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Transdisciplinary Systems Thinking: Sustainability of Coastal Systems

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Abstract

Sustainable development requires integrating economic, social, cultural, political, and ecological factors into evaluation and decision-making processes. Sustainability benefits from transdisciplinary systems thinking, since the integrated global coastal system collectively and continuously evolves with natural and human subsystems competing for resources. Disparity between multidisciplinary models in socio-economic and physical sciences introduces unique challenges when applying transdisciplinary methodologies to complex coastal systems. Systems science training and early adoption of a collaborative systems approach framework are critical to success. Transdisciplinary research provides opportunity for integrating and advancing *a posteriori* knowledge. The IN-CORE v1.0 model released on January 8, 2020 utilized a transdisciplinary systems approach in development.

Keywords
Sustainability; Coastal Systems; Transdisciplinary; Reliability; Systems Thinking

1. Introduction
Sustainable engineered coastal systems benefit from integrating systems engineering with coastal and other transdisciplinary sciences. External forcings are constantly changing and increasing for engineered and natural coastal systems subjected to increasingly extreme storm hazards. Defining logical and physical system architecture for complex coastal systems is problematic with complex external interfaces and variable boundary conditions. Engineered, natural, and meteorological coastal systems evolve spatially and temporally during extreme storm events.

Increased coastal development places greater numbers of engineered structures at risk of damage from coastal hazards. Functional sustainability and adaptability of human development within these at-risk coastal zones benefit from transdisciplinary systems thinking and modeling. Even in the absence of relative sea level rise (RSLR) or other equally significant climate change impacts, developed coastal system sustainability is at greater risk from increasing property development, coastal population growth, and dependence on coastal and marine related economies.

Risk is the cumulative product of failure probability and consequences. Risk can change in these complex systems even if the hazard probabilities remain fixed, due to the potential for changing consequences associated with increased development in, and/or reliance on, coastal areas and resources. The predictable stakeholder threat response is to protect developed areas and coastal infrastructure at great expense without regard to robustness and sustainability [1].

Sustainable development requires integrating economic, social, cultural, political, and ecological factors into the evaluation and decision-making process [2, 3]. UNCED Article 21 (§17.15) encourages integrated planning and decision-making for sustainable development of coastal zones and the contiguous marine environment. Sustainability priorities include systematic assessment of critical coastal areas, eroded zones, physical processes, development patterns, user conflicts, environmental hazards, climate change stressors, and sea level rise impacts.

A key difficulty with sustainable development of engineered coastal systems in a natural system environment involves the inability to control or regulate an open system. A second difficulty involves definition. Gallopin [3] notes that output and state variables are typically synonymous when considering a "sustainable" system, in which preservation of the system itself is the desired objective. Conversely a "functionally sustainable" system, where the desired objective is system performance or output sustainability, produces differing output and state variables. Since human development fundamentally changes coastal systems, sustainability requires either improving or transforming built-components to adapt and preserve functionality or adapting the system architecture to maintain functionality.

Sustainable development benefits from transdisciplinary systems thinking, since the changing state of natural and human subsystems collectively and continuously evolve. Rapidly increasing external stressors created by extreme storm events impact system functionality and threaten continued development and livability within coastal zones, forcing system component interactions into catastrophic and often unrecoverable damage states. When the system model includes socio-economic and political variables, an optimized or peak performance outcome that guarantees sustainable development over extended generations and territories becomes highly unlikely. The challenge becomes how best to evaluate and adapt engineered coastal systems with a sustainable development approach in an integrated systems framework, given the alternative paradigms for sustainability objectives defined by Schellnhuber [4].

Coastal systems resiliency assessments typically include some minor considerations relative to sustainability. Typical coastal risk evaluation methodologies applied by the United States Army Corps of Engineers (USACE) [5] include one or more of the following tools: (1) multi-criteria decision analysis (MCDA) [6]; (2) scenario analysis [7, 8]; (3) risk analysis [9]; and, (4) engineering for climate change and other emergent conditions [7, 10]. Transdisciplinary sustainability considerations typically emerge as independent system evaluations synthesized together in final work products. Environmental impact statements (EIS) conforming with the National Environmental Policy Act (NEPA) assess socio-economic and environmental impacts for proposed engineered systems during the project development phase [11]. Independent consultants typically execute this task independent of the project design team to limit bias in decision making. The USACE North Atlantic Coast Comprehensive Study (NACCS) [12] and Systems Approach to Geomorphic Engineering (SAGE) (http://www.sagecoast.org/) programs both represent a changing trend within the coastal practice community. The United States Department of Transportation (USDOT) Federal Highways Administration (FHWA) is applying transdisciplinary policies to the NEPA process through its relatively new Eco-Logical framework (https://www.environment.fhwa.dot.gov/env_initiatives/eco-logical.aspx).

Complex sustainability problems for diverse and interconnected systems of interest requires transdisciplinary systems thinking. Transdisciplinary research projects typically involve three phases: problem transformation, interdisciplinary integration, and transdisciplinary integration [13, 14]. Brink et al. critically examined various transdisciplinary urban development and coastal adaptation post-research efforts in Sweden to identify actionable sustainability measures that proved useful to social actors and satisfied rigorous scientific quality criteria [13]. This review of transdisciplinary research projects found that epistemic integration would greatly benefit from establishing an initial systems framework to navigate and integrate the often-disparate transdisciplinary approaches, not only among the researchers, but also among the community and governmental stakeholders directly impacted by sustainability issues.

2. System Approach Framework

The SPICOSA (Science and Policy Integration for Coastal Systems Assessment) was a 4-year European Union (EU) project (2007-2011) purposed to stimulate systematic research restructuring and stimulate integration of new knowledge and methods throughout the European Region (http://www.spicosa.eu/) [15]. The resultant SAF (Systems Approach Framework) research product provided an organic holistic research approach for continued integrated assessment of diverse complex systems. The project involved 18 Study Site Applications (SSAs); 22 countries; 54 research institutes, universities, and small enterprises; and, multidisciplinary linking of ecological, economic, social, and governance sectors [16]. The program purpose was to create a collaborative system for scientific and transdisciplinary practitioners to improve the Coastal Zone Systems (CZS) sustainability decision-making process.

This intensive research and planning effort identified problems with integrating natural and social systems. The system model framework envisioned an improved coastal zone feedback loop by implementing systematic Ecological-Social-Economic (ESE) assessments. Reducing delay in feedback responses between economic or social changes in local communities in response to loss of natural system goods and services could potentially mitigate irreversible impacts on the natural system, and thereby improve system sustainability [16]. Reviewers identified lack of researcher training in applying systems science to the various disciplines as a consistent and fundamental research project weakness.

Disparity between multidisciplinary models in socio-economic and physical sciences also led to uncertain and sometime infective outcomes in applying transdisciplinary methodologies to complex coastal systems. Innovative alternative solutions for sustainability issues sometimes created controversy. Identifying and viewing coastal systems as a relational network with complex emergent properties can generally be beneficial when applying system thinking to developing effective policies that address local and regional sustainability issues [17]. As system boundaries grow and become more complex, effectiveness and enforceability of policies often conflict with self-preservation interests.

Hopkins et al [17] report that integrating systems thinking into research and policy making within the SAF research program generally resulted in expanding single-issue studies into multi-issue studies; expanding static to dynamic indicators; better defining boundaries between system-dependent and system-independent problems; and, establishing a quantitative basis for collaborative decision making. A key challenge involves consideration of scale interdependency and need for global scale-free networks to maximize integrated sustainability of human increasing dependency on coastal systems, particularly when facing growing risk factors from climate change combined with growing population density, development, and dependency on coastal at-risk environments.

3. IN-CORE Model Development

Evaluating sustainability for diverse natural and social systems when exposed to extreme natural hazard events challenges system sustainability models developed for non-extreme events. Resiliency systems models seek to incorporate sustainability by treating these extreme events as risk and recovery resilience paradigms [18]. Extreme events often cause irreversible damage to the fundamental environment and socio-economic systems, effectively creating an unsustainable system for both the environment and human actors. Quantifying resiliency and response of a system to an extreme event facilitates adapting built infrastructure to improve sustainability.

Predicting system vulnerability and failure limit states typically involves complex stochastic and empirical models. Modeling community disaster resilience requires transdisciplinary experts to collaborate in modeling how physical, economic, and social infrastructure systems within a real community interact and affect recovery efforts. A transdisciplinary research team from 10 universities evaluated diverse engineered and socioeconomic systems in assessing hurricane hazards for the Galveston Test Bed Model, along with other types of natural disasters as subsystem models within the parent Interdependent Networked Community Resilience Modeling Environment (IN-CORE) all-hazards model (http://resilience.colostate.edu/index.shtml). The model evaluates community impacts during extreme events and quantitatively measures resilience (https://ssa.ncsa.illinois.edu/isda/projects/in-core/).

The Colorado State University (CSU) Center for Risk-Based Community Resilience Planning integrates engineering, social sciences, and economic disciplines in comprehensively modeling community resilience. Systems that are essential for the recovery and vitality of a community (technological, financial, social/political support, healthcare delivery, education, and public administration) integrate within the IN-CORE model by simulating natural hazards and geospatially applying system fragility functions to publicly available asset inventories and databases. The model provides a quantitative and science-based approach to assess community resilience at the local and regional levels in response to natural disasters of varying intensities. The goal is to make local communities more resilient, and in doing so, improve the likelihood of long-term sustainability [19]. Developing the underlying systems science is challenging.

Marchese et al [20] examine the complex interrelation of resiliency and sustainability terminology with a thorough literature review. They note that there is significant opportunity to develop sustainability practices that improve consistency and integration with resiliency methods. They suggest framing sustainability as a critical function of a project, policy, or system, with that functionality maintained during and after an event. They recommend modeling those critical functions as a combination of environmental, social, and economic indicators. Integration of these two mutually inclusive system frameworks into a combined transdisciplinary approach potentially makes policy implementation more palatable, and risk mitigation measures more defensible.

Development of these models stimulates the subsequent challenge in applying systems thinking when integrating resiliency and risk assessment models into sustainability model system frameworks. Just as with the SPICOSA EU effort [17], the challenge in model development is to account for the core methodology's long-term sustainability and adaptability through research integration into policy and practice. If these transdisciplinary models and system frameworks are not resilient and robust in application, then developing and adapting these complex systems models becomes challenging and potentially ineffective.

4. Emergent Knowledge

The system design process should assess system vulnerabilities in evaluating sustainability. Sustainability infers the ability of a system of interest to be maintained at a given level or state. Functional sustainability infers the ability to maintain a certain rate or level of system functionality for the system of interest, while the system itself evolves and adapts. This requires either providing additional system inputs or expanding the system boundaries that allows the system to adapt with new emergent behavior properties while maintaining a consistent system functionality or output. Extreme vulnerability and lack of resiliency decreases a system's ability to adapt and demonstrate sustainability.

Transdisciplinary systems thinking considers various measures of adaptability and integration in assessing system sustainability, unlike independent disciplinary approaches. Assessing emergent behavior of integrated subsystems is extremely complex relative to subsystem and component functions, just as with transdisciplinary systems thinking. Coastal design concepts most often focus on spatial definition and performance of subsystems, with limited integrated system response analysis, particularly in response to extreme events and natural disasters. Prevailing reasoning predicts that all disasters generate catastrophic failure forcings for complex interrelated systems, such that the coastal system response is unpredictable and most likely unsustainable. While a coastal defense system may protect the built environment, resisting storm surge or wave forcings may cause consequential damage to the natural environment.

Direct epistemic benefits encourage continued integration of diverse disciplines for resiliency and sustainability research efforts, since literature shows *a posteriori* knowledge consistently emerges from most transdisciplinary research projects. Assessing coastal road system resiliency functions for the IN-CORE Galveston Test Bed Model included identifying critical system components shown in the Figure 1 systemigram.

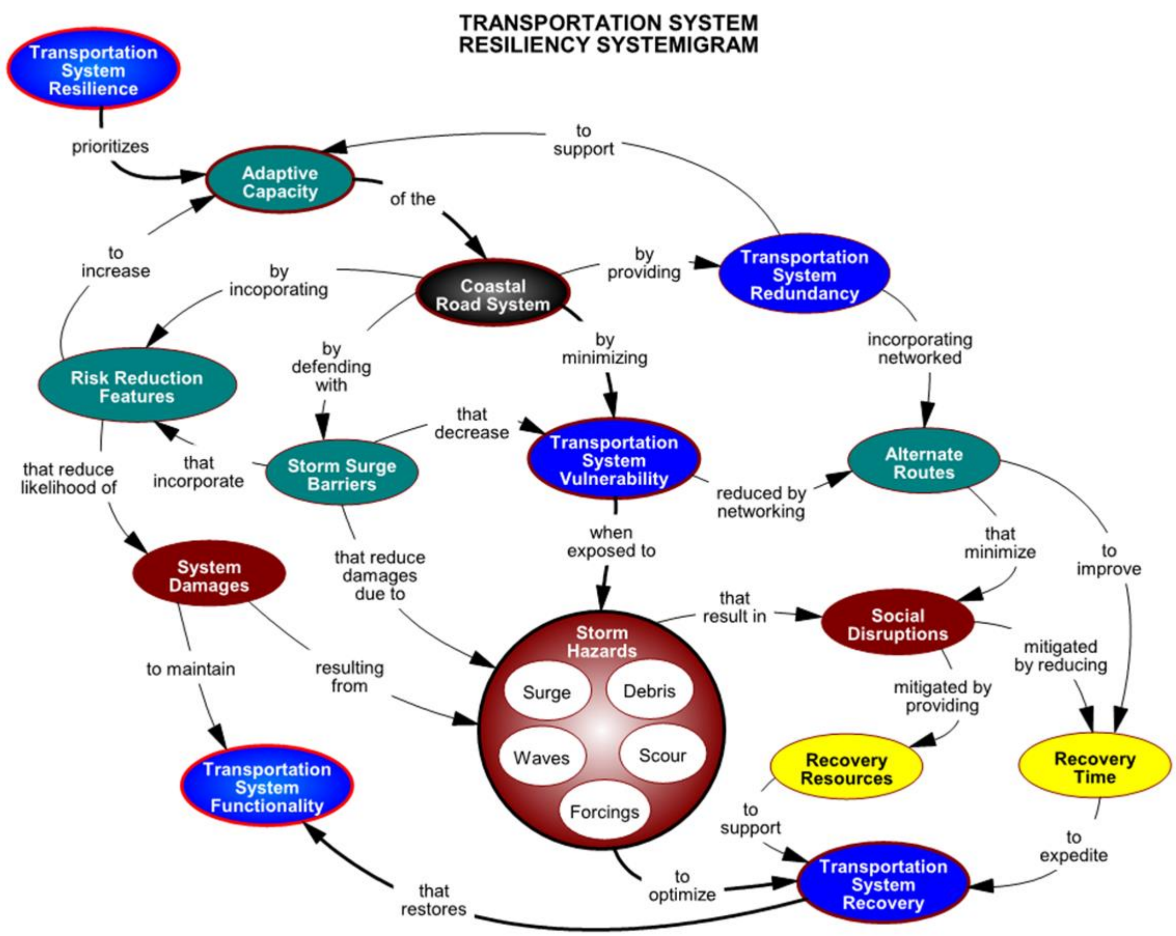

Figure 1: Transportation system resiliency systemigram.

Probabilistic systems analysis applied to ADCIRC+SWAN coastal model data for Hurricane Ike that hit the Galveston area in 2008 [21], identified strong correlations between road system damage relative to nodal site characteristics and coastal storm model data. Initial analyses compared various incremental intensity measure (IM) data from coastal model output to other measured and modeled attributes of the storm event, engineered, and natural system components. Output data for the Hurricane Ike hindcast model included wind fields, currents, storm surge elevations, flooding depths, and wave characteristics. Other transdisciplinary research teaming partners collaboratively and concurrently assessed storm model data and pre- and post-event records, including detailed damage assessments, in developing fragility function models [21]. These geospatial damage and recovery models evaluate economic, social, building, utility, and transportation infrastructure systems.

By analyzing incremental IM hourly output data from coastal storm numerical hindcast models, functional decomposition and coastal engineering disciplinary research identified cumulative celerity dispersion (CCD) functions that strongly predict likelihood and degree of coastal highway damage during extreme storm events. The coastal road system model responds to extreme storm events based on several key components as shown in Figure 2.

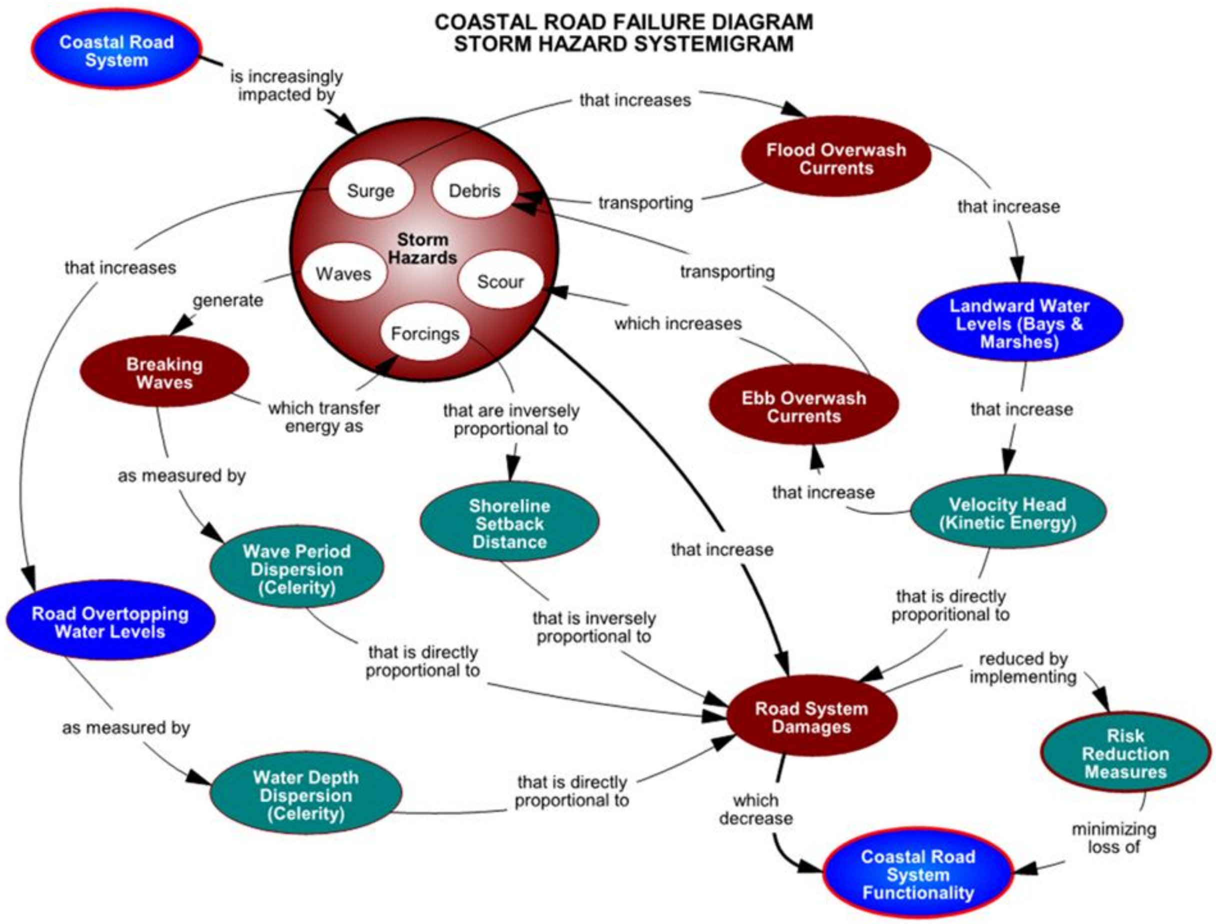

Figure 2: Coastal road resiliency systemigram.

5. Transdisciplinary Systems Thinking

Integration of systems thinking in a transdisciplinary team research effort provides opportunity to develop sustainable solutions for complex problems associated with any system-of-interest. The IN-CORE model research program is making significant advancements in defining resiliency and sustainability functions for complex natural and engineered systems. By evaluating engineered system failure during extreme events, numerical model data evaluated using both systems and coastal engineering analytics, led to significant findings regarding coastal road system failures. Correlating cumulative energy dispersion with likelihood and degree of failure will improve coastal road systems.

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