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Adaptive Climate Risk Control of Sustainability and Resilience for Infrastructure Systems

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Background

Many challenges are facing our global society that include, for example, natural, technological and human caused threats potentially affecting property and life costing annually hundreds of billions of dollars. Other examples are:

- Income disparity that may lead to societal or international conflicts and disorders;
- Population growths with time-variant differences in consumption cultures that may potentially be converging towards the high ends of consumption behavior for significant population segments, thereby stressing or threatening our limited resources;
- A changing climate and growing populations with significant increases in urbanization;
- New and emerging technological threats, etc.

Resilience and sustainability as system characteristics are necessary for societal endurance and survival. Enhancing them at the element, network, community, etc. levels could lead to not only massive savings through efficiencies but also through risk reduction and expeditious recovery in case of disasters. The rational management of such reduction and recovery is facilitated by practical and fundamental resilience and sustainability metrics. This paper contrasts resilience and sustainability and discusses a research need to concurrently address and manage them using a dynamic risk control framework.

Resilience

The concept of resilience appears in different domains ranging from ecology to child psychology and psychiatry to infrastructure systems. It was formally introduced in ecology, defined as the persistence of relationships within a system, [1] and measured by the system's ability to absorb change-state variables, driving variables, and parameters and still persist. In discussing the philosophical basis of risk analysis, Starr et al. [2] characterized the resilience of a system as its ability to bounce or spring back into shape or position, or to recover strength or spirits quickly. Ayyub [3,4] provide a comparative examination of these definitions and their suitability as a basis for resilience quantification and measurement science.

U.S. federal agencies are defining resilience according to the Presidential Policy Directives (PPD) 8 [5] and 21 [6] (For example, see the National Institute of Standards Technology Community Resilience Planning Guide for Buildings and Infrastructure Systems [7].

Presidential Policy Directive [PPD] 8 [PPD-8 2011] defines resilience as "the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies." PPD-21 [2013] expanded the definition to include "the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."

For engineering, resilience is a system characteristic and the system is a system of systems. For instance, to be functional after a disruption, a building needs communications, power, water, and transportation for access of its users as well as to be functional itself. Usually a water utility depends on a power utility to be functional and a power plant requires cooling water and all depend on natural, human, social and financial capitals for functionality.

Sustainability

As for sustainability, the American Society of Civil Engineers (ASCE) defines sustainability, in its Policy Statement 418 [8], as a set of economic, environmental and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely, without degrading the quantity, quality or the availability of natural, economic and social resources. Sustainable development is the application of these resources to enhance the safety, welfare, and quality of life for all of society. Several other definitions are available as provided by Webb and Ayyub [9] (see example in Table 1 below).

Contrasting Resilience and Sustainability

Redman [14] provides a discussion on contrasting elements of resilience and sustainability. A resilience theory approach recognizes the following:

Context	Definition and Source
General	"Creating and maintaining conditions under which humans and nature can exist in productive harmony and that permit fulfilling social, economic, and other requirements of present and future generations." [10] "Ability to maintain or improve standards of living without damaging or depleting natural resources for present and future generations." [11]
Manufacturing	"The creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound." [12]
Green buildings	"The practice of increasing the efficiency with which buildings and their sites use and harvest energy, water, and materials; and protecting and restoring human health and the environment, throughout the building life-cycle: siting, design, construction, operation, maintenance, renovation and deconstruction." [13]

Table 1: Selected sustainability definitions (adapted after Webb and Ayyub) [9].

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- Change is normal with multiple stable states.
- Experience leads to a gracefully adaptive cycle.
- Resilience originates in ecology for maintaining ecosystem services.
- Results of change are open ended and emergent.
- Resilience is concerned with maintaining system dynamics.
- Stakeholder input is focused on desirable dynamics.

On the other hand, a sustainability science approach recognizes the following

- This approach envisions the future, and acts to make it happen.
- It utilizes transition management approach.
- It originates in social sciences with the presumption that a society is flawed.
- Its desired results of change are specified in advance.
- Its focus is on interventions that lead to sustainability.
- Stakeholder input is focused on desirable outcomes.

Redman's sustainability science approach is descriptive on how an engineer addresses both sustainability and resilience where resilience is treated as an aspect of sustainability during the lifecycle of a project or in the management of a system, enterprise or community. The lifecycle includes conception, design, construction, operation, maintenance and renewal or removal. The necessary steps are:

- Envision the future, for normal function and response to a perturbation, and act for sustainability and resilience.
- Use a transition management approach from current to desired conditions.
- Seek desired results of change that are specified in advance.
- Focus on interventions that lead to sustainability and resilience
- Seek stakeholder input by focusing on desired outcomes.

How are Resilience and Sustainability Related?

The following precepts should be captured in relating resilience and sustainability:

1. Systems that are resilient might not be sustainable;
2. Systems that are not resilient are not sustainable; and
3. Systems that are not sustainable might be resilient.

Let's define

R: Resilient infrastructure systems

R: Non-resilient infrastructure systems

S: Sustainable infrastructure systems

S: Non-sustainable infrastructure systems

Using a Venn diagram (Figure 1) of two ovals representing resilient and sustainable infrastructure systems within a rectangular sample space set, the following cases were considered:

- Case 1: R and S are mutually exclusive

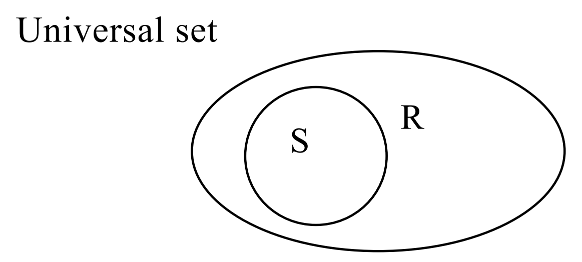

Figure 1: Case 6 where R and S are perfectly dependent with S nested in R.

- Case 2: R and S are independent
- Case 3: R and S are with positive dependency
- Case 4: R and S are with negative dependency
- Case 5: R and S are perfectly dependent with R nested in S
- Case 6: R and S are perfectly dependent with S nested in R

The most general cases are 2, 3 and 4; whereas the most appropriate representation of infrastructure systems is Case 6. Case 6, as shown in Figure 1, is consistent with the above three precepts. The figure basically states that generally sustainable infrastructure systems are subset resilient infrastructure systems.

Concluding Remarks: Uncertainty and Adaptive Risk Control

The economic valuation of resilience and sustainability necessitate fresh thinking by reconsidering the meaning of "value" in meeting direct needs and safeguarding the interests of future generations. Any concepts adopted should meet a set of guiding requirements and be compatible with previous practices including risk analysis and management [15]. The latter requirement is necessary for computing benefits and costs to inform decision and policy making. Using a risk framework would offer a basis for competing on limited resources against other societal needs in familiar terms used for trade-off analysis, such as benefit/cost analysis and internal return on investment.

The nature of uncertainty in resilience and sustainability are domain and hazard dependent, and its magnitude is affected by the time-span of a planning horizon. For example in addressing sustainability under a changing climate, uncertainty can be significant and time variant. Adaptive risk control, in such cases, is necessary as illustrated in Figure 2. The figure shows an illustrative example of constructing defences, such as a seawall, for a rising sea level due to a changing climate with the potential for surges and waves. The planning horizon is to the year 2100. The vertical axis shows the predicted sea level for the year 2100 as a function of time starting with a prediction made in the 2015. The uncertainty is assumed to decrease as the prediction year becomes closer to the year 2100. The height of a seawall can be based on the most probable level with an appropriate consideration for potential needs to increase the height. Accommodating such a potential increase might require the instalment of an oversized foundation system and other details to facilitate the height increase without needing to demolish the entire wall. The sea level is tracked in future years and the height is kept the same or increased as needed. Several decision points are shown on the figure for the purpose of illustration. Such an adaptive management approach would help to counter the indecisiveness associated with great uncertainty levels. This approach can be combined with risk methods to create adaptive risk control strategies for economic analysis.

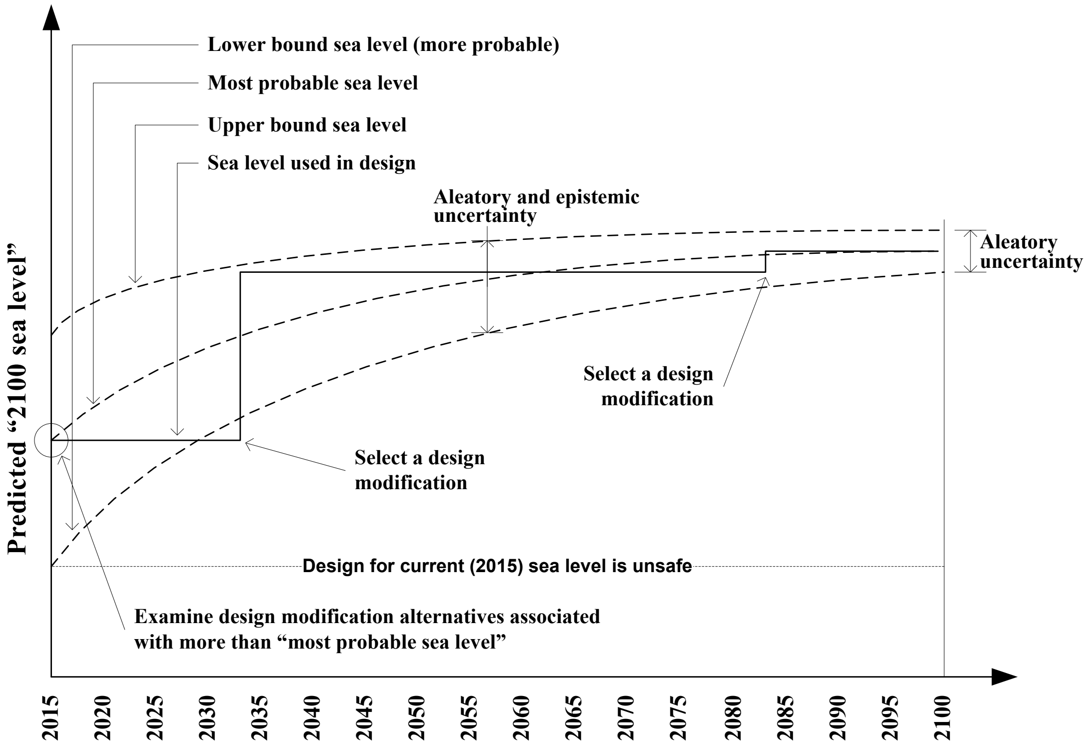

Figure 2: Adaptation in 2015 with increasing sea level and decreasing uncertainty.

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