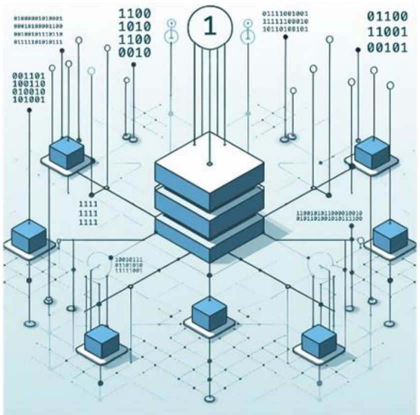
Scuola Superiore Meridionale

MERC PhD Project Proposal 2023/2024

Title of the research project

Robust and Resilient Complex Networks:
Data-Driven Analysis and Optimal Design



Keywords

Complex networks; Robustness and Resilience; Data-driven methodologies; Critical transitions; Network design

Supervisors

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Expertise: Statistics, Probability, Risk analysis

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Supervisor 4: **Mario di Bernardo** (mario.dibernardo@unina.it)
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Expertise: Control theory, Complex systems, Dynamical systems

Project description

Introduction

Context and motivation. The operation of the modern world is based on several critical network infrastructures, such as power grids, road networks, airports, the Internet, supply chains, and more. Normally they work seamlessly, but occasionally some disrupting events expose their limitations. Relevant examples include blackouts during peak energy consumption, traffic jams, global shortages of goods (e.g., face masks and tests during the Covid-19 pandemic, the 2020–2023 global chip shortage), and the 2021–2022 energy crisis in Europe. Additionally, more crises and shortages are prospected to come, as the demands for batteries and power distribution facilities increase in an electrifying world. Therefore, it is of uttermost importance to devise techniques to predict these events and to build infrastructure networks that can avoid or mitigate them. However, a crucial issue is that almost all modern essential infrastructure networks have a level of complexity for which models are either unavailable or intractable; therefore, there is the need for an approach that does not rely on the presence of a complete mathematical model to carry out these predictions and design.

In this project, we aim to exploit data-driven model-free or semi-model-free methodologies to analyze and design complex network systems.

State of the art. Sudden and noticeable changes in operation are called *critical transitions* (CT) and correspond, in dynamical systems theory, to bifurcations or changes in the stable solution. These events can be anticipated without the need for a model by assessing the statistical properties of so-called *early warning signals* [Scheffer, 2009]. For example, an increase in the variance of electrical brain activity can predict an epileptic seizure minutes before it happens. Other general indicators include an increase in autocorrelation and slowness in recovering from perturbations. In other cases, the occurrence of a critical transition cannot be easily forecast, because the event determining it is an impactful external event (e.g., a storm damaging a distribution line in a power network). In these cases, to prevent CTs it is still possible to characterize the *robustness* of the network (see, e.g., [Stürmer 2024])—i.e., its ability to withstand perturbations without undergoing a CT—or to study its *resilience*—i.e., its ability to adapt to new working conditions with little disruption (see, e.g., [Gao, 2016]). A significant body of work also exists that characterizes network robustness indirectly by studying dismantling attacks; nonetheless, these studies seldom account for the dynamics of nodes and edges, and the principles for designing resilient networks are often inferred indirectly from the analysis of successful attacks rather than being derived formally [Artime, 2024].

A limitation of most research concerning critical transitions in complex systems is that the existence of a possible network of interconnections is not explicitly accounted for. A recent exception is contained in [Masuda, 2024], which proposes a method to select a subset of nodes in a network, whose signals should be studied to better detect CTs. Still, it is unclear what is the best method to combine the signals from the nodes.

Concerning the design of robust and resilient complex networks, model-free methodologies are still lacking. Arguably, the first attempt at designing optimal network graphs from data was presented in [Coraggio, 2023], exploiting relevant examples to build optimally synchronizable graphs.

Objectives

The workplan and objectives are flexible and will be adapted depending on the inclination of the student and the results obtained in the early phases of the project.

- O1. Determine which signals are needed to forecast CTs in complex networks and how to combine them.
- O2. Determine if and how network signals can be used to characterize robustness and resilience of the network, and to infer the causes of faults.
- O3. Devise methods to build networks that are optimally robust/resilient.
- O4. Application and validation to a complex network of choice.

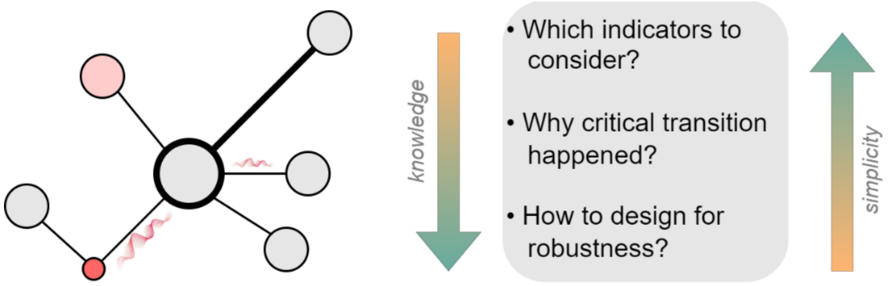

Figure 1: Illustration of a complex network with different perspectives on robustness. Node sizes and edge widths represent diversity in dynamics. Red coloring and waves represent early warning signals.

Methodology

The project will start with a comprehensive study of the literature concerning (i) the prediction of critical transitions in complex systems via early warning signals, and (ii) structural and dynamical resilience in networks.

Next, the focus will be on determining which and how many signals (coming from the nodes and links in a network) are needed to infer the occurrence of a CT, and what is the best way to combine them. The problem might be studied through a constructive approach, building networks with increasing levels of complexity (heterogeneity, state dimensionality, nonlinearities, noise, etc.), to then study their reaction to induced CTs. Then, the information on the most important early warning signals will be used to characterize the robustness of the network, measuring the capability to avoid/mitigate unpredictable events. Additionally, this knowledge will be used to obtain causality information regarding faults, possibly through *causal diagrams* [Pearl and MacKenzie, 2020]: that is, finding nodes/links that, if modified, can prevent the occurrence of a CT (see Figure 1).

Once the analysis is completed, the project will focus on the design of optimally robust graphs. The study might consider as a starting point the data-driven framework presented in [Coraggio, 2023] and expand it on the basis of the knowledge acquired in the first part of the project.

Finally, the newly developed methodology will be applied to study a realistic application scenario, chosen during the project. The possible application systems are energy/resource distribution networks or supply chains: the choice will depend on the availability of real data and on the interest of the student. Moreover, the project will culminate with actionable advice oriented towards designers and policy makers to build more efficient and resilient future infrastructure networks.

Relevance to the MERC PhD Program

Relevance and beneficiaries

With an ever more interconnected world, failures and poor planning of infrastructure networks affect millions of people. Fundamentally, this project aims at developing new methodologies to study the complex structures that sustain our societies. In particular, we aim to move away from the common assumption that mathematical models are available and tractable and wish to predict critical transitions and shortages only relaying on available data. If we are successful, we will provide usable tools not only to predict incoming shortages and outages—allowing us to better prepare for them—but also to build more resilient infrastructures to stand the test of time.

Relevance to the MERC PhD program

This project has a significant interdisciplinary component, combining both complexity science and the study of risk. Indeed, infrastructure networks will be studied in the framework of complex networks, and the risk of occurrence of critical transitions will be characterized through probabilistic and statistical data-based approaches.

Skills. During the project, both tutored by the supervisors and through self-study, the student will develop skills in several fields, including:

- Network science,
- Dynamical systems,
- Statistical inference and risk assessment.

Additionally, tutoring will also focus on sharpening the student's technical writing and presentation skills, as well as developing the ability to study scientific literature swiftly and effectively.

References

Key references

- O. Artime et al., "Robustness and resilience of complex networks," Nature Review Physics, 6:114–131, 2024
- M. Coraggio, M. di Bernardo, "Data-driven design of complex network structures to promote synchronization." arXiv.2309.10941, 2023.
- J. Gao, B. Barzel, A.-L. Barabási, "Universal resilience patterns in complex networks," Nature, 530(7590):307–312, 2016.
- N. Masuda, K. Aihara, N. G. MacLaren, "Anticipating regime shifts by mixing early warning signals from different nodes," Nature Communications, 15(1), 2024.
- M. Scheffer et al., "Early-warning signals for critical transitions," Nature, 461(7260):53–59, 2009.
- J. Stürmer, A. Plietzsch, T. Vogt, F. Hellmann, J. Kurths, C. Otto, K. Frieler, M. Anvari, "Increasing the resilience of the Texas power grid against extreme storms by hardening critical lines," Nature Energy, pp. 1–10, 2024.

Additional references

- C. Boettiger and A. Hastings, "Quantifying limits to detection of early warning for critical transitions," J. R. Soc. Interface., 9(75):2527–2539, 2012.
- M. Grassia, M. De Domenico, G. Mangioni, "Machine learning dismantling and early-warning signals of disintegration in complex systems," Nature Communications, 12(1):5190, 2021.
- J. Pearl and D. Mackenzie, The book of why: the new science of cause and effect, First trade paperback edition. New York: Basic Books, 2020.

Joint supervision arrangements

The student will meet at least weekly with at least one of the supervisors. The whole team will meet at least once every 1 or 2 months for a progress update.

Location and length of the study period abroad (min 12 months)

The student will be able to spend a research period (or research periods) at the lab of Prof. Jürgen Kurths at the Potsdam Institute for Climate Impact Research, in Germany.