.

I have read and understand this information.

DesalDesign Exercise Post-Survey

General Questions

* 1. What is your Participant ID?

* 2. What role / version of the exercise were you assigned? This is the second half of your Dialog Name, after the numbers...

◯ **CKCD-FV**

◯ **CKCD-PV**

◯ **CDCK-FV**

◯ **CDCK-PV**

DesalDesign Exercise Post-Survey

* 3. In a few words, describe your approach to solving the design problems in this exercise

* 4. In a few words, describe your approach to communicating with your collaboration partner in this exercise

DesalDesign Exercise Post-Survey

For each question, please select a postition on the scale that most accurately reflects your opinion. Some of the questions are similar to each other; this is to ensure the reliability of the questionnaire.

* 5. How much did your understanding of the design problem improve by the end of the exercise?

Not at all			Moderately			Very significantly
◯	◯	◯	◯	◯	◯	◯

* 6. Did seeing your collaborator's performance results confuse you?

I was not at all confused			Moderately			I was very confused
◯	◯	◯	◯	◯	◯	◯

* 7. How much did communicating with your collaborator improve your understanding?

Not at all			Moderately			Very significantly
◯	◯	◯	◯	◯	◯	◯

* 8. Did you feel pressured by the amount of time you had to to finish the problems?

No, no pressure			Moderate pressure			Yes, a lot of pressure
◯	◯	◯	◯	◯	◯	◯

* 9. Would you have liked more time to communicate with your collaboration partner?

No, I had plenty of time			Just the right amount of time			Yes, significantly more time
◯	◯	◯	◯	◯	◯	◯

DesalDesign Exercise Post-Survey

IMPORTANT: If you feel a question does not apply to the collaborative design process you just experienced or would prefer not to answer a particular question, please select 'Not Applicable (N/A)'.

* 10. How satisfied are you with your OWN final outcomes based on your performance objectives?

Not at all satisfied			Moderately			Perfectly	Not Applicable (N/A)
◯	◯	◯	◯	◯	◯	◯	◯

* 11. How satisfied are you with the balance between your performance outcome and your collaboration partner's outcome?

Not at all satisfied			Moderately			Perfectly	Not Applicable (N/A)
◯	◯	◯	◯	◯	◯	◯	◯

* 12. Did you feel like you conceded, gave too much or "lost" in the design collaboration?

Did not lose at all			Moderately			Lost a great deal	Not Applicable (N/A)
◯	◯	◯	◯	◯	◯	◯	◯

* 13. Do you think the terms of your final agreement meet the objective of "social value", defined as providing water reliably at a reasonable cost to society?

Not at all			Moderately			Perfectly	Not Applicable (N/A)
○	○	○	○	○	○	○	○

DesalDesign Exercise Post-Survey

IMPORTANT: If you feel a question does not apply to the collaborative design process you just experienced or would prefer not to answer a particular question, please select 'Not Applicable (N/A)'.

* 14. Did you "lose face" (i.e. lessen your sense of pride) in the design exercise?

Not at all			Moderately			A great deal	Not Applicable (N/A)
○	○	○	○	○	○	○	○

* 15. Did this exercise make you feel more or less competent as a**DESIGNER**?

Made me feel **LESS** competent			Did not make me feel more or less competent			Made me feel **MORE** competent	Not Applicable (N/A)
○	○	○	○	○	○	○	○

* 16. Did this exercise make you feel more or less competent as a**NEGOTIATOR**?

Made me feel **LESS** competent			Did not make me feel more or less competent			Made me feel **MORE** competent	Not Applicable (N/A)
○	○	○	○	○	○	○	○

* 17. Did you behave according to your own principles and values?

Not at all			Moderately			A great deal	Not Applicable (N/A)
○	○	○	○	○	○	○	○

* 18. Did this exercise positively or negatively impact your self-image or your impression of yourself?

Negatively impacted my self-image			It did not positively or negatively impact my self-image			Positively impacted my self image	Not Applicable (N/A)
◯	◯	◯	◯	◯	◯	◯	◯

DesalDesign Exercise Post-Survey

IMPORTANT: If you feel a question does not apply to the collaborative design process you just experienced or would prefer not to answer a particular question, please select 'Not Applicable (N/A)'.

* 19. Do you feel your partner listened to your arguments or concerns?

Not at all			Moderately			Perfectly	Not Applicable (N/A)
◯	◯	◯	◯	◯	◯	◯	◯

* 20. Would you describe the collaboration process as fair?

Not at all			Moderately			Perfectly	Not Applicable (N/A)
◯	◯	◯	◯	◯	◯	◯	◯

* 21. Did your partner consider your point of view, objectives, or needs?

Not at all			Moderately			Perfectly	Not Applicable (N/A)
◯	◯	◯	◯	◯	◯	◯	◯

* 22. How satisfied are you with the ease (or difficulty) of reaching an agreement ?

Not at all satisfied			Moderately			Perfectly satisfied	Not Applicable (N/A)
◯	◯	◯	◯	◯	◯	◯	◯

DesalDesign Exercise Post-Survey

IMPORTANT: If you feel a question does not apply to the collaborative design process you just

experienced or would prefer not to answer a particular question, please select 'Not Applicable (N/A)'.

* 23. What kind of "overall" impression did your collaboration partner make on you?

Extremely negative			Neither positive nor negative			Extremely positive	Not Applicable (N/A)
○	○	○	○	○	○	○	○

* 24. How satisfied are you with your partnership as a result of this collaboration?

Not at all			Moderately			Perfectly	Not Applicable (N/A)
○	○	○	○	○	○	○	○

* 25. Did the collaboration make you trust your partner?

Not at all			Moderately			Perfectly	Not Applicable (N/A)
○	○	○	○	○	○	○	○

* 26. Did the collaboration build a foundation for future partnerships with this partner?

Not at all			Moderately			Perfectly	Not Applicable (N/A)
○	○	○	○	○	○	○	○

DesalDesign Exercise Post-Survey

27. OPTIONAL: Any comments or feedback not captured in the questions above?

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Appendix K

Reliability Tests of the Mood (*M*) variable

Developing and using a scale for the construct of *Mood* requires some analysis of both its validity and reliability for the purpose of a specific measurement. Broadly, validity of a tool is a statement about whether it measures what it is supposed to measure. Reliability is about the consistency of the tool's measurements across time, situations, and evaluators (Juni, 2007). Four main types of validity are discussed in the context of the *mood* scale here:

- Face Validity: Does the proposed scale (*Mood*) and its items (*motivated*, *nervous*, *confident*) convey *prima facie* the notion of the construct being evaluated (Mostert, 2007)? Since these items are all specific descriptors related to the idea of *Mood*, I argue that the scale is valid on its face. However, this is just a cursory filter.

- Construct Validity: Do the scale and its items taken together reliably measure the intended construct (Sawilowsky, 2007; Lavrakas, 2008)? I demonstrate below that the *Mood* scale has a high-degree of reliability, i.e. internal consistency among its items. This observation taken together with face validity lends support to the construct validity of the scale.

- Content Validity: Does the scale appropriately represent the content of the domain it purports to measure Sireci, 2007? This type of validity is much less applicable for the *Mood* scale, because the survey questions intend to sample mood, a transient variable that changes continuously. Content validity would be more applicable if the questions intended to assess facts or knowledge of established phenomena.

- Criterion Validity: Does the scale closely relate to the items or components of other similar instruments for measuring the same construct (Eaves and Woods-Groves, 2007)? Since the survey was a one-shot measurement of the participants' mood, and was not conducted concurrently with the use of another instrument, this analysis cannot claim criterion validity.

Of the four types of validity, I show that the scale is valid for measuring the construct of mood for this type of experimental design because of relatively high degree of reliability. The specific type of reliability is the internal consistency of the item and total scale scores. Other types of reliability tests like inter-rater reliability and test-retest reliability are inapplicable because the survey instrument is administrator independent and then survey was administered only once. The other reliability tests become important if the scoring depends on the administrator(s) and if test is administered repeatedly at different times.

Among the tests of reliability or internal consistency for a measurement scale, Cronbach's α is the most well-know and widely used (Cronbach, 1951; Cronbach and Shavelson, 2004). Its advantages over other reliability tests are that it is mathematically equivalent to the split-half technique which measures correlations between all possible items and also requires fewer assumptions about the statistical properties of the individual items (Multon and Coleman, 2010). This method, also called the "raw" coefficient alpha, measures the proportion of variance in observation to the variation in true score of a variable and ranges between 0 and 1. The greater the value of α the more internally consistent the scale, and therefore more reliable. Some researchers suggest a lower threshold of 0.7, however the choice of a cut-off depends on the context of measurement.

Table K.1 shows the reliability test on *Mood* with its items as discussed above. In addition to the "raw" Cronbach's α based on inter-item covariance, two other adjustments are also reported. The standardized alpha accounts for inter-item correlation (Peterson and Kim, 2013;Falk and Savalei, 2011), whereas the Guttman's Labda 6 (G6) test accounts for the squared multiple correlation (smc) among items. The three measures suggest scale reliability higher than 0.5 with average inter-item correlation of approximately 0.3. The signal-to-noise ratio (S/N) indicates the quality of the test; the higher the S/N ratio the better. Finally, the table also shows the mean and standard deviation for the whole scale, the sum of the item scores.

After the preliminary scale reliability analysis, a check for reliability gains (Table K.2) shows the effect of dropping individual items one by one. This test shows that dropping the item *Nervous* actually improves the scale reliability significantly to around 0.65, with corresponding improvements in the S/N ratio, scale mean, and scale standard deviation. The reliability results for the final two-item *Mood* scale comprised of the items *motivated* and *confident* is shown in Table K.3 with item summary statistics in Table K.4. This *Mood* score is used in the rest of the analysis in this chapter.

Table K.1: Reliability test for *Mood* scale with items: *motivated, nervous*, & *confident*. Dropping one or more items could increase the scale reliability α

Cronbach's α	std-α	G6(smc)	average_r	S/N	ase	mean	sd
0.558	0.575	0.503	0.311	1.355	0.126	3.866	1.018

Table K.2: Reliability test gain with each item removed. Dropping the item *nervous* increases scale α

	Cronbach's α	std-α	G6(smc)	average_r	S/N	alpha se
Motivated	0.285	0.293	0.172	0.172	0.415	0.195
Nervous	0.644	0.647	0.478	0.478	1.829	0.163
Confident	0.438	0.442	0.284	0.284	0.792	0.186

Table K.3: Reliability test for final *Mood* scale with items: *motivated* & *confident*, resulting in a higher α of around 0.65

Cronbach's α	std-α	G6(smc)	average_r	S/N	ase	mean	sd
0.644	0.647	0.478	0.478	1.829	0.163	4.359	1.108

Table K.4: Item statistics for final *Mood* scale; a high item-whole scale correlation of 0.86

	n	r	r.cor	r.drop	mean	sd
Motivated	92	0.860	0.594	0.478	4.587	1.352
Confident	92	0.860	0.594	0.478	4.130	1.224

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Appendix L

Statistical Tests for SV Outcomes

Table L.1: Test of difference in means in SVI sub-scales by Gender

	Difference	Female	Male	statistic	p.value	parameter	conf.low	conf.high
Instrument	−0.130	4.778	4.908	−0.541	0.591	44.866	−0.614	0.354
Self	0.077	4.926	4.849	0.390	0.698	38.892	−0.320	0.473
Process	0.508	5.226	4.717	1.521	0.135	45.345	−0.165	1.182
Relationship	0.722*	5.281	4.560	2.237	0.031	40.329	0.070	1.374
Rapport	0.654*	5.253	4.600	2.123	0.040	42.091	0.032	1.275
Global	0.289	5.020	4.731	1.398	0.169	41.707	−0.128	0.707

Table L.2: Test of difference in means in SVI sub-scales by Role

	Difference	Firm	Water Authority	statistic	p.value	parameter	conf.low	conf.high
1	0.247	4.989	4.742	1.121	0.265	86.951	-0.191	0.686
2	0.019	4.880	4.861	0.114	0.910	86.944	-0.310	0.348
3	0.256	4.978	4.722	0.802	0.425	75.919	-0.380	0.892
4	0.305	4.902	4.598	1.042	0.301	81.459	-0.277	0.886
5	0.340	4.940	4.600	1.200	0.233	82.238	-0.224	0.904
6	0.240	4.924	4.684	1.329	0.187	89.827	-0.119	0.600

Table L.3: Test of difference in means in SVI sub-scales by Treatment

	Difference	Comm first	Info first	statistic	p.value	parameter	conf.low	conf.high
1	-0.207	4.756	4.963	-0.930	0.355	83.302	-0.649	0.235
2	0.118	4.938	4.820	0.728	0.469	87.543	-0.204	0.440
3	-0.355	4.664	5.020	-1.134	0.260	81.005	-0.978	0.268
4	0.291	4.926	4.635	0.976	0.332	73.573	-0.303	0.884
5	0.009	4.783	4.774	0.031	0.976	80.690	-0.560	0.577
6	0.021	4.821	4.800	0.115	0.909	87.148	-0.340	0.381