Chapter 7

The bigger picture

7.1 INTRODUCTION

The previous chapters discussed how to use models for the evaluation of risk in engineering projects. They covered the identification and classification of the sources of uncertainty, their prioritisation and quantification and the methods by which we can incorporate them into a modelling project. However, the execution of engineering projects entails additional sources of uncertainty and risk.

This chapter provides a wider perspective of risks that can impact important decisions in infrastructure projects. Uncertainty and risk in Water Resource Recovery Facilities (WRRF) design can be analysed not just through the lens of a modelling project, but also through the lens of the project phase, stakeholder involvement or project delivery method:

- Project phase (Section 7.2): The degrees of freedom change dramatically depending on the project phase. Especially at the early stages of a project many decisions need to be made that have a huge impact on the final outcome. Uncertainty associated with these early decisions remains an issue that to date has received little attention.
- Stakeholders (Section 7.3): When planning, designing or operating treatment plants, various stakeholders become involved in the decision-making process. The involvement of these stakeholders may occur at different times during project development. Each stakeholder may bring a unique perspective of project uncertainty and will bring his/her own attitude towards delineating between acceptable and unacceptable risks. This creates uncertainty in how these conflicting perspectives are eventually resolved.
- Project delivery method (Section 7.4): Project delivery methods can distribute risk in different ways amongst stakeholders. In a design−build−operate (DBO) situation, all risk is borne by a single entity. In contrast, one party may be given a contract to design the project, a second party the contract to build, and a third party a contract to operate. Decisions will be influenced by each party's natural incentive to maximise project benefits for itself and to minimise the project downsides.

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These three ways of framing and the way they are interrelated are examined in more detail in the following sections.

7.2 ENGINEERING PROJECT PHASES

7.2.1 Overview

Figure 7.1 captures how decisions taken at different project phases – from the regulatory to the construction phase – impact the final process design (configuration and sizing) of a plant. This impact is proportional to the amount of uncertainty involved in the decisions taken in each of these phases. The graph also shows that following start-up, during commissioning and operation, additional decisions need to be taken that impact efficiency in plant operations.

In the permit specification phase (regulation), the regulator must define the-end-of-pipe requirements, thus determining plant effluent concentration and load limits. The effluent permit is a major driver in plant sizing and technology selection.

In the planning stage, the owner typically specifies the service-life time, the location, and the design flow and loads. Together with the regulatory requirements, the decisions in the planning stage are of major influence for the final design.

Given these criteria, engineering consortia will compete at the level of preliminary design or detailed design. It is at this stage that the process engineers are responsible for finding an optimal process solution given the regulatory permit and the boundary conditions specified in the planning stage. The degrees of freedom associated with uncertainty are the choice of a technology, the process configuration, parameter values for process models, among other things.

During the detailed design phase these choices are further refined, down to the detailed construction and implementation plans.

The construction phase typically does not have a large influence on decisions affecting the process design of the plant. During start-up and commissioning, the plant may not work as intended (e.g., non-ideal mixing or flow splitting), thus again increasing the degrees of freedom. Decisions need to be taken on how to adjust operations (e.g., operational set-points) to meet the intended plant performance.

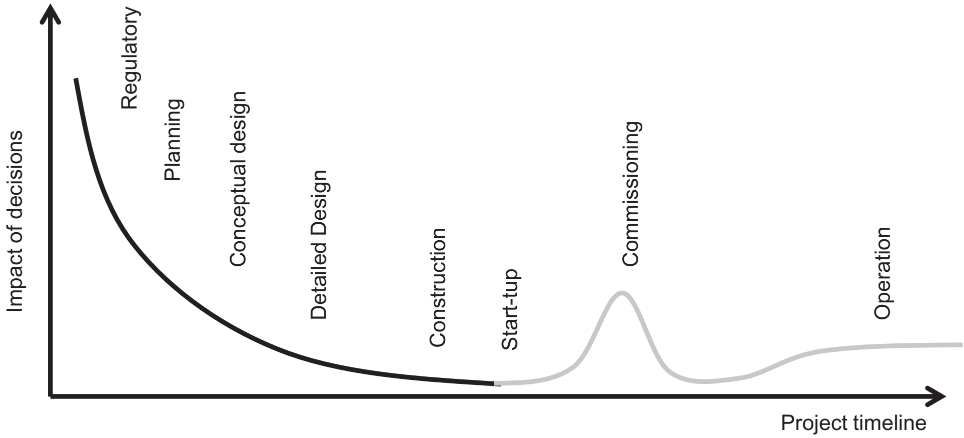

Figure 7.1 Impacts of decisions on plant process design are dependent on the project phase. Black line: decisions occurring from conception to start-up. Grey line: decisions occurring following start-up to continuous operation.

Table 7.1 Typical engineering project phases.

Project Phase	Definition
Regulatory phase	Defining treatment plant permits based on water quality considerations driven by local, regional and national legislation.
Planning	Developing the overall criteria for a facility, such as location, flows, loads, effluent quality, biosolids disposal, resource recovery and project time horizon. May include conceptual level unit process configuration. Conceptual level capital and operating costs are normally developed.
Preliminary design	Developing the overall concepts for a facility which includes control philosophy, process flow diagram, unit process sizing, and development of approach for support disciplines such as electrical, mechanical, structural, odour control, and site. Often considered approximately 10% of the total design effort.
Detailed design and construction	Producing the final design documents for all aspects of the facility, followed by the construction of the facility/improvements. Detailed design is sometimes split up into multiple phases, such as schematic design (30% of the total design effort), design development (60%), and construction documents (100% of the total design effort). Normally also includes start-up and troubleshooting of the new facilities.
Operations	The new facilities are operated by the permanent plant operations and maintenance staff to meet the regulatory requirements imposed on the facility

In the operations phase of a project, the risks are qualitatively different in that the owner is interested in minimising both the operating cost and as well as the risk of effluent non-compliance at the same time. The WRRF becomes an adaptive system and continuous changes to the initial design will take place during the infrastructure's lifetime. Table 7.1 includes more details on the tasks included during each project phase.

The degrees of freedom are the decision variables of each project phase. By making design decisions in the different project phases, the degrees of freedom are reduced throughout the project (Figure 7.2). If, in a

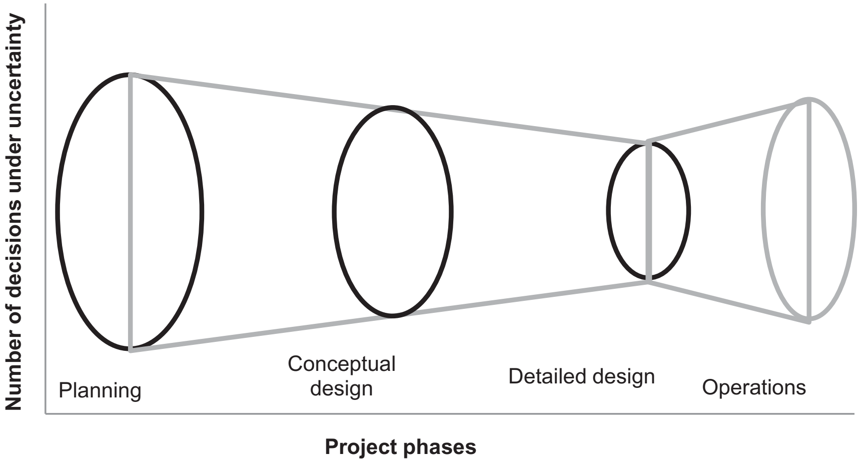

Figure 7.2 The number of decisions under uncertainty are reduced as the project progresses and increase again following plant start-up.

specific phase, a decision is made, that degree of freedom is eliminated and is considered as given in the subsequent project phases. The uncertainty associated with that degree of freedom is not always reduced or eliminated but is no longer considered. For example, design flows and loads are typically decided at the end of the planning phase. In the detailed design phase, the design flows and loads are typically assumed as given, even though uncertainty may still exist regarding their actual values. Table 7.2 includes examples of the typical degrees of freedom and the project phase where they are fixed.

Table 7.2 Typical degrees of freedom and phase where they are fixed (P = planning, PD = preliminary design, DD = detailed design, O = operation).

Phase/Degree of Freedom/Decision Variable	Project Phase where Degrees of Freedom are Fixed	Project Phase where Uncertainty is Evaluated
Plant location	P, PD	
Load and flows	P	PD
Temperature profiles		P, PD
Output requirements	P	PD
Definition of desired reliability/allowable risk	P, PD, DD	PD, DD, O
Technology pre-selection	PD	PD
Budget estimation	P	PD, DD
Technology selection	PD	
Process unit dimensions (preliminary)	PD	DD
Aeration capacity	PD	DD
Operational targets	PD, DD, O	
Chemical selection and dosing	PD, DD	DD, O
Number of reactors	PD	DD
Process unit dimensions (as builds)	PD	DD
Number and capacities of pumps	PD	DD
Number and capacities of blowers	PD	DD
Aeration system, number of diffusers	PD	DD
Redundancies	PD	DD
Mechanical equipment and redundancy	DD	
Electrical equipment and redundancy (UPS)	DD	
Control system and instrumentation	PD	DD
Operation of process equipment	PD	O
Set-points of automatic control loops	PD, DD	O
Software	PD, DD	O

7.2.2 Regulatory phase

Effluent criteria, which are key drivers for both the design and operation of treatment plants, are established by regulators. These criteria are either technology-driven or water-quality driven (e.g., Lijklema *et al.*, 1993). The criteria typically target the minimisation of acute toxicity, chronic toxicity or nutrient loading. Using water quality modelling and dilution calculations, site-specific WRRF permits are obtained.

Deriving these permits involves decisions which are subject to (sometimes significant) uncertainty. Various complex decisions are required in determining appropriate permit requirements for the WRRF that will protect the beneficial uses designated for the receiving water body. Normally, the final permits are a combination of effluent concentrations and load limits, either averaged over variable time limits or using statistical approaches such as 95th percentiles and medians. Although the decision processes of regulators are not the central focus of this STR, it is important to acknowledge that safety considerations take place when developing permits. In some cases, it is impossible to reach water quality objectives. In these cases, technology-based effluent limits are set.

Being responsible for the effluent discharge limits, the regulator assumes the risk that the effluent limits will maintain or improve the quality of the receiving water body. The assumption in this case (and by extension the risk), is that the information upon which the limits are based on is correct.

7.2.3 Planning phase

In the initial planning phase, the owner (typically with the assistance of a consulting engineer) makes choices that will heavily determine the final design. These choices need to deal with uncertainty in future loading, design life, costs and expected performance.

During the planning effort, the uncertainty considered by the designer/engineer and the owner is primarily associated with the development of flow and loading projections for a given facility, as well as the future effluent requirements. Uncertainties in flow projections are due to changes in population, rainfall, and changes in inflow/infiltration in the collection system. Uncertainties associated with loading projections are linked to changes in industry and population behaviour. Water conservation programmes for example, can impact hydraulic loading projections due to flow reductions to the wastewater treatment plants.

Moreover, uncertainty may be associated with the future impact on receiving water quality or ecology; often, safety factors are (implicitly) introduced here. The degree of treatment required is also subject to change over the life cycle of a project, and various scenarios must be considered during the planning process.

The sources of uncertainty of most importance to the owner are budget availability, changes in city/county/state design standards, and environmental requirements related to current and future regulations.

During this stage, both owners and designer/engineers need to review and understand uncertainties to ensure that client goals and technical requirements have been met. Typically, this is done by evaluating a range of possible scenarios and developing a path forward that addresses the needs of the stakeholders.

At the end of the planning phase, the degrees of freedom are reduced due to the decisions made and as a result several sources of uncertainty will not be considered in the subsequent project phases.

7.2.4 Preliminary (conceptual) design

In the preliminary design stage, the process engineer proposes a technology, the layout and sizing of the plant, as well as design effluent target levels. Design guidelines, simulators and costing tools are applied by the engineer to find the best solution, given the requirements and constraints set during the planning phase.

The choice of technology will depend on the criteria, the estimated costs and the engineer's familiarity and confidence in the technology. In the case of bioreactor selection, a first decision could be whether to use conventional suspended activated sludge treatment, a membrane or a biofilm system. In the next step, a basic process configuration is decided upon. This includes such decisions as the use of step-feed, the number of treatment lines, the number of bioreactors and their basic geometry.

The sources of uncertainty during preliminary design are related to the assumptions needed to develop the conceptual approach and hydraulic profile. The engineer typically has to make assumptions about the chemical/physical properties of the wastewater and its effects on unit process performance. Examples include the influent profiles for wastewater flows and loads.

Tansel (1999) states that uncertainties are introduced into the design process as a result of gaps between available and needed information at different points of the design process. This often leads to plants that are 30–50% overdesigned based on municipal codes and, after safety factors are used by designer/engineers, are overdesigned by 100% or more (Russell, 2006).

Other sources of uncertainty for the designer/engineer are associated with the veracity of the existing as-built information (for upgrade projects), topographical mapping, and geotechnical report.

The goals of this phase are typically technology selection, plant dimensioning of bioreactors, clarifiers, and other unit processes as well as the evaluation of aeration capacity, and the determination of all major control loops. In addition, the associated instrumentation and chemicals to be used are selected.

7.2.5 Detailed design, construction, and start-up

The detailed design stage deals with issues related to equipment redundancy and the selection of mechanical and electrical equipment in view of robust and safe operations. Regarding uncertainty and risk, it is in this step that reliability engineering gains importance.

Where the goal of preliminary design is to refine the design criteria and concepts initially established in the scope of work, the purpose of detailed design is to produce the final contract drawings including the plans, specifications and any other supporting documents. The number of uncertainties which have not been addressed by the designer/engineer is reduced at this design stage with the goal of managing any remaining uncertainties during construction.

The goal of the detailed design phase is to develop the conceptual design to the level of detail required for plant construction. Fixed degrees of freedom at this stage are final reactor and other unit dimensions, volumes, required flows, aeration capacities, chemical dosage type and amounts.

During the last decade, a shift has occurred, from identifying the main source of uncertainty as the kinetic parameters, to influent variability and dynamics and proper model structure of transport physics, such as mixing, aeration and sedimentation as well as chemical processes like precipitation. Modelling scenarios focus on better aeration distribution modelling, improved clarifier modelling with computational fluid dynamics (CFD) and controller models (Nopens *et al.*, 2015; Rehman *et al.*, 2017; Sin *et al.*, 2008).

The main uncertainties that are dealt with in the detailed design phase relate to process reliability as a result of equipment reliability and redundancy.

The determination of the number, sizing and configuration of equipment is made in view of reliable plant operations. At this stage, robustness and redundancy are considered. Precautions are taken to provide adequate treatment under malfunction as well as maintenance scenarios. Malfunction scenarios include failure of equipment, such as pumps, valves, aeration equipment. A typical maintenance scenario is a tank being out of service due to cleaning or repair.

Blower configuration and tank geometry, inlet and outlet structures are specified to guarantee optimal transport and mass transfer. CFD, introduced above, is a methodology that can assist the engineer with this.

Also, the design of robust Instrumentation/Control and Automation (ICA) equipment is considered at this stage. Methods include failure detection and the use of soft sensors.

Although construction itself includes many risks, they are not strongly related to the final plant configuration. However, during start-up, new degrees of freedom may be introduced. It is here where some of the assumptions made in the design are tested and some decisions may need to be revised: for example, sludge settleability, inhibition of organisms, obtaining the required population of microorganisms in the bioreactors, non-ideal mixing or flow splitting, among others.

7.2.6 Operations

After the commissioning phase, a treatment plant is not typically running at the design load but will be initially under-loaded. From this point onwards, the plant becomes an adaptive system (Dominguez & Gujer, 2006; Neumann *et al.*, 2015). As part of a robust design, plant operating strategies will be preliminarily defined by the design engineer. Operations staff then determine how best to run the facility within the designed constraints. For example, a facility might be designed to operate as a plug flow system under normal conditions but switched to step feed for wet weather conditions. Daily decisions are made on how much sludge to waste, how much chemicals to dose, how to time digester supernatant return, and so on. The daily operation includes the management of problems such as bulking and foaming, toxic inflows and equipment failure. A typical longer-term decision the operator needs to take is how close to the permit to run the plant. This will typically depend on the penalty scheme in place related to permit compliance (e.g., incrementally increasing taxation, binary penalty (pass/fail) or penitentiary sentence). Incentives such as maintaining prestige may also be present. Figure 7.3 gives an

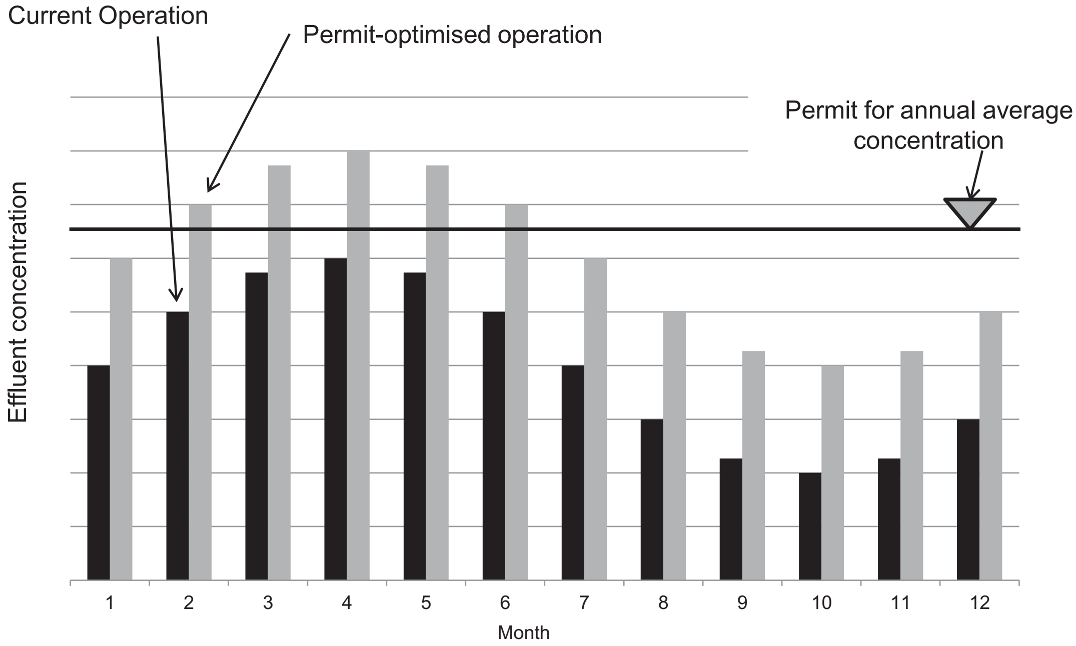

Figure 7.3 To safeguard against violating the annual effluent permit the plant is operated so that (black bars) the plant effluent concentration is permanently (e.g., for the maximum month) below the legal annual permit (bold horizontal line). The grey bars indicate how it may be possible to operate the plant, and still meet the annual permit.

example in which an operator runs the plant at a high margin of safety in the presence of a yearly average concentration limit. To safeguard against violating the annual effluent permit, the operator aims (black bars) to maintain the plant effluent concentration below the legal yearly permit in every month. In this way, the operator eliminates the risk of not complying. The grey bars indicate how it may be possible to run the plant, and still meet the yearly limit. However, this strategy implies that the operator could predict the loads and plant performance for the coming months with a small margin of error.

A feasible strategy will lie between the two extremes. It is one objective of the Task Group to highlight the importance of considering how the incentives of different stakeholders may lead to a risk-taking or risk-averse strategy.

Table 7.3 summarises the typical project phases, the uncertainties associated with each phase, the decisions that need to be taken under uncertainty, the expected deliverables of each project phase and examples of how models can be used to assist in uncertainty evaluations.

7.3 STAKEHOLDERS

7.3.1 Overview

When planning, designing or operating treatment plants, various stakeholders make decisions at different points in time. Uncertainty is associated with the degrees of freedom available when making those decisions. This is a function of how far project development has progressed (see Section 7.2). As the project moves forward, certain decisions either become irreversible (like the regulator has made the decision on permit level) or they can only be reversed at tremendous cost. The associated uncertainties can be removed from the analysis.

Project decisions vary with each stakeholder. The regulator needs to decide on the plant's permit. The planner needs to specify a design horizon and an associated design load. The design engineer needs to make assumptions on the current and future wastewater composition; he needs to choose an appropriate configuration as well as a process technology and values for the associated parameters. The operator needs to decide on how close to the permit to run the plant. Finally, the owner needs to decide on an upgrading and investment strategy. Depending on the contract type, the stakeholder sequence may differ.

7.3.2 Regulators

Translating water quality objectives into WRRF permits is associated with considerable uncertainty. It is not uncommon for safety factors to be included at this stage of the process. Often some form of pollution allocation takes place when the WRRFs in the same watershed need to comply with different permits. Exposing the rationale of these regulatory decisions may reveal alternative solutions for water infrastructure planning at the watershed level (e.g., set bubble permits where a single permit is set that covers multiple plants within a watershed).

7.3.3 Utilities – owners and operators

Utilities' decisions that pertain to uncertainty can range from the normal decision making that is a part of everyday operations to strategic management choices such as bid selection or finding an optimal investment strategy. The risks and benefits from these decisions accrue at the level of individuals. For example, if the plant operator lowers dissolved oxygen in the plant to reduce energy costs, she may not be acknowledged for the associated benefits even though she has increased her highly visible risk of not meeting effluent limits. Clarifying how incentives and penalty schemes affect individuals and their decisions is therefore a basis for modifying behaviour.

Table 7.3 Typical project phases, associated uncertainties and examples of how models can be used to assist in uncertainty evaluations.

Project Phase	Risk/Uncertainties	Decisions	Deliverables	Model Implementation Examples	
				Model Use	**Key Sources of Uncertainty**
Regulatory	Information upon which the limits are based on is correct	Permit limits	Permit limits	Simulate receiving water body quality	Flows and loads Measured data
Planning	**Designer:** Flow and load projections Future effluent requirements **Owner:** Budget availability Changes in design standards Environmental requirements related to current and future regulations	Future wastewater infrastructure Plant location Technology selection Wastewater flows/loads during dry/wet weather Performance requirements (extent of treatment)	Capital improvement plan Specifications Location selection Budget planning	Future scenario evaluation Technology investigation Checking if future output requirements are achievable	Flows and loads Boundary conditions (i.e., temperature profiles)
Preliminary design	**Designer:** Wastewater chemical/physical properties Influent flows/loads/characterisation Variability in influent flows / loads Data quality Veracity of the existing as-built information (for upgrade projects) Topographical mapping Geotechnical report	Design inputs Safety factors Process design parameters Selection of effluent design criteria Selection of design values for unit processes and mechanical equipment	Technology selection Process configuration Sizing Layout Capital costs Operational costs	Plant dimensioning Performance evaluation System selection System optimisation Control system design Selection of sensors, actuators and locations	Flows and loads Model structure Model parameters Influent fractionation Mass transfer model Kinetic Stoichiometric Actual (imperfect) flow distribution
Detailed design, construction, start-up and commissioning	Project management Low bid environment and poorly written specifications Lack of flexibility in design features Errors and omissions in contract documents Cost estimating errors by designer/engineer Equipment reliability/redundancy Process reliability from equipment reliability and redundancy	Schedule Selection of mechanical and electrical equipment Quality control of documents and plant systems installed Design change orders during construction Manual control handles Automatic control loops Fall-back procedures	Final contract drawings Plans, specifications and other supporting documents Design of instrumentation/control and automation (ICA)	Impacts of tanks out of service Impacts of equipment malfunction CFD modelling	Aeration system design Required equipment redundancy to achieve requested reliability CFD models to design flow patterns and proper mixing
Operation	**Designer**: Proper implementation of any control systems **Owner:** Compliance Financial risk of power/chemical use, mechanical failures and maintenance	Operational decisions	Operational risk management action plans	Process optimisation Controller settings Limits of performance Debottlenecking Operational strategies Performance benchmarking Post project audits Impact of failures on effluent quality Redundancy evaluations	Equipment failures Unforeseen weather Toxic spills Pandemics

7.3.4 Engineers

Inherent variability in the inputs to a WRRF, along with uncertainty in the value of parameters critical to design, complicates the engineer's effort to design a system that will produce an effluent of acceptable quality at all times. The incentive to minimise the probability of a performance failure creates incentives for oversizing the system. WRRFs will always be subjected to unanticipated events that are difficult to design for.

In-depth knowledge about uncertainty and variability and how to successfully address them can give an engineering company a competitive advantage and help owners better understand the proposed designs. As the degrees of freedom increase when moving from guidelines to mechanistic model-based design, addressing the uncertainties and the associated risks becomes more important for engineers.

7.3.5 Public

A common assumption is that communicating the risk involved in engineering projects will reduce public trust. However, a lack of systematic research makes it difficult to evaluate such claims. Van der Bles *et al.* (2020) found that transparency on issues of uncertainty does not harm the public's trust in the facts or in the source. On the contrary, people 'can handle the truth' about the level of certainty or uncertainty in scientific facts and knowledge. Based on their results, the authors recommend that the communication of uncertainty in the media is best conveyed through numerical ranges with a central point estimate. This format, in particular, did not seem to significantly influence (i.e., reduce) perceived trust and reliability in either the number or the source of uncertainty. In addition, they draw attention to the fact that using the word 'estimate' or increasing the magnitude of the confidence interval did not seem to alter people's perception of uncertainty, which points to the need to better contextualise the degree of uncertainty for people.

A key challenge to maintaining public trust in science is for communicators to be honest and transparent about the limitations of the current state of knowledge.

7.4 CONTRACT DELIVERY METHODS

7.4.1 Overview

In infrastructure procurement, the contract delivery mechanism determines how risk is allocated among different stakeholders. Depending on the way the infrastructure procurement contract is set-up, risk will be allocated differently to the owner, engineer or contractor. The type of contract determines who is going to profit from the opportunities and who is going to bear the cost of possible failures. For instance, a consortium competing in a design bid might want to optimise between not being sued due to proposing a plant that turns out to be under-sized and not losing the bid to a competitor due to being too conservative in the choice of the values for the design inputs. It is obvious that the incentives for different stakeholders are dependent on how risks and opportunities are shared in these contracts. Molenaar *et al.* (2004) discuss the risk allocation among stakeholders for different contract types in the wastewater sector.

7.4.2 Examples of delivery methods

A common method of project delivery method is the design−bid−build (DBB). In a DBB delivery, the owner normally hires a designer/engineer to develop project documents. Once the design is complete, the owner bids the work and hires a contractor to construct the project. The successful bidder then builds the project, with oversight by the owner and (normally) the designer/engineer. In this delivery method the owner and the contractor each assume cost risks. Most of the cost risk is assumed by the owner and builder. The designer/engineer assumes only a small amount of the cost risk.

For DBB-type projects, the owner, and to some degree the engineer, take responsibility for the influent parameter selection. In this case it is the engineer's responsibility to provide the owner with adequate information to make informed decisions about the design parameters, and their impacts upon the project.

Alternate delivery methods, such as design–build (DB), and design–build–operate (DBO) have become increasingly popular to owners because these delivery methods shift in varying degrees the financial and process risk to the contractor. In addition, they also move the risk to the party that is best able to balance the various process-related and financial risks. The alternate delivery methods often result in a different analysis of risks than a conventional design approach.

Additional discussion on these project delivery methods has been included in Appendix E.

7.4.3 Stakeholder involvement as a function of contract type

Table 7.4 illustrates the involvement of different stakeholders as a function of contract type and project phase.

In many parts of the world, traditional procurement in the water sector has relied on DBB contracts. In this example, based on water quality considerations, a regulator (R) will develop an effluent permit for the new treatment plant. The utility (U) together with the municipality (M) and a private company (P0) will develop the requirements for the future plant, possibly in collaboration with the regulator.

Usually, the utility will hire a private company P1 to assist in developing the preliminary and detailed design. This is followed by a tender for the construction of the plant which is then carried out by construction company P2. The commissioning of the new plant will typically be undertaken by both the design company P1 and the construction company P2. Then, the utility (U) will operate the plant.

During the past 30 years, there has been a steady increase in public–private–partnerships (PPP) leading to many different types of delivery mechanism. This has led to the rise of DB contract where consortia bid for both the design and the construction. In some cases, it may also include operation (DBO) and in some other cases, also ownership is transferred for a pre-determined length of time (design–build–own–operate–transfer: DBOOT). Some of these different schemes are discussed in

Table 7.4 Stakeholders responsible for taking decisions within the project phases for two contract delivery methods.

	Delivery Method	
Project Phase	**DBB**	**DBO**
Regulatory	R	R
Planning	P0, U, M, R	P0, M, R
Preliminary design	P1, U	**P1**
Detailed design	P1, U	**P1**
Construction	**P2**	**P1**
Commissioning	P1/P2	**P1**
Operation	U	**P1**

P0: private company, U: utility; M: municipality; R: regulator. The indices 1 and 2 in P differentiate between different companies. In bold the phases covered by the actual contract.

more detail in Appendix E. Appendix E also includes examples of the types of project delivery methods used in several countries across the world.

7.5 SUMMARY

Engineering decisions taken under uncertainty are heavily influenced by the contractual environment, the role of the stakeholders and the phase of an infrastructure project. This chapter discussed how these play a far greater role in shaping the final outcome of an infrastructure project than is widely acknowledged.

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