Ecology network analysis methods for balancing efficiency and resilience of critical systems and infrastructures

- ## Context of the research

Resource and infrastructure networks are critical to the functioning of society. These networks include electric power distribution networks, municipal water supply and wastewater treatment networks, public transportation systems, and supply chain networks. Traditionally the design of these networks aims to minimize their capital and operational costs and increase their efficiency. Efficiency as a system design goal can be tricky as it is defined and quantified differently depending on the field.
The uncertain nature and extent of hazards emerging in changing environments calls for attention to the properties of resilience of systems, in the face of large uncertainties. Differently from the concept of risk, resilience is focused also on the ability to prepare and recover quickly from an accident or disruptive event, which may be known or un-known. Managing for resilience, then, requires ensuring a system's ability to plan and prepare for the potential occurrence of accidents and disruptive events, and then absorb, recover, and adapt in case of occurrence.
Resilience is nowadays considered a fundamental attribute for systems that should be guaranteed by design, operation and management. It is characterized in terms of four properties, i.e. robustness, redundancy, resourcefulness, rapidity and four interrelated dimensions, i.e., technical, organizational, social, economic. It can be considered a new paradigm for risk engineering, which proactively integrates the accident preventive tasks of anticipation (imagining what to expect) and monitoring (knowing what to look for), the in-accident tasks of responding (knowing what to do and being capable of doing it) and learning (knowing what has happened), the mitigative tasks of absorbing (damping the negative impact of the adverse effect) and the recovery tasks of adaptation (making intentional adjustment to come through a disruption), restoration (returning to the normal state).
Resilience is inherently tied to the three pillars of sustainability: social, environmental and economic. A system that can effectively recover from a disaster is sustainable in that it can restore the original quality of life and function for the environment, society, and the economy.
There is, then, a need for an integrated approach to sustainability and resilience: if a system is to be designed for sustainability, it must take into account also vulnerabilities to possible disruptions.

The objective of the research is to study, develop and advance metrics, methods and frameworks for the balanced resilience and efficiency optimization of critical infrastructures, considering the large uncertainties, the heterogeneities and all relevant attributes involved. The research will look at exploiting the analogy with ecological systems, introducing concepts of information theory, entropy and ecological network analysis.

- **Objective of the research**

Methodology study, development and advancement; software tool development; case study solution.

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Quantifying sustainability: Resilience, efficiency and the return of information theory

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ABSTRACT

Contemporary science is preoccupied with that which exists; it rarely accounts for what is missing. But often the key to a system's persistence lies with information concerning lacunae. Information theory (IT), predicated as it is on the indeterminacies of existence, constitutes a natural tool for quantifying the beneficial reserves that lacunae can afford a system in its response to disturbance. In the format of IT, unutilized reserve capacity is complementary to the effective performance of the system, and too little of either attribute can render a system unsustainable. The fundamental calculus of IT provides a uniform way to quantify both essential attributes – effective performance and reserve capacity – and results in a single metric that gauges system sustainability (robustness) in terms of the tradeoff allotment of each. Furthermore, the same mathematics allows one to identify the domain of robust balance as delimited to a "window of vitality" that circumscribes sustainable behavior in ecosystems. Sensitivity analysis on this robustness function with respect to each individual component process quantifies the value of that link "at the margin", i.e., how much each unit of that process contributes to moving the system towards its most sustainable configuration. The analysis provides heretofore missing theoretical justification for efforts to preserve biodiversity whenever systems have become too streamlined and efficient. Similar considerations should apply as well to economic systems, where fostering diversity among economic processes and currencies appears warranted in the face of over-development.

1. Introduction: the importance of being absent

The late Bateson (1972) observed that science deals overwhelmingly with things that are present, like matter and energy. One has to dig deeply for exceptions in physics that address the absence of something (like the Pauli Exclusion Principle, or Heisenberg's uncertainty). Yet any biologist can readily point to examples of how the absence of something can make a critical difference in the survival of a living system. Nonetheless, because biology aspires to becoming more like physics, very little in quantitative biology currently addresses the important roles that lacunae play in the dynamics of living systems.

One might object that the use of information theory (IT) in genomics does indeed address matters like missing alleles, but

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Mimicking nature for resilient resource and infrastructure network design

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ABSTRACT

Increasingly prevalent extreme weather events have caused resilience to become an essential sustainable development component for resource and infrastructure networks. Existing resilience metrics require detailed knowledge of the system and potential disruptions, which is not available in the early design stage. The lack of quantitative tools to guide the early stages of design for resilience, forces engineers to rely on heuristics (use physical redundancy, localized capacity, etc.). This research asserts that the required quantitative guidelines can be developed using the architecting principles of biological ecosystems, which maintain a unique balance between pathway redundancy and efficiency, enabling them to be both productive under normal circumstances and survive disruptions. Ecologists quantify this network characteristic using the ecological fitness function. This paper presents the required reformulation required to enable the use of this metric in the design and analysis of resource and infrastructure networks with multiple distinct, but interdependent, interactions. The proposed framework is validated by comparing the resilience characteristics of two notional supply chain designs: one designed for minimum shipping cost and the other designed using the proposed bio-inspired framework. The results support using the proposed bio-inspired framework to guide designers in creating resilient and sustainable resource and infrastructure networks.

1. Introduction

Resource and infrastructure networks are critical to the functioning of society. These networks include electric power distribution networks, municipal water supply and wastewater treatment networks, public transportation systems, and supply chain networks. Traditionally the design of these networks aims to minimize their capital and operational costs [1,2] and increase their efficiency. Efficiency as a system design goal can be tricky as it is defined and quantified differently depending on the field. Thermodynamic engines define efficiency (first law efficiency) as the ratio of useful work extracted to the energy used [3]. Network efficiency [4] can be described as using the shortest path or the minimum number of paths to meet an end [5,6]. Economic efficiency is the smart allocation of sunken costs and imports to maximize profit from useful exports [7,8]. Sustainability-related efficiency seeks to minimize emissions [9,10], minimize resource consumption, and minimize waste generation [11,12].

Efficiency objectives are essential, especially at a time when economic growth and technology enable almost everything to be connected, but their exclusive use fails to account for a system's ability to respond to external disruptions. Natural disasters and extreme weather events are becoming more prevalent, presenting a counter-argument against single-minded efficiency goals. The United States has sustained more than 254 weather and climate disasters with damages of $1 billion or more (CPI adjustment to 2019) since 1980, with a total cost exceeding 1.7 trillion USD [13] (Fig. 1). Resource and infrastructure networks need to be capable of withstanding and recovering from disruptive events like these, a characteristic known as system *resilience*.

1.1. Resilience in engineered systems

Resilience is the ability of a system to *withstand and recover*, as defined by normal performance levels, from a disruptive event [14]. Readers looking for a comprehensive review of the emergence of the concept of engineering resilience and progress made towards quantitatively assessing its various aspects are encouraged to refer to [15–17].

System *resilience* is a multifaceted quantity. Currently, there is no single, universally accepted measure of resilience [efforts are being made in this direction, notably Ayyub [18], Henry and Ramirez-Marquez [19], and Yodo and Wang [20]]. Based on a survey of available literature [17,21–25], the following measures of resilience were selected: *survivability, time to recovery, and recoverability*. Survivability measures the ratio of the avoided drop in system functionality following a disruption against the maximum possible drop in system

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