6 Project Pipeline:
Pre-Development and Prioritization

Introduction

There are a number of critical steps that must be taken to develop a single, linked or bundled set of projects (i.e., a “project pipeline”), that can attract financing from lenders or investors. Only well-advanced (“shovel-ready”) and clearly-prioritized projects get implemented on the ground.

To realize the vision of The Climate-Safe Path for All introduced in Chapter 4, it is important in the pre-development process to take forward-looking climate science, social equity and systems thinking into account. Calls for improvements in the pre-development phase are becoming widespread[223], but the approach we rely on here was proposed by re:focus partners in their Re:Invest Guide[224] [1] and has been adopted and recommended in the Financing Guide to project teams involved in the San Francisco Bay Area Resilient by Design competition[225]. While none of the analytical, design, financial planning or legally required steps (e.g., permitting, environmental review) are omitted in the re-envisioned approach, the sequence of steps and the systemic approach taken is far better aligned with the Climate-Safe Path proposed here than traditional approaches (Figure 6.1).

Pre-development is more than a technical planning and design exercise. If one broadens the focus from a single project to a statewide, sectoral or cross-sectoral and

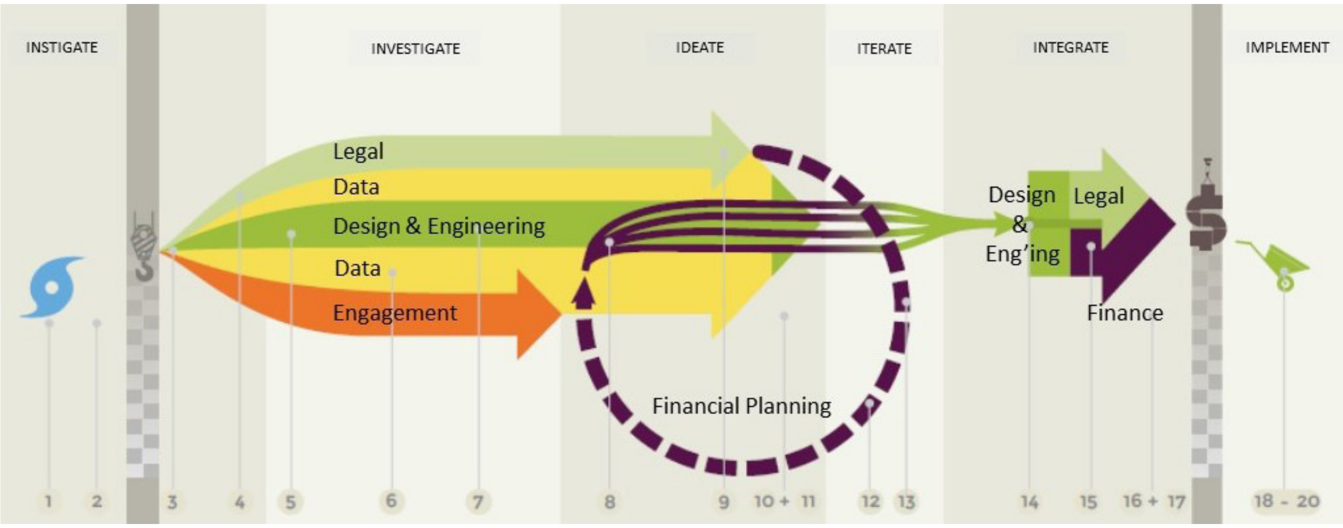


Figure 6.1: The six phases of the pre-development process are far better aligned with the systemic approach proposed in this report compared to traditional project development approaches (individual steps explained in re:focus partners 2015) (Source: adapted from re:focus partners 2015[224]; used with permission)

[1] Readers interested in the full report and a detailed treatment of the steps in the proposed approach including case examples can access the guide at: http://www.reinvestinitiative.org/wp-content/uploads/pdf/RE.invest_Roadmap-For-Resilience.pdf.

systems-oriented infrastructure investment strategy that will be implemented in stages over time, with deliberate movement toward upgrading existing infrastructure and adding new infrastructure that accounts for climate change, then a prioritized line-up of well-integrated projects needs to be developed. And, if the goal is to create climate-safe infrastructure for all as this report proposes – a perspective that takes social equity seriously – then stakeholder engagement is not an add-on late in the project development process, but an integral part of pre-development from the conceptual start in meaningful and creative ways all the way to construction. The difference lies in what questions drive the planning and design process and what problems are being solved. The questions we ask either focus us narrowly or open up to more creative possibilities of solving infrastructure and related problems.

Similar opportunities exist for state infrastructure planning. Traditional single sector-driven projects tend not to be able to take advantage of multi-sector benefits; roles and responsibilities cannot be shared; financing opportunities are more limited; and communities tend to benefit less. While more complex and potentially more time consuming (especially when this approach is still new to participants), doing more of the same will result in more of the same: underinvestment, a high risk of negative unintended consequences and political resistance from those most directly affected. There are, in short, risks involved in both approaches, but only the former is aligned with the Climate-Safe Path for All.

Recommendation 4

During the all-important pre-development phase, projects are conceptualized, planned and designed. The State budget should improve this process by building staff capacity and greatly increasing project funding to better account for a changing and uncertain climate, by addressing social inequity, and by assessing and accounting for the true costs and benefits of integrated projects across their full life-cycle.

Below we note the emerging shift in thinking in the engineering and architecture communities already underway that points to climate-conscious building in support of this overarching recommendation, then describe ways to operationalize it through a more systems-oriented project development process that takes stakeholder engagement and social equity seriously. In the latter part of this chapter we introduce and recommend that engineers and architects use a number of more sophisticated methodologies increasingly available to:

- Better account for the true costs and benefits of infrastructure over the entire life of the infrastructure along an adaptive but uncertain pathway;
- Screen for climate risks so as to determine the best assessment approach to use;
- Assess risks probabilistically and – where that is not possible – still arrive at a robust decision; and
- Design infrastructure in the face of uncertainty.

Infrastructure Planning in a Changing Climate

There is consensus among climate scientists that weather and climate stationarity is no longer a good predictor for the future (as discussed thoroughly in Chapter 2). All types of infrastructure in California (and in many other places) are now being exposed to record high temperatures, prolonged and more extreme heat waves, droughts, wildfires, unpredictable deluge rain events, sea level rise (SLR) as well as mud and debris flows. While these are acute extreme events, they serve as exemplars of what infrastructure in California will experience more frequently and for longer periods of time in the future. Existing and new infrastructure must be able to withstand this new future – a future that was not planned for previously. At a minimum, it is thus critical for forward-looking climate information to be included in updates of existing standards and guidelines while new standards are being developed so that new infrastructure can be designed to be climate safe, as we described in Chapter 4.

At a minimum, it is critical for forward-looking climate information to be included in updates of existing standards and guidelines while new standards are being developed.

In recent years, there has been a growing recognition within the engineering and architecture community that, despite challenges with using forward-looking climate information, it is important to develop methodologies and practices for doing so. In 2015, the American Society of Civil Engineers (ASCE) published a report entitled *Adapting Infrastructure and Civil Engineering Practice to a Changing Climate*[178]. In this report, the society provides four recommendations to start moving in this direction:

1. Engineers[2] and climate scientists must engage in cooperative research;
2. Practicing engineers, project stakeholders, policy-makers and decision-makers should be better informed about uncertainty;
3. Engineers need a new paradigm for a world in which climate is changing; and
4. Critical infrastructure most at risk should be identified.

There is still, however, considerable resistance to, and questions about, doing this. A U.S. Government Accountability Office (GAO) report from 2016, entitled *Improved Federal Coordination Could Facilitate Use of Forward-Looking Climate Information in Design Standards, Building Codes, and Certifications*, identified several of these challenges. As the GAO[226], pp. 18-19], notes:

> "[Representatives from standard setting organizations indicated that] technical challenges include difficulties in identifying the best available forward-looking climate information and incorporating it into standards, codes, and certifications. For example, representatives from one organization said that climate models provide a wide range of possible temperatures that is difficult to use in their standards..., that they need forward-looking climate information for a site-specific project area rather than at the country or state level, which is what is available from climate models..., or that they needed additional detailed information, such as whether any projected increased precipitation would occur evenly throughout the year or in concentrated bursts."

Moreover, as discussions among CSIWG members revealed, many engineers and architects do not feel confident enough to be able to defend climate science in debates with skeptical project sponsors.[3] Because cost is always an issue, arguing for potentially higher upfront outlays to protect against an uncertain (climate) future requires not only solid understanding of climate science but a considerable degree of mastery of approaches for decision-making under deep uncertainty, neither of which are standard components of engineers' and architects' professional education.

Many engineers and architects do not feel confident enough to be able to defend climate science in debates with skeptical project sponsors.

Below, we address some of these challenges (beyond the climate science already discussed in Chapter 2) to equip engineers and architects with concepts and tools that help address these obstacles.

[2] While the ASCE report is geared primarily to licensed engineers, we view these recommendations as transferable to architects.

[3] In early 2018, the ASCE published Policy Statement 556, which recommends that public and private infrastructure owners incorporate sustainability principles (including resilience) into infrastructure projects; the policy also advocates for owners to become more aware and better educated about the need for sustainability with the intent to lessen climate and sustainability skepticism.

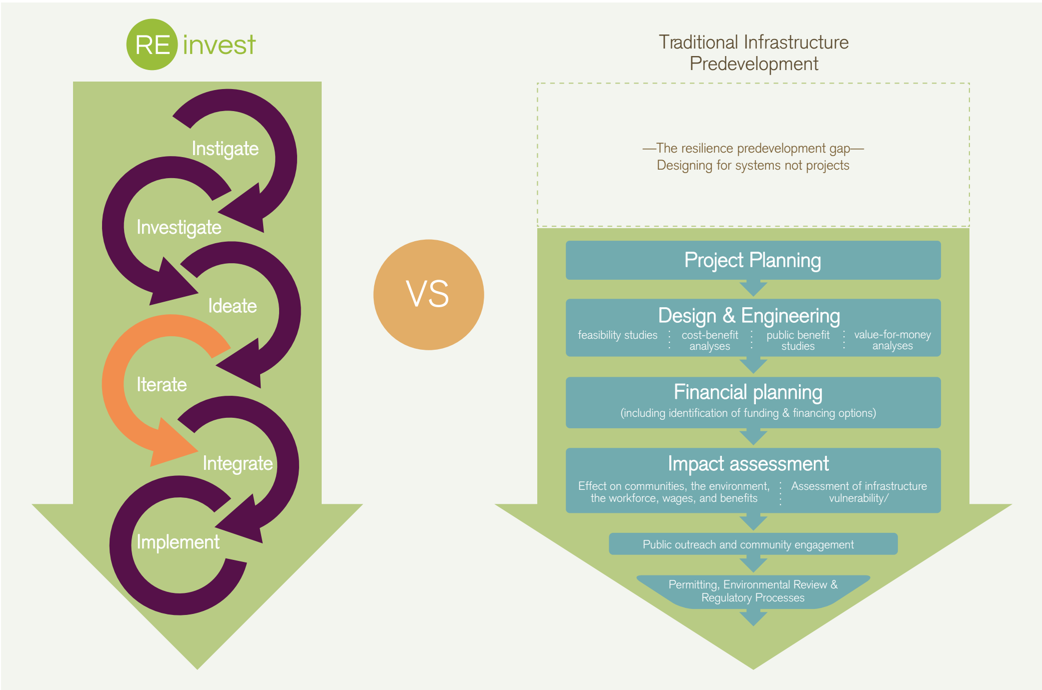


Figure 6.2: Comparison of a traditional versus Re:Invest's 6 I's infrastructure pre-development process (Source: re:focus partners 2015[224], used with permission)

Pre-Development

During pre-development, infrastructure projects go from being just an idea to being well-laid plans and designs ready be built. Often supported by short-term funding from general funds and grants, pre-development determines the goals of the project, assesses their economic and technical feasibility, explores and decides among different design options, and involves all necessary components of project planning – including developing financial plans to make projects investor-ready. As Figure 6.2 illustrates, traditional approaches to project development tend to be narrowly project or sector-focused and do not make room for design choices with broad, multi-sector benefits. Stakeholders come late into the process, and typically only after design choices have been made.

The modified step-by-step process proposed by re:focus partners[224] reshuffles the order of steps, remains open to reiteration to ensure greater stakeholder engagement and satisfaction emphasizes cross-sector integration to solve multiple problems at once, opens up additional funding sources and reaps more benefits. "Examples of this approach include integrating broadband or fiber networks into water system upgrades, running utilities through new sea water berms, or finding ways to create new energy or water efficiencies. These approaches bring conventional revenue-generating infrastructure into a larger portfolio of resilience solutions to help fund project implementation"[225].

Effective Stakeholder Engagement

This reworked pre-development approach emphasizes the early building of "communities of benefit" as a source of ideas, funding and political support. Some partners will be directly affected, for example through job opportunities, environmental co-benefits of infrastructure investments, improved property values in neighborhoods with upgraded infrastructure (i.e., measurable benefits) and greater safety from climate-related risks (i.e., the absence of damages, a calculable benefit). In widening circles out from the direct beneficiaries, other partners may benefit in indirect, but still tangible ways such as from greater economic activity and hence greater tax revenues.

During the Climate-Safe Infrastructure webinar series, numerous speakers reiterated the importance of engagement. Similarly, subject matter experts invited to CSIWG meetings emphasized this point. While the arguments are well known and often repeated, the fact that they were made so frequently suggests that early, repeated and meaningful stakeholder engagement is not common or sophisticated practice yet. Dr. Beverly Scott (presentation at CSIWG meeting, June 2018) in particular emphasized the importance of engagement of communities most directly affected by infrastructure projects. She emphasized that social equity should not be thought of as an "initiative" or an "add-on" to projects but as the heart of any project and the underlying policies and programs that drive them. Benefits to communities is what

Recommendation 5

Difficult decisions will have to be made and the impacts of potential policies or decisions on different stakeholder groups are complex and challenging to assess. It is critical therefore to engage all affected stakeholders in a meaningful way, from early on and throughout any decision-making process, using the seven principles of equitable planning and decision-making.1 The Strategic Growth Council is well positioned to take a range of steps to encourage, improve and provide guidance on effective stakeholder engagement in the context of infrastructure development.

Central components necessary to operationalize this recommendation to advance effective stakeholder engagement in state infrastructure projects include the following:

1. Create opportunities for timely and meaningful engagement by a wide range of stakeholders to help develop and evaluate potential policies and programs;
2. Develop guidelines (or even requirements) for effective stakeholder engagement in infrastructure projects;
3. Encourage agency staff to attend relevant conferences and meetings to make their constituents aware of proposed guidelines and to solicit comments;
4. Hold trainings for stakeholder engagement facilitators; and
5. Track progress on social equity (e.g., by using the questions and indicators proposed in Box 4.2).

infrastructure should be about. In her words, "If you do not center what is important, it will not happen later." She considered this necessary shift in thinking a "culture shift" in engineering.

If equitable climate safety is the outcome of the Climate-Safe Path for All, achieving it requires, as Chione Flegal put it, "shared decision-making that is rooted in transparency and a commitment to changing inequitable policies and practices, intended and unintended." Engineers and architects and their project partners must thus see community leaders as experts in and of their communities. Failing to include them can result in unintended harm, while inclusion can create buy-in. She warned, however, that "community engagement and partnerships are necessary vehicles towards achieving equity, but in and of themselves, do not achieve equity." To achieve equity requires tangible changes in policy, projects, decision-making processes and outcomes.

Identification of relevant project outcomes – through meaningful engagement – thus must begin by co-creating a shared, community-endorsed vision that is at once broad enough to matter and specific enough to shape decisions. Defining needs, identifying shared priorities, assessing opportunities and availability of resources as well as obstacles to access necessary resources, and joint setting of priorities (different ones for different scales of action) are critical steps in the process. Starting small as part of bigger projects can satisfy immediate needs and build trust. Effective communication to link initial steps and small successes with the goals of the larger pathway to the shared visions is equally important as any one project alone may not achieve the shared priorities and vision, but multiple projects together can.

Public participation in State planning processes can be very time consuming and impact work and family schedules. In the development of the 2017 Safeguarding California Plan Update, the Natural Resources Agency benefited greatly from organized input from a coalition of environmental justice and community-based organization that were supported by philanthropic funding. The State should build on this model by both funding its own representatives to prioritize stakeholder engagement and by working with philanthropic funders to support funded participation of these organizations in infrastructure policy and project development. These external organizations often also provide the added and immeasurable benefit of being trusted by the impacted communities, which can lead to more efficient and effective engagement.

Importantly, training will be required on each of the above-mentioned principles and approaches to ensure that practitioners are employing these strategies appropriately.

Climate-Screening Tool

In Chapter 4 we articulated a way to prioritize infrastructure projects (Figure 4.6). One of the prioritization criteria was exposure to climate risks. How should this get operationalized?

It begins by requiring an assessment of how future changes in climate might affect the infrastructure. In some cases, it is relatively straightforward to assess the potential effects of climate and account for this in the design of infrastructure. For example, warming temperatures are not likely to cause a significant increase in additional heat stress of existing road materials in the coastal areas of California over the next 20 years (at which time they will be resurfaced and the assessment would be repeated). In other cases, the effects of climate may be complex, and the infrastructure design could be particularly sensitive to potential changes. Flood control infrastructure, for example, can be highly sensitive to changes in hydrology. Recognizing that different infrastructures need different climate vulnerability evaluations, we recommend that California develop a screening process that can be used to guide how much climate analysis is necessary in order to design climate-safe infrastructure in an efficient way.

Drawing on other screening processes in the literature and in practice[227-230], the CSIWG proposes a simple, straight-forward three-tiered approach (Figure 6.4).

The first level – Initial Screening – consists of two steps: (1) defining a performance threshold for infrastructure and (2) assessing qualitatively whether current or future climate change – both the average changes as well the potential projected extremes (particularly on the high-emissions scenario) - might degrade performance beyond thresholds. The result of a Level 1 evaluation could be a simple check-list indicating that different aspects of the infrastructure as designed would not be sensitive to plausible changes in climate over the lifetime of the infrastructure (i.e., lifetime = design life + reasonable period over which well-maintained infrastructure is expected to function). If the qualitative assessment reveals potential sensitivity, then the evaluation would move to Level 2.

The second level – Climate Stress Test – would involve some quantitative analysis. First, it would evaluate quantitatively the system performance over a wide range of plausible current and future climate parameters (again, averages and extremes from a range of global climate models), with particular emphasis – in concordance with the Climate-Safe Path – on climate impacts under a high-emissions pathway. Second, the analysts would compare any identified vulnerabilities to available climate information to ascertain how plausible the identified vulnerabilities are. If the identified risks appear low, then the evaluation would stop with a climate risk statement documenting the findings. If the risks are found to be high, then the third level of assessment would be required.

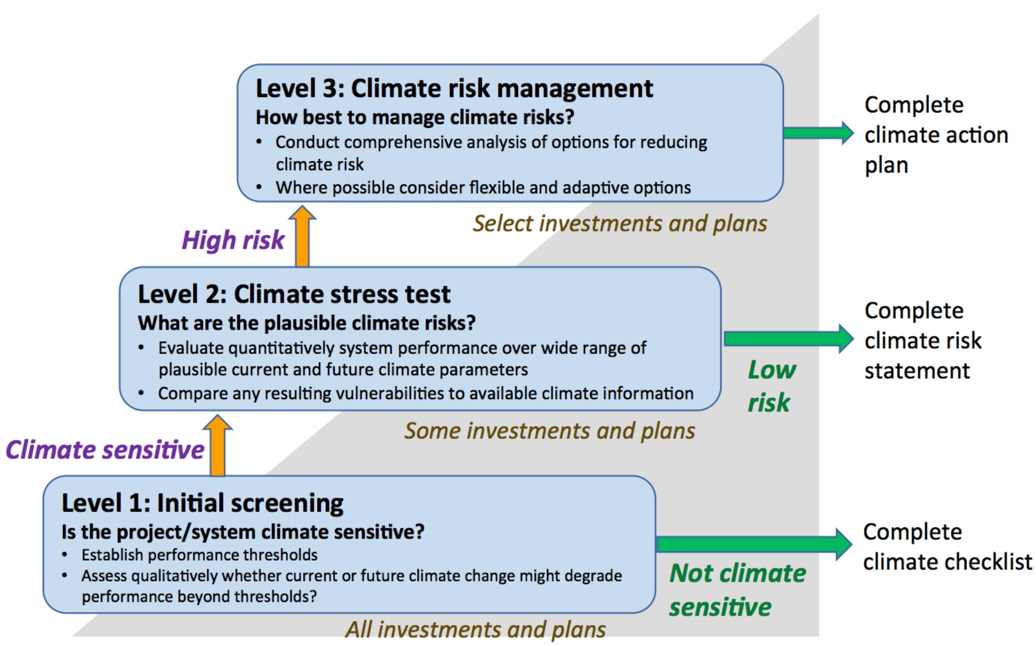


Figure 6.4 The proposed three-tiered screening process (Source: Robert Lempert, used with permission)

The third level – Climate Risk Management – requires a comprehensive evaluation of options for reducing the identified risks, including alternative designs that are flexible and adaptable (see further discussion below). As future climate is deeply uncertain, i.e., it is not easily described through probability statements, alternative methods for the analysis of options are required (see Box 6.1 below on decision-making under deep uncertainty). The results of the third level of analysis would be a climate action plan that describes a modified infrastructure design that is shown to be climate-safe through the combination of a number of different strategies (Box 4.1 in Chapter 4) over a wide range of plausible climate futures.

> To further operationalize how California can move toward climate-safe infrastructure – both at an agency and at a project level, the CSIWG recommends that infrastructure planners, engineers and architects employ this climate screening tool to identify assets that require an extensive climate action plan. Together with the other prioritization criteria outlined in Chapter 4 (infrastructure investment gap and potential to reduce social equity), this will help move toward a priority list of projects that will make a significant contribution to realizing the Climate-Safe Path for All.

Project Feasibility: Calculating Cost Effectiveness of Climate-Safe Infrastructure

Assessing the economic feasibility of infrastructure projects is often the first step after a project has been proposed. As we argued earlier, the traditional approach has been too narrow, and often predetermines certain "solutions" before a more comprehensive analysis has been undertaken.

Over the course of the work of the CSIWG, members discussed and learned about a number of ways in which traditional benefit cost analysis (BCA) is limited. For example, BCA:

- Focuses on easily monetized costs and benefits, but externalizes or ignores many more difficult-to-assess benefits and costs;
- Often is carried out only for the initial cost (capital outlay) and does not consider operations and mainteance (O&M) costs over the entire lifecycle of the infrastructure;
- Significantly discounts the future (a values choice, often reflected in signals from capital markets);
- Is not well suited for infrastructure using adaptive design approaches over the course of many decades in order to better deal with uncertainty in scientific projections; and
- Is often narrowly project-focused, rather than system-focused and typically does not account for costs and benefits that accrue to other sectors.

Taken together, these problems result in upfront costs of protective measures being overstated while the systemwide benefits of taking them are underestimated.

There are better tools available, but these are not always widely known or appropriately applied. Over the course of CSIWG deliberations and webinar presentations, the Working Group learned of several more sophisticated alternatives:

- The life-cycle cost and benefit assessment tool developed by the Zofnass Program for Sustainable Infrastructure at Harvard University (a compliment to the increasingly commonly used ENVISION tool[4] (see also[231]);
- Real Options Analysis – an economic cost-benefit approach that operationalizes the notion of adaptation pathways from an economic perspective by combining decision tree analysis with BCA;
- Robust decision-making – an iterative analytic process, often used in engagements with stakeholders, designed to support decision making under deep uncertainty by trying to identify strategies that work cost-effectively over a wide range of climate futures and other decision-relevant factors; and
- Triple bottom line analysis, which evaluates cost effectiveness based on social, environmental and economic criteria.

While by no means a complete list, these alternative approaches complement and enhance traditional BCA and illustrate that more sophisticated economic tools are available but not commonly used – to the detriment of the ultimate choices made and outcomes achieved. These tools must be brought to engineers', architects', and project managers' attention, and those individuals must learn when and how to use such tools appropriately.

> The CSIWG sees an important opportunity for the State to improve the benefit-cost assessment approaches it uses. Instead of conventional BCA, the State should use more sophisticated methods that account for:
>
> - The full infrastructure life-cycle, not just initial capital outlays;
> - The cost of inaction;
> - The deep uncertainty in both climatic and non-climatic aspects of the future;
> - Adaptation pathways and the adaptive implementation of design choices;
> - Benefits and costs to systems, not just projects; and
> - The social costs and benefits to ensure that equity is explicitly accounted for.

[4] For more information, see: http://economictool.zofnass.org/ and: http://sustainableinfrastructure.org/envision/.

Probabilistic Risk Management

In Chapter 2, we explained the fundamental sources of uncertainties in making climate change projections. We also explained (see Box 2.2) that probabilistic climate change projections as developed for the Ocean Protection Council's (OPC) SLR guidance[49] or the Fourth Assessment are only conditional probabilities: they provide the odds for particular outcomes under the assumption of a particular emissions pathway that society may or may not follow. OPR's State guidance[230] urges planners and decision-makers to consider projections using the high-emissions scenario for decisions with time horizons up to 2050; beyond that, OPR suggests assessing risks under both a mid-level and the high-emissions scenario, but emphasize the latter for high-risk infrastructure. In this report, we similarly urge the State to consider the high-end emissions scenario across all projects to be consistent with the legislative intent of AB 2800.

But even with just that one, high-emissions scenario, considerable uncertainties remain that must be accounted for. While probabilistic projections are increasingly being made available for this scenario at the temporal and spatial scales needed by engineers and scientists (see Chapters 2 and 5), how should engineers and architects use that information in project development?

Probabilistic risk management approaches are increasingly common and widely recommended for climate change planning, but many are not yet deeply familiar with them. The typical arguments for employing such approaches, include the following:

- The magnitude of potential hazards from climate change are both diverse and potentially large, but there is irreducible uncertainty as to their timing and likelihood of hazardous events;
- Risk management seeks to eliminate or reduce hazards, and then to mitigate the hazards that remain. For cases when hazardous events occur, risk management also involves absorbing or resisting damage, and when the magnitude is too great, accepting and spreading the burden from the harms that result;
- Risk-based approaches weigh the likelihood of a hazard and the severity of the potential consequences against a defined set of criteria that can be used to make high-level decisions about how to act; and
- The goal of a managed risk approach is to quantify the potential hazard severity and the likelihood and frequency of its occurrence to enable an agency to rank all the risks it faces and to make reasoned decisions as to where to focus efforts and limited resources.

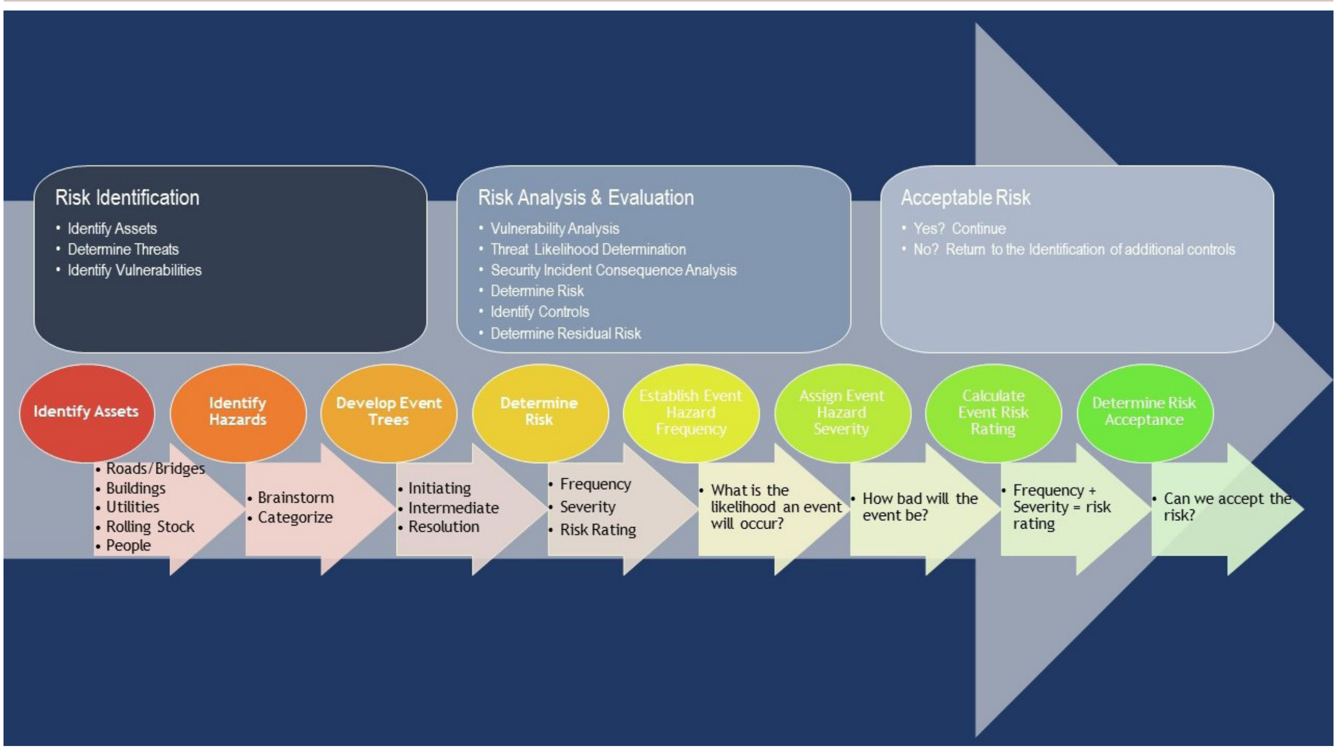


Figure 6.5 Steps in a probabilistic risk management approach to climate adaptation (Source: Image courtesy of James Deane, California High-Speed Rail)

The process to assess risk involves five critical steps (the complete process with additional steps is shown in Figure 6.5 using eight circles), to: identify hazards; determine frequency; assign severity; assign event risk ratings; and evaluate risk acceptance in light of the ratings. This basic approach has been used in a variety of contexts and cases; a useful one related to developing a climate risk management approach for infrastructure design is the assessment undertaken for New York City[232]. We include a case example of probabilistic risk assessment and management in Appendix 7. The Working Group believes that the basic risk assessment approach illustrated by these examples is a helpful approach to infrastructure decisions and related risk management for time horizons of 20-30 years. Over time, infrastructure planners and operators should monitor and update their risk assessment to ensure observation and updated science continue to inform the risk calculus and needed updates to the risk management strategy.

Given the limits to providing probabilities for climate change impacts with confidence, however, particularly over long time horizons (i.e., for infrastructure expected to be functional past 2050), other approaches can be employed in tandem with traditional probabilistic risk management, helping to identify ideal project designs, given multiple sources of deep uncertainty (Box 6.1). Appendix 8 offers a simplified example of considering climate change impacts when upgrading existing infrastructure.

Innovative Design Choices

Toward A New Paradigm for a Changing World

With actionable climate science in hand, improved approaches to project development that include deliberate and enhanced stakeholder engagement, more sophisticated economic feasibility analyses and risk analysis and management approaches, including those developed for DMDU, the final question during the project design phase concerns how to design for uncertainty.

As the ASCE noted in its 2015 report on adaptation[178], there is growing recognition within the infrastructure community that "engineers [and architects] need a new paradigm for a world in which climate is changing." While still (and necessarily) rooted in the world of standards, codes, regulations and guidelines, there are efforts underway now to transform traditional standard-setting processes. Many of the concepts that are starting to gain resonance across the engineering community today have already been circulating for years to decades, but in different disciplines. Concepts such as "adaptive design" have emerged from the theory of adaptive management first proposed in ecology in the 1980s[240,241]. Core risk management concepts such as "safe-to-fail" versus "fail-safe" have long been established in areas ranging from environmental safety to hazardous materials management, from handling lawn mowers to operating big infrastructure projects like the Thames River Estuary barriers[5] (Box 6.1), and increasingly in the context of climate change[242-244]. The necessity to move to "safe-to-fail" becomes notoriously obvious when things go wrong, i.e., when things thought to be safe do fail (such as the BP oil spill or the Fukushima Daiichi nuclear power plant disaster)[245, 246]. We define these concepts below and provide recommendations for what California can do to implement the best of these approaches in developing climate-safe infrastructure.

Adaptive Design

With the recognition that a changing climate will lead to not just one type or level of impact but shifting impacts to existing and new infrastructure over time, the engineering community is increasingly embracing the concept of adaptive design, or adaptive, flexible infrastructure. As most recently defined by Chester and Brady[247], p.10):

> An adaptive infrastructure is one that has the capacity to perceive and respond to perturbations in such a way as to maintain fitness over time. Adaptive infrastructure have the capacity to recognize that stimuli or changes in demand are occurring or will occur including the effects of these stimuli, and have the socio-technical structures in place to change quickly enough to meet future demands.

Some examples of adaptive design can include:

- Levees with adjustable crests;
- Seawalls with adjustable heights;
- Structures that can be dis- and re-assembled;
- Floating structures;
- Non-permanent structures such as long-term campgrounds or temporary housing; and
- Movable structures.

While the ideas of adaptive management have been used by planners for decades, transferring these principles to infrastructure design and implementation by engineers and architects is still in the early days. While this may initially slow adoption of adaptive pathways and design, more research on effective adaptive design principles will help advance the field and provide information for wider support of this methodology. Important questions to examine include (among others):

- How and when should adaptive designs be applied?
- How should uncertainties in future climate projections be included in the context of adaptive design?

[5] In some cases, safe-to-fail approaches can be made adaptive in that failures serve as triggers to move to the next adaptive measure(s). This is the case with the Thames River Barrier.

Box 6.1 : How to Make Good Infrastructure Decisions When Future Climate Change is Hard to Quantify with Confidence?

Traditionally, engineers and others manage risk by quantifying hazards such as flooding with a probability distribution. For instance, transportation engineers might look at historical records and observe the magnitude of the 100-year storm. Based on the resulting probability estimate, engineers would size culverts for a road to most cost-effectively meet desired performance goals. Such risk management approaches are called predict-then-act, because they start with predictions about the future and then recommend actions based on those predictions.

Engineers recognize that probability distributions may not be accurate, so sometimes they add a safety margin (see Box 3.3). But this can get expensive when, as described in this report, the imprecision in the probability distributions is large. For instance, OPC's *2018 Updated Sea-Level Rise Guidance for California*[49] provides a probability distribution that suggests an average of 2 ft of SLR by 2100 as well as an "extreme" sea-level rise scenario of 10 ft that has no probability attached. In most instances, the design of coastal infrastructure systems would be significantly different for 2 ft vs. 10 ft of SLR. State guidance recommends considering many contextual elements of projects in qualitative terms, but how should engineers develop a single approach that quantitatively addresses these different numbers?

AdaptLA Regional Sea Level Rise Planning Project stakeholders play Decisions for the Decade, a role-playing game developed by the World Bank, in partnership with RAND Corporation, to help practitioners learn how to make decisions under deep uncertainty. (Photo: Holly Rindge, used with permission)

In recent years, new risk management approaches have come into use that address this type of challenge. The approaches, which go under the broad label of Decision Making Under Uncertainty (DMUU), or more precisely, Decision Making Under Deep Uncertainty (DMDU)[227], view the future as inherently uncertain, identify a wide range of plausible futures, and use this information to craft infrastructure designs and systems that perform well no matter which future comes to pass.

A variety of such DMDU approaches are commonly used but all share the following common elements. Rather than starting with predictions, they: (1) begin with a proposed infrastructure design; stress test that design over a wide range of futures, including projected extremes; (2) use this information to identify potential vulnerabilities in the design; and then (3) identify modifications to the design, or new designs altogether, that significantly reduce these vulnerabilities.

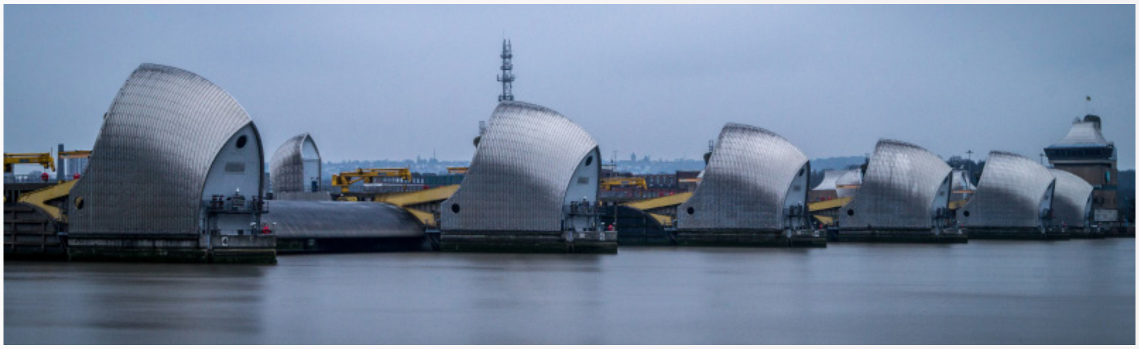
For instance, engineers might modify the design of a levee, making its base larger than currently needed so it might be more easily raised if needed in the future. An example of choosing an entirely new design, engineers seeking reliance against hurricanes of hard-to-predict future intensity, might replace a bridge over a river with bollards. The latter would flood more often, but only for a short while, and could not be destroyed by even the largest storm. We discuss these newer, non-traditional strategies in greater detail below.

What are some of these alternative DMDU approaches? The most common include:

- **Scenario planning,** the most widely used DMDU approach, develops several internally consistent descriptions of the future[233], often using participatory stakeholder processes or expert opinion to choose the scenarios. Engineers can seek designs that perform well in each of the selected scenarios;
- **Robust Decision Making (RDM)**[234-236] is a simulation model-based approach that combines scenario planning with more quantitative risk analysis and is often used in deliberative stakeholder engagements. RDM stress tests proposed infrastructure systems over myriad plausible paths into the future and then uses the resulting database of model runs to identify policy-relevant scenarios and robust adaptive strategies. As one important product, RDM and related approaches such as Decision Scaling[206, 237], often generate scenarios that identify specific vulnerabilities of infrastructure systems due to climate change;
- **Adaptation (or adaptive) pathways**[238] provides a framework for developing, visualizing and evaluating plans that can adjust over time. The approach links the choice of near-term adaptation actions with identifying pre-determined threshold events. Observation of such threshold events would trigger subsequent actions in the planning or implementation stages of adaptation strategies. Often an adaptation pathway includes low-regret near-term actions that preserve future options to adjust if necessary; and
- **Flexible engineering design analysis**[239] uses tools such as real options analysis (see above) to help designers of complex, long-lasting projects – such as communication networks, power plants or hospitals – to abandon fixed specifications and narrow forecasts and build infrastructure system that can be easily adjusted as conditions change.

DMDU methods do use any probabilistic information that scientists can provide. But rather than start the design and planning process with probabilistic forecasts, DMDU methods use them to adjudicate among alternative designs. For example, imagine engineers designing infrastructure systems in a watershed in which the historic 500-year flood is becoming more frequent. With an RDM or adaptive pathways and design approach, the engineers identify two (or more) combinations of flexible design, green infrastructure and land use options that would meet performance goals. The first combination might meet those goals if the historic 500-year flood occurred as frequently as once every century. The second, more expensive than the first, would meet those goals if the historic 500-year flood occurred as frequently as once a decade. The engineers would then work with climate scientists to determine if there is any evidence that the historic 500-year flood could occur once a decade and, ideally, if there were any trends in climate indicators engineers could observe that would signal whether and when such storms are becoming more frequent in the future.

The use of these DMDU approaches is becoming more prevalent. For instance, the *2018 California Sea-Level Rise Guidance*[49] recommends communities choose a near-term coastal adaptation strategy consistent with current probabilistic SLR projections and also develop adaptive pathways that include contingency plans appropriate for the extreme SLR scenario if in fact, actual SLR turns out to be larger than projected.



While a massive structure, the Thames River Estuary Barrier uses failures to protect London from the growing risks of coastal flooding as triggers to deploy the next adaptive measures. (Photo: Phil Dolby, flickr, licensed under the Creative Commons license 2.0)

- How should multi-model and multi-scenarios simulations be incorporated into adaptive design concepts?
- How should a cost-benefit analysis be conducted that accounts for the true costs today and in the future with these modular types of designs?

There are two important steps forward for the State to take in order to support the greater adoption of adaptive design:

1. To support applied research and testing of adaptive design for different types of critical infrastructure as well as developing rigorous economic methodologies for determining true cost and benefits of implementing adaptive design; and
2. Design policies that allow and encourage infrastructure which is either sufficiently "modular" or built with sufficient "safety buffer" to accommodate changing climate change risks over time.

Safe-to-Fail

Traditional engineering design accounts for risk by including safety factors (also referred to as factors of safety, see Box 3.3). Given known and predictable conditions, safety factors provide the load carrying capacity of a system beyond the expected or actual loads. The goal is to make structures fail-safe – in that the safety factor presumably predicts accurately what can go wrong, and accounts for it, thereby reducing the risk that a structure will fail entirely. In a changing climate, where the past is no longer a reliable predictor of the future and the future has large uncertainties, the fail-safe paradigm may not be as dependable as before.

Safe-to-fail is an emerging design principle that assumes that the safety factors may not adequately protect an asset, and the structure is thus developed so that if some part of it fails, the damage is controllable or minimized. In fact, safe-to-fail "recognizes that the possibility of failure can never be eliminated"[195], p.9. As described by Kim et al. (2017)[248], safe-to-fail infrastructure embody these characteristics in the following ways. They:

- Focus on maintaining system-wide critical services instead of preventing component failure[249];
- Minimize the consequences of the extreme events rather than minimize the probability of damages[250];
- Privilege the use of solutions that maintain and enhance social and ecosystem services[251];
- Design decentralized, autonomous infrastructure systems instead of centralized, hierarchical systems[250]; and
- Encourage communication and collaboration that transcend disciplinary barriers rather than involving multiple, but distinct disciplinary perspectives[251,252].

Modularity is one potential mechanism to design for safe-to-fail. As described by LA Metro in its 2015 *Resiliency Indicator Framework*[195], modularity can be achieved by:

- System components having enough independence so that damage or failure of one part or component of a system has a low probability of inducing failure of others; and/or
- System components being constructed in a 'modular' manner that facilitates rapid rebuild/restoration following failure.

As with adaptive infrastructure design, this is a new concept with few implementation examples from which to draw best practices. However, LA Metro's *Resiliency Indicator Framework* includes two safe-to-fail indicators (one for design approach and one for design guidelines) to assess a project's potential resilience[195]. Given the newness of the approach, case examples presented in their indicator framework do not yet include safe-to-fail features. The framework, with guidance on how to use it, is a good example, however, of how to measure and track features that make infrastructure more robust and resilient in the face of greater demands, change and uncertainty.

It is also critical to apply a social equity lens with these new and adaptive approaches to ensure that any decisions are just, fair and equitable to all. With safe-to-fail, for instance, some part of the system may be down for the sake of preventing more widespread failure. Clear procedures must be developed to help infrastructure operators and regulators choose equitably which part will be planned for disruption or even failure, and how to compensate those affected in a fair manner.

With Safe-to-Fail, clear procedures must be developed to help infrastructure operators and regulators choose equitably which part of a system will be planned for disruption or even failure, and how to compensate those affected in a fair manner.

In Chapter 7 we turn to governance, which should provide this sort of guidance and lay out requisite processes.