(SEC) SINGAPORE-ETH CENTRE 新加坡-ETH 研究中心

(FRS) FUTURE RESILIENT SYSTEMS 未来韧性系统

FUTURE RESILIENT SYSTEMS (FRS)

CREATE ETH zürich NANYANG TECHNOLOGICAL UNIVERSITY NUS National University of Singapore PAUL SCHERRER INSTITUT PSI SMU SINGAPORE MANAGEMENT UNIVERSITY

CONTENT 内容

FOREWORD 前言

Singapore and Switzerland have been the top performers in the WEF global competitiveness assessment, which is based on an evaluation of the basic requirements, efficiency enhancers, and innovation and sophistication factors. Infrastructure is one important indicator, for which Singapore and Switzerland both perform among the top 4%. Those figures may create the impression that everything is under control.

From a systemic point of view, the perception might reveal the extremely limited space for development in Singapore and Switzerland, requiring a development of infrastructure systems, which are spatially arranged at very high density. This growth in density is in tandem along with an increasing degree of interconnectivity within and between systems, which–concurrently with the growth in asset density–makes the systems more vulnerable.

Singapore and Switzerland are both so-called SWOP (small well organised prosperous) countries with innovation-based economies, multi-ethnic contexts, high standards of living, and economic competitiveness that is commendable. In a fast moving, dynamic world, stagnancy would have severe consequences.

Future-oriented, problem-anticipating mind sets are important prerequisites to continuously improve the development for sustainability and robustness. The Future Resilient Systems is a research programme that will help Singapore to become one of the world leaders in future-oriented infrastructure design, and infrastructure management for robustness and resilience.

Prof Dr Hans Rudolf Heinimann
Future Resilient Systems Programme Director

INTRODUCTION 简介

In 2010, ETH Zurich and Singapore's National Research Foundation (NRF) established the Singapore-ETH Centre under the NRF's CREATE programme. The guiding idea was to present a cross-cultural, cross-disciplinary research platform to address the challenges of sustainable global development. The Future Cities Laboratory was launched in 2010 as the centre's first programme, aimed at developing new knowledge, technologies, and approaches for a sustainable urban future with an Asian perspective.

The Future Resilient Systems (FRS) is the second programme of the Singapore-ETH Centre, which aims to investigate critical infrastructure systems and explore novel approaches to make them more robust and resilient.

Critical infrastructure systems supply the essential services that support modern societies and maintain their anthropogenic metabolism. They are even more important for innovation-driven economies, among which Singapore and Switzerland have been key players. Improvements to such systems accompany the considerable growth of interconnections among system components as well as coupling between systems. Examples include those between supervisory control and data acquisition (SCADA) and engineered systems, which have resulted in gains in effectiveness and efficiency.

However, those achievements can also be overshadowed by an opposite trend in which novel phenomena and threats that arise from those couplings affect 'aggregated' behaviour on a systems level. Cascading failures are common within electrical power grids, such as those observed during blackouts in Italy (2003), Europe (2006), and New York City (2012).

The Future Resilient Systems programme provides a unique cross-disciplinary, cross-cultural environment in which to jointly explore how a team can make network-type infrastructure systems more robust and more resilient in the face of internal and external strains. Its approach of looking at infrastructure from a socio-technical perspective offers an opportunity to overcome discipline-driven research streams. That particular approach integrates engineered, operational, and user subsystems, thereby building bridges between disciplines and patterns of thought.

Albert Einstein once remarked, "We cannot solve our problems with the same thinking we used when we created them."

As Project members, we hope that this spirit will direct the work of FRS researchers and enable them to achieve more collaboratively than what might be attained through the sum of isolated, individual contributions.

(FRS) FUTURE RESILIENT SYSTEMS, 2014 – 2017 (Phase 1)

Management Committee (MC)
Prof Dr Hans Rudolf Heinimann (ETH)
Prof Dr Teck Hua Ho (NUS)
Prof Dr Tso-Chien Pan (NTU)

Cluster 1
INTERDEPENDENT CRITICAL INFRASTRUCTURE SYSTEMS

1.1 Understanding Interdependencies
1.2 Modeling Complex, Socio-Technical Infrastructure Systems
1.3 Resilience Metrics and Outliers
1.4 Optimal Management Strategies and Tactics

Cluster 2
ENERGY SYSTEMS AND COMPARATIVE ASSESSMENT

2.1 Assessing and Measuring Energy System Resilience
2.2 People and Operations in Resilient Systems

Cluster 3
SOCIAL AND BEHAVIOURAL FACTORS IN DECISION-MAKING

3.1 Human Decision-making in Risky, Dynamic and Complex Environments
3.2 Making Energy Demand More Sustainable and Resilient

GOVERNANCE

Future Resilient Systems (FRS) is the second programme of the Singapore-ETH Centre, which Governing Board is responsible for its strategic orientation. The Singapore-ETH Centre is led by the Director and Managing Director, supported by an administrative team in running the centre's two programmes.

The FRS programme is led by the Programme Director, and taps on the expertise of three groups of individuals in its management and research direction.

FRS Scientific Advisory Committee is made up of eminent scientists and technologists of international standing and is responsible for evaluating the progress of research carried out by FRS, consistent with ETH Zurich's standards of excellence and according to performance indicators.

FRS Management Committee consists of the FRS Programme Director as a representative from ETH Zurich, as well as representatives from local universities, NTU and NUS. The committee oversees the management of the FRS programme and progress of the programme in meeting its research and operational objectives.

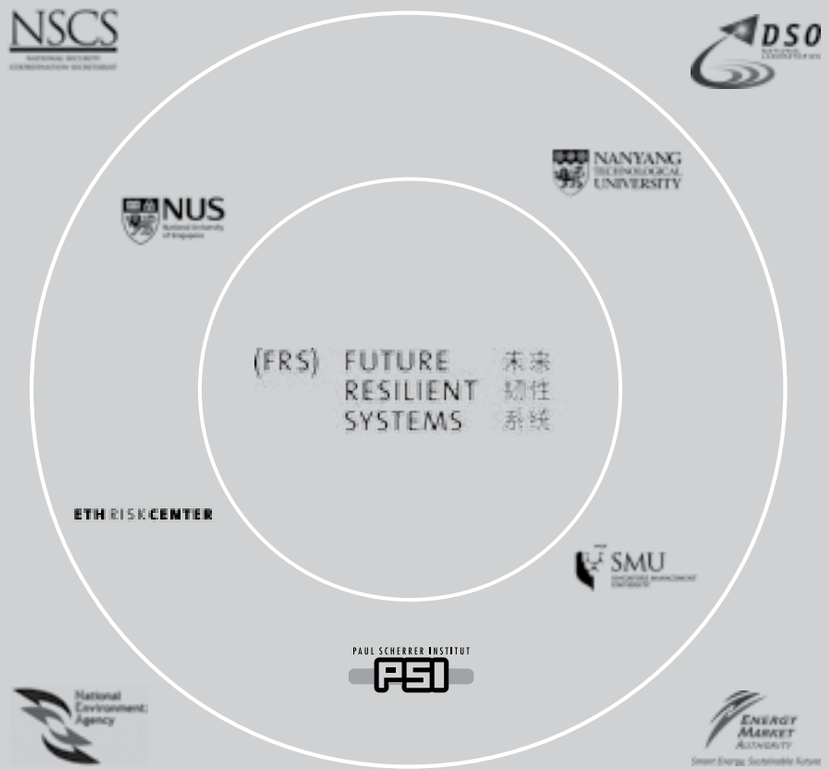
FRS Partnership Council brings together individuals from local government agencies and industry partners, with the main aim to foster and stimulate the interfaces between FRS, government agencies and industry, as well as to identify and frame emerging issues and trends that fall within the remit of FRS.

SEC inauguration ribbon-cutting ceremony officiated by (left to right) Prof Dr Ralph Eichler, Permanent Secretary Yong Ying-I, Federal Councillor Alain Berset, Minister Vivian Balakrishnan, Dr Fritz Schiesser, Prof Dr Gerhard Schmitt.
(Keng Photography, 2012)

PARTNERS 合作伙伴

Four universities - ETH Zurich, National University of Singapore (NUS), Nanyang Technological University (NTU), Singapore Management University (SMU) and one research organisation - Paul Scherrer Institute (PSI) jointly shape the research of the FRS programme.

The FRS also works closely with Singaporean government agencies, including the National Security Coordination Secretariat (NSCS), DSO National Laboratories, the Energy Market Authority (EMA) and the National Environment Agency (NEA).



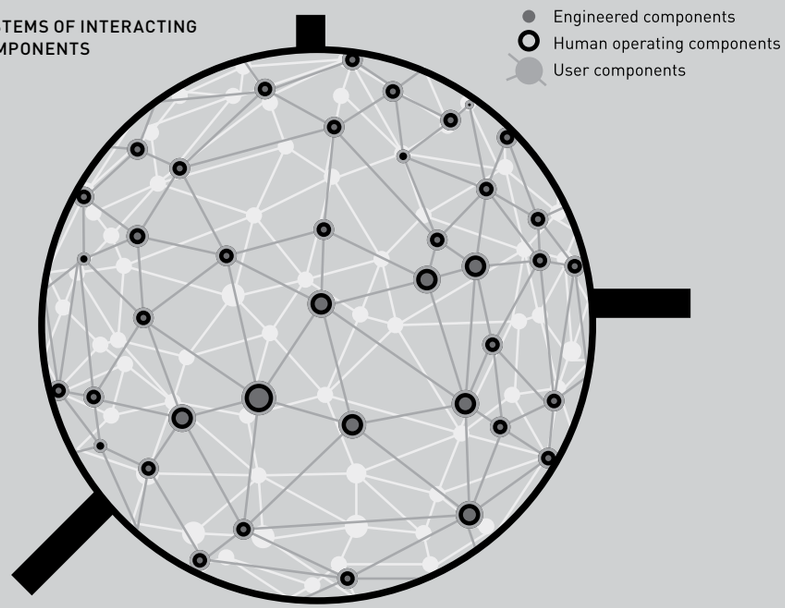
THE CHALLENGE

Both Singapore and Switzerland are small, well-organised, prosperous (SWOP) countries that are densely populated, and whose well-being and development depend upon critical infrastructure systems. This type of 'backbone' provides a reliable energy supply, transportation, communication, banking and finance, emergency, and other services that are essential for maintaining the 'metabolism' of urbanised societies, the disruption of which would have far-reaching consequences.

These infrastructure systems and services have grown into a web of inter-dependent components, and their interactions increasingly govern their behaviour. However, such enhanced connectedness causes novel types of disruptions that result from coupling. What usually begins as a small, local disaster eventually spreads and is amplified both within and between systems.

Critical infrastructures are not only physical but also include socio-technical systems that comprise three sub-systems: (1) the engineered system itself, (2) the organisational operation, and (3) users who consume those infrastructure services. Analyses of large-scale disruptions (NASA Columbia and Challenger explosions, toxic leaks at Bhopal, radiation contamination at Fukushima, etc.) have demonstrated that social sub-systems are often the weak link triggering the development of those disruptions.

SYSTEMS OF INTERACTING COMPONENTS



Our ability to understand those systems and events, to reveal their underlying complexities, and to model and analyse them, is quite limited. Novel scientific concepts, approaches, and tools are urgently needed to cope with this new type of 'complex, systemic behaviour', for which innovative, cost-effective strategies would then be developed to make systems more robust.

Because system disruptions and breakdowns are considered the result of an 'event-exposure-strain-response-effect' process, FRS is designed to address the following challenges:

- The range of hazards that are threatening and straining critical infrastructure systems has been increasing, whether natural, technological, economic, financial, social, or geopolitical in nature. It now includes novel types, such as cyber and political threats. We have also seen more 'beyond-statistical-distribution' events that are sometimes called 'black swans' or 'dragon kings'.
- The systemic behaviour of a socio-technical system – including decision-making behaviour – results in the emergence of new patterns of disruptive behaviour, such as the cascading spread of disturbances, oscillations triggered by feedback loops, multiple states of partial equilibrium, and phase transitions between different equilibria-regime shifts.
- Population growth, changing demographics, new technologies, ageing infrastructures, modified operating regimes, and the growing value density of assets in space – most prominently observed in mega cities – have amplified the emergence of such disruptions and system-associated responses.
- The traditional design approach was to set an upper, ultimate-strain boundary, against which a system's resistance was not to be pushed beyond its 'elasticity limit'. This assumption no longer holds for complex systems because the quantitative characterisation of triggering events and responses, such as cascades, has become quite uncertain. Systems must now be made more fault-
tolerant beyond pure resistance, enabling them to self-organise, recover, and learn. Such a design would, in fact, follow the model of a biological system.

OUR GUIDING IDEAS

The FRS stems from three guiding principles: (1) complex, socio-technical systems, (2) resilience, and (3) integrative risk management. Together, they are the foundation for a conceptual model of how the FRS should examine a critical infrastructure system, acting as a 'Pole star' to direct individual research programmes toward a joint, overarching goal.

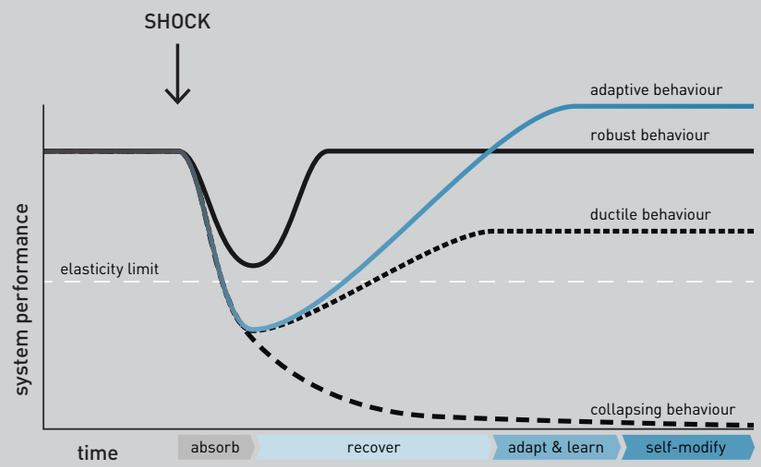
The term **socio-technical** refers to the interconnections between social and technical subsystems, and encompasses a variety of linear and non-linear relationships. Each of those subsystems has its own interacting components. Because social subsystems can be the weak link when dealing with large-scale disruptions, the FRS is intended for investigations of those subsystems, their operational organisation, and users, all of which are essential for improving the reliability and robustness of a particular system.

System resilience is the antagonist to system **resistance**, which has been the guiding concept to design a system that will withstand external shocks and strains. This concept works well as long as it is possible, within reason, to characterise the upper limits for potential strains and responses. The frequency of outliers, 'black swans', and 'dragon kings' is increasing, and the growing interconnectedness of systems has produced complex behavioural patterns. Therefore, a novel design approach that extends beyond simple resistance and stability is required.

Resilience is the capacity of a system to absorb disturbance and to reorganise so as to retain essentially its structures, functions and feedback loops. The first part of this definition refers to the capacity to absorb external strain by storing and transforming energy, while the second applies to recovery, which entails the release of 'shock energy', restoration of structure and functions, adaptive behaviour gained through self-organisation, or, eventually, self-transformation into a system with altered structure, functions, and feedback loops. Therefore, the combination of energy release, recovery, adaptation, and self-transformation is the essence of resilience that makes a system fault-tolerant.

Integrative risk management (IRM) is an emerging concept for coping systemic risks by (1) weighing an entire set of risk factors that could affect assets and important functions, and (2) considering the whole range of management options, from preparation to rehabilitation. This type of approach has been introduced because the frequency of catastrophes has quadrupled in the last 30 years, while related economic losses have risen by a factor of about 2,000. These phenomena are primarily explained by the dramatic increase in societal complexities and the growing cross-linking between systems and their individual components. However, there is still a lack of understanding about what functionalities IRM should provide and how to make this new, holistic approach effective and efficient.

WHAT IS RESILIENCE?



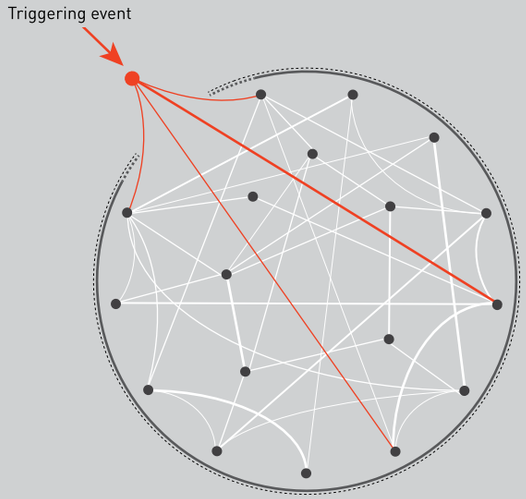
Resilience as response behaviour of a self-organising system to endogenous or exogenous shocks

The behaviour of an ant colony is not simply the sum of the behaviour of a group of average ants, but the result of coupled interactions that are making the difference. Such a system can be understood as a network of entities, the behaviour of which depends on the interactions with neighbours and on the coupling architecture. The key issue is how networks of interacting dynamical systems – be they electric power systems, the system neurons, or social systems – are behaving collectively.

The scientific study of complex networks emerged by the end of the 1990s when Barabàsi and Albert discovered that the distribution of connections from nodes may be characterised by a power law distribution, which triggered a new stream of research. Cascading failure is a phenomenon observed in complex networks, describing how the failure of a single component triggers the failure of successive components, or even the network as a whole.

Cascading failures in electric power networks caused outages, such as the Italian blackout in 2003, the European blackout in 2006, or the New York blackout in 2012, which left about 2.5 million people without power. Cascading failures have been observed in other systems, too, such as the financial crisis of 2007-2008 that spread around the world, resulting in downturns of the stock markets and in the collapse of large financial organisations.

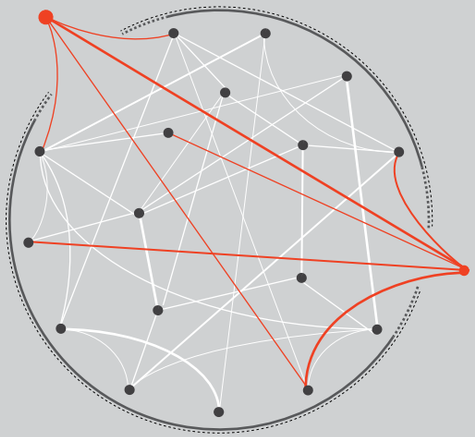
The key challenge is how to make whole systems robust for disruptions, which requires an improved understanding of how the topology of interactions governs the overall behaviour, and how the behavioural diversity of node entities affect the system as a whole.



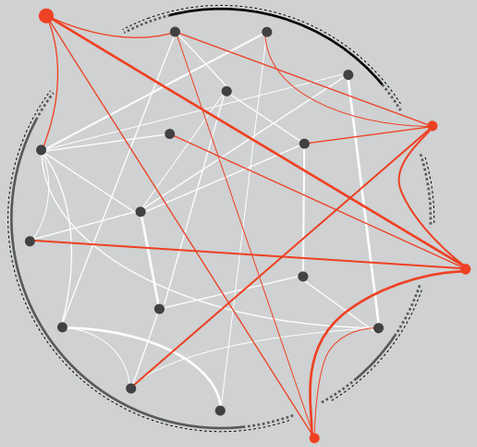
Triggering disruption

Cascading failure is a phenomenon in systems that consists of a large number of interconnected parts. A trigger event generates a local failure, straining nearby connected parts directly. This strain can result in an additional wave of disruption spread, resulting in a chain reaction, which can affect large parts of the system or even the whole system.

Superstorm Sandy, a hurricane hitting the northeastern United States in 2012, is an example of an event that triggered cascading failures. It led to a multitude of consequences. Subway and ferry services were disrupted for days, the three major airports had to be closed down, and the New York Stock Exchange and NASDAQ had to close for 2 days. A power blackout affected about one million homes and businesses, leaving a population of about 2.5 million without electricity.



Connections transfer the initial disruption



Disruption spread and cascade

OUR VISION

The FRS establishes a research platform based on cutting-edge expertise from the Swiss ETH Zürich and Paul Scherrer Institute (PSI), and from Singapore's National University of Singapore (NUS), Nanyang Technological University (NTU) and Singapore Management University (SMU). Its main objectives include:

- devising levers that concurrently improve the robustness and resilience of socio-technical systems, especially (1) novel methods to optimise the system-of-systems, (2) enhanced institutional arrangements, and (3) factors and contexts that positively frame decision-making by entities and individuals, jointly generating a target-oriented force field;
- increasing our understanding of the behaviour of complex systems, and developing the capability to model and predict their behavioural patterns, such as the emergence or cascading of social and physical disruptions;
- designing institutions ('rules of the game') and approaches that purposefully influence and shape decision-making; and
- educating a cohort of approximately 30 PhD students and 23 postdoctoral fellows who will experience cross-cultural, cross-disciplinary work in an inspiring and challenging research environment.

OUR APPROACH

Any large research project that ultimately aims to improve the robustness and resilience of complex infrastructures must deploy different dimensions of insights. The FRS combines methods to accomplish this by mapping and predicting the behaviour of large-scale systems, assessing system reliability, improving system robustness and resilience and encouraging conceptual/analytical work to develop new scientific approaches.

- Researchers within the FRS will perform observational studies, surveys, and experiments that evaluate organisational interdependencies and infrastructure growth as well as factors that shape decision-making in general and energy-efficient decision-making in particular.
- An essential goal is to improve our understanding of the behaviour of complex infrastructures under different conditions. Models will be developed to map a system's behaviour 'close-to-reality' and support an environment for studying responses induced by disruptions. Distributed simulations will provide a means for testing the system-of-systems. By improving the methods used for assessing the reliability and resilience of various energy and energy-supply systems, policy-makers will be able to obtain more informed counsel on such matters.

- New tools will be developed to analyse multi-criteria decisions related to energy systems, as well as to evaluate human reliability across several sectors of infrastructure.
- Another cluster of insight, which then influences system structures and behaviour, involves the identification of optimal, cost-effective solutions for improvement and learning how to deploy a controlled engineering approach to detect and suppress disruptions in close to real-time, adjust the requisite institutional arrangements, and design the best architectures and framing instruments so one can shape the process of decision-making.
- Finally, conceptual and analytical insights are expected to provide new approaches to identify hidden interdependencies, developing frameworks to quantify resilience, and detect and suppress 'outlier' events 'beyond statistical distributions'.

The FRS focuses on energy-supply systems as a model that could be applied to complex infrastructure systems in general. Participating researchers are interested in creating generic approaches and methods that are transferable to other systems.

The three clusters within FRS include: (1) interdependent critical infrastructure systems, (2) energy systems and comparative system assessment, and (3) social and behavioural factors in decision-making. Further divisions into 8 modules and 23 submodules will present unique opportunities to approximately 30 PhD students, 23 postdoctoral fellows, and other researchers, all of whom will be able to develop their skills and contribute toward the endeavour to achieve more robust and more resilient critical infrastructure systems.

CLUSTER

1

INTERDEPENDENT CRITICAL INFRASTRUCTURE SYSTEMS

(Socio-Technical Systems)

重要基础设施系统的相互依赖性研究

MODULE

1.1

TEAM

Prof Dr Sulfikar Amir (NTU)
Prof Dr Hans Rudolf Heinimann (ETH)
Prof Dr Edmond Lo (NTU)
Prof Dr Tso-Chien Pan (NTU)
Prof Dr Defeng Sun (NUS)
Prof Dr Kim-Chuan Toh (NUS)
Prof Dr Huan Xu (NUS)

UNDERSTANDING INTERDEPENDENCIES

基础设施的系统架构与内在机理

Critical infrastructure systems are socio-technical entities. They comprise engineered, organisational, and user subsystems that interact physically, logically, and socially. Previous research efforts have modeled those interactions as links, assuming that they were primarily of a physical nature.
In contrast, only a few studies have explored the effect of social interactions.

This submodule addresses three major challenges by:

- improving our understanding of social interdependencies;
- developing a methodology to identify hidden interdependencies, of which is assumed to be rising with increasing system complexity; and
- learning how critical infrastructure networks are adapting to greater urbanisation.

Examining social interdependencies will allow us to measure the extent of organisational interdependencies so that we can explore how a system responds to failure and malfunction. Participants can also gain insights into how organisational arrangements affect system-level robustness and resilience.
As the basis for this submodule, a comparative study of the electrical grid systems in Singapore and Switzerland will be conducted. The main focus will be on developing methods to modify or adapt systems to increase their capacity to cope with crisis and disruptions.

Hidden interdependencies will be analysed so that one can devise a novel method for representing and modeling socio-technical critical infrastructure systems. Researchers will investigate the existence of latent, unobserved interdependencies, which is a pioneering problem. They will approach this challenge by using/adapting sophisticated data-mining techniques (Gaussian graphical models), the power of which must be determined from standard data sets before being tested and validated with real-world data sets.

Finally, study of infrastructure growth will be based on the fact that infrastructure systems are not static, but expand in line with urban development. We will investigate historical data for energy infrastructures that are currently at different stages of development in Singapore, Zürich, and a third Asian city. This will reveal how parameters for city growth are related to mechanisms for establishing infrastructure. Based on those same cities, we will assess the predictive power of scaling laws recently developed at the Santa Fe Institute which have been demonstrated to be rather generic across cities, nations, and time scales.

MODULE

1.2

TEAM

Prof Dr Sulfikar Amir (NTU)
Prof Dr Sai Hung Cheung (NTU)
Prof Dr Hans Rudolf Heinimann (ETH)
Prof Dr Tso-Chien Pan (NTU)
Prof Dr Peng Wang (NTU)

MODELING COMPLEX, SOCIO-TECHNICAL INFRASTRUCTURE SYSTEMS

基础设施的社会技术系统复杂建模

The complexity of critical infrastructure systems arises from numerous interacting components within and between systems. The best available simulations do not yet map system properties close enough to reality, with the majority based on topology only. Physical components are usually assumed to behave discretely and to respond without delay. Also, most approaches consider only individual human error and behaviour, neglecting organisational factors and adaptation.

By contrast, the components of this submodule are intended to:

- conceptualise , specify, and utilise a distributed-simulation environment;
- concurrently implement an environment that integrates available built-to-purpose models, newly developed FRS models, and the coordinating runtime infrastructure; and
- execute system-of-systems simulations that represent interactions among physical, cyber (SCADA), and social systems.

The *Systems Integration* component is meant to develop a distributed-simulation environment that can integrate a set of models (available, newly developed within FRS, or newly developed elsewhere) to produce a *system-of-systems* environment. This will facilitate the study of interactions between systems. The submodule will support and coordinate all model-development processes through a rigid systems-engineering approach to guarantee that model interoperability is a development issue from the very beginning of the process.

The *Efficient Physical Infrastructure Modeling* component improves the touch of reality within critical infrastructure models, which often assume a discrete physical state of its components (working/not working) and the lack of delay in behavioural responses. An agent based modelling system, in which physical agents behave according to underlying physical laws, will enable the exploration of different mechanisms for system failure to understand cascading collapses and blackouts.

The *Socio-Technical Modeling* component aims to enhance the confidence of human/organisational reliability models by explicitly considering organisational factors and dynamics. It will develop a hybrid simulation model that represents mutual interactions between social and technical entities, and is also linked to a disruption model that generates endogenous organisational disturbances. The expected outcome of these efforts is a compound system for simulating the behaviour of a technical-organisational infrastructure system.

MODULE

1.3

TEAM

Prof Dr Hans Rudolf Heinimann (ETH)
Prof Dr Didier Sornette (ETH)
Dr Dorsa Sanadgol (ETH)

RESILIENCE METRICS AND OUTLIERS

稳健性的量化与异常事件管理

The traditional approach for protecting against external and internal disruptions has been to design a system with *limit-state resistance* that can withstand high magnitude-low probability disruptions, based on statistical analysis. Complex infrastructure systems face new challenges because disruptions that are *beyond extreme value distributions* cannot be predicted through outdated methods.

Resilience is an emerging concept that enhances the *resistance* view with *recovery, adaptation, and learning* capabilities so that a system can cope with increasing uncertainties. Other promising strategies can anticipate or even predict *beyond-extreme-distribution* events.

This submodule aims to:

- develop metrics to characterise the resilience of both single socio-technical systems and system-of-systems;
- identify a network representation for critical infrastructure systems that utilises node resilience and between-node interdependencies to estimate overall system resilience, while also integrating site- and technology-specific disruptions;
- investigate the predictive strength of methods for detecting dragon kings ex-post and ex-ante; and
- evaluate strategies to cope with such dragon kings.

Potential resilience metrics can be explored through real-world data sets (e.g. financial systems, electric power grids) to determine how the real-time response-recovery functionality of a set of components may be quantified and aggregated at the systems level. Moreover, participants can evaluate how combinations of different disruption classes may be assessed at that level.

One component – *Extreme Events in Industrial and Cyber Systems* – will examine the power of different methods to detect *dragon king* events by systematically studying the conditions and circumstances under which dysfunctions and breakdowns can cascade. It will model the interactions of endogenous components, pre-existing vulnerabilities, and the fragility of the human–industrial complex in a dynamic framework to understand the path by which extreme events emerge. Finally, researchers will introduce tiny, occasional perturbations so that they can identify potential ways to suppress such events.

MODULE

1.4

TEAM

Prof Dr Stefan Bechtold (ETH)
Prof Dr Gerard Hertig (ETH)
Prof Dr Tsan Sheng Ng (NUS)
Prof Dr Tso-Chien Pan (NTU)
Prof Dr Melvyn Sim (NUS)
Prof Dr Chung Piaw Teo (NUS)
Prof Dr Kevin Gaoxi Xiao (NTU)

OPTIMAL MANAGEMENT STRATEGIES AND TACTICS

风险管理策略与方法优化

The management of critical infrastructure systems still mainly relies on rules of thumb, whereas mathematical optimisation techniques are rarely used to identify the best possible solutions. Assuming that budget constraints become more far-reaching in the future, the cost-effectiveness of decisions must be improved on three levels: operations, governance, and institutional framework.

This submodule aims to:

- identify the most cost-effective strategies and tactics for system improvements mathematically,
- achieve early detection of unwanted disruptions and regime shifts using real-time systems data, and
- develop risk-informed policy-making approaches as an alternative to incentive regulation.

The *optimisation* component focuses on the idea that uncertainties often rely on stochastic random variables with known probability distributions and correlations, which is problematic for critical infrastructure systems. The goal is to overcome the weaknesses inherent to mathematical optimisation, simulation, and stochastic and dynamic programming. Instead, a scalable and rigorous approach for network-modeling can be taken to describe, analyse, and optimise critical infrastructure systems.

The *infrastructure systems risk monitoring, detection, and control* component assumes system protection to be a control problem, so that one must either pin a system to a favourable status or else identify a means for optimal control that drives a system back to its normal region. Here, participants will devise novel monitoring schemes for complex networks, develop reaction and/or isolation schemes, and introduce protection schemes based on real-time systems control.

The *infrastructure policy-making as an alternative to incentive regulation* component addresses the problem of how to make systems for communication and business transaction infrastructure more reliable and robust. Two alternative approaches are possible: (1) constrain transaction flows ex ante with design rules (structural remedies), or (2) influence the operation and use ex ante with liability regimes or disincentives (behavioural remedies). This study will aim at determining which of the two performs best, based on a comparative analysis of different jurisdictions (Switzerland, Singapore, the European Union, and the United States).

CLUSTER

2

ENERGY SYSTEMS AND COMPARATIVE ASSESSMENT

(Holistic Energy System Assessment)

能源系统与比较评估研究

MODULE

2.1

TEAM

Dr Peter Burgherr (PSI)
Prof Dr Nan Chen (NUS)
Prof Dr William B. Haskell (NUS)
Dr Stefan Hirschberg (PSI)
Prof Dr Kim Leng Poh (NUS)
Dr. Matteo Spada (PSI))
Prof Dr Loon Ching Tang (NUS)

ASSESSING AND MEASURING ENERGY SYSTEM RESILIENCE

能源系统稳健性的评估与度量

Energy systems are one of the backbones of developed societies. Their failure can have dramatic consequences, as witnessed in the northeastern United States during the blackouts associated with Hurricane Sandy in 2012. Therefore, we must advance our knowledge about how different types of energy systems are affected by technical, human-induced, or natural disruptions. In doing so, we can improve current systems and develop more robust long-term energy strategies.

Within *comparative assessment of energy systems*, the following activities will be carried out:

- performing comparative assessment of accident risks across a broad range of current and future energy supply chains, based on available historical experience and probabilistic approaches, complemented by hybrid approaches including use of expert judgment;
- establishing a comprehensive set of resilience indicators with emphasis on security of supply;
- developing tools to support decision-making and to contribute to improving possibly conflicting energy planning processes.

The *energy system accident risks and indicators* component will investigate a wide spectrum of energy technologies (centralised, decentralised, fossil, renewable and nuclear) that may be affected by technical failures, human failures, intentional attacks and natural hazards. Information about relevant historical accidents available within PSI's Energy-related Severe Accident Database (ENSAD), the most comprehensive database on accidents in the energy sector, will be further extended both in terms of content and scope of analytical methods for comparative evaluation.

The focus will be on Singapore and the neighbouring countries, although comparisons with other regions are also essential to put results into perspective. The study will account for the impacts of prospective technological advancements with a time horizon until year 2050.

The *security of supply and resilience* component will focus on the entire energy supply chain, covering the procurement of energy carriers, energy conversion operations, energy distribution and waste disposal. The study will explore different methodologies, e.g., robust optimisation, system dynamics, and resilience network modelling that can be applied to support planning problems under uncertainty.

MODULE

2.2

TEAM

Prof Dr Michel-Alexandre Cardin (NUS)
Dr Vinh Dang (PSI)
Prof Dr William B. Haskell (NUS)
Dr Stefan Hirschberg (PSI)
Dr Luca Podofillini (PSI)
Prof Dr Kim Leng Poh (NUS)

PEOPLE AND OPERATIONS IN RESILIENT SYSTEMS

稳健性系统的人员与运筹

The *People and Operations in Resilient Systems* module concentrates on the human factor in socio-technical systems, recognising that human actions and decisions can contribute to as well as mitigate system disruptions. The awareness that human actions can strongly affect other system components and disturbance scenarios motivates an essential part of probabilistic risk assessments (PRAs), the human reliability analysis (HRA).

HRA and other methodologies that address how human interactions with systems impact their resilience can be improved by:

- performing assessments of human tasks across infrastructure sectors to devise a cross-sectorial HRA tool,
- exploring novel ways to monitor and forecast the reliability of energy systems with advanced statistical methods, and
- developing tools to assess maintenance and/or adapt decisions to enhance the reliability of a particular system.

The *human performance and the resilience of sectors* submodule involves a comparative assessment of sectors within energy, transport, and distribution networks. It aims to identify equivalent tasks, their working contexts, and reference reliability values. Based on those findings, we have proposed that a framework be created for HRAs that can then be used to analyse critical scenarios within and across sectors.

The *operations, maintenance policies, flexibility and resilience component investigates* ways to increase system reliability. The goal is to assess how training, performance monitoring, and evaluation can effect better operation and maintenance. It also looks at the degradation of system components and whole systems by taking a random-effect model approach that should produce more realistic estimates of their remaining useful life (RUL).

Upon completion of that assessment, researchers can analyse different maintenance policies for operational costs, risk, expansion, flexibility, and resource constraints. Finally, this component should serve as a guide in developing an economic model that determines the best way to design, deploy, and strategically manage, while also accounting for uncertainties in the long term.

CLUSTER

3

SOCIAL AND BEHAVIOURAL FACTORS IN DECISION MAKING

(Behaviour of System Users)

决策理论的社会学与行为学研究


AIG

MODULE

3.1

TEAM

Prof Dr Georgios Christopoulos (NTU)
Prof Dr Teck Hua Ho (NUS)
Prof Dr Jochen Reb (SMU)
Prof Dr Eko Riyanto (NTU)
Prof Dr Walter Theseira (UniSIM)

HUMAN DECISION-MAKING IN RISKY, DYNAMIC, AND COMPLEX ENVIRONMENTS

复杂环境下人类的决策行为分析

Infrastructure is a facet of engineered, organisational, and user subsystems that relies heavily upon human behaviour. Conscious action is a result of decision-making, i.e. the choice element of a broader *perception-appraisal-choice-response* process. Although there is evidence that factors such as working context, cultural habits, norms, personality traits, or affective status can influence and modulate that process, our knowledge about how those factors shape decision biases or cognitive failures is limited.

The objectives of this submodule are to:

- Improve the descriptive accuracy of decision-making models beyond perfect rationality by considering psychological effects more realistically, and
- Investigate the impact that design of decision contexts (choice architecture) has on the effectiveness of resource consumption.

The *insurance purchase* component investigates why take-up rates to protect against catastrophic events are much lower in Asia than in Western countries, hypothesising that large family networks affect those rates negatively and actual rates are being crowded out by realised insurance contracts. Therefore, a series of laboratory and field experiments will be run to obtain evidence that might be useful in formulating informed public policies.

The *social decision-making* component examines how people's preferences are changing due to disruption-induced stresses. It involves a series of laboratory experiments on how stress alters social preferences, and how social and cultural identities shape those changes. The goal is to gain insights into changes in preferences and behaviour when stress is induced by crisis and duress.

The *choice architecture* component builds on the hypothesis that an intelligent design of the choice context enables decision-makers to make *good* decisions. Here, several choice architecture principles will be tested for their effectiveness, with the intent to reduce energy consumption while improving our under-standing of how those principles affect resource consumption in general.

The *portfolio preference* component looks at dynamic decision-making contexts. It comprises a set of risky prospects for which the outcome probabilities are changing. It aims to investigate how people make choices, update their risk preferences, and adapt their behaviour, and seek to determine what type of interventions can bring decisions closer to optimality.

MODULE

3.2

TEAM

Prof Dr Youngho Chang (NTU)
Prof Dr Georgios Christopoulos (NTU)
Prof Dr Teck Hua Ho (NUS)
Prof Dr Euston Quah (NTU)
Prof Dr Renate Schubert (ETH)

MAKING ENERGY DEMAND MORE SUSTAINABLE AND RESILIENT

可持续与稳健性的能源需求

Infrastructure systems provide a network of service flows between sources (production facilities) and sinks (end-users). Electricity is an essential service that consumers and companies *pull* through the system. One approach to make those systems more robust and resilient is to control the investment and consumption behaviour of private households and companies, on the basis that modulating mechanisms will significantly dampen consumption growth rate.

Therefore, this module is designed to:

- investigate factors that shape energy-efficient purchase and usage behaviour;
- evaluate instruments that have a positive effect on energy-efficient behaviour for a set of outcome benefits and disservices, e.g. the tendency to offset the beneficial effects (rebound effects).

The *purchase/investment decisions* component will analyse the lifecycle costs associated with electrical appliances, and to look at how sensitive it is to electricity costs. Qualitative interviews on approximately 2,000 appliance buyers will be conducted to identify the most important factors that shape behaviour when purchasing energy-efficient equipment. This study will compare time preferences (discount rates) with purchase behaviour, and look for differences between the Swiss and the Singaporean subsets.

The *usage behaviour* component will investigate energy-efficient consumption behaviour to evaluate the impact of inertia, mental accounting, time and risk preferences, and links by individuals to a social environment. It will evaluate employee energy-efficiency, the activation of social networks, and the effectiveness of smart payment mechanisms. Additionally, it will examine the effect of mental budgeting and energy-savings contests, to better understand how feed-back mechanisms and conditions trigger positive spillover effects.

The *instrument choice* component aims to provide evidence about which instruments are the most promising for fostering energy-efficient behaviour. Measures of effectiveness will be analysed, such as cost-benefit ratios, possible energy-savings, potential greenhouse gas emissions, and corresponding rebound effects that represent behavioural responses and that tend to offset benefits. Data will be collected from a panel study with 2,000 voluntary participants, accompanied by a longitudinal survey to obtain information on increasing and decreasing energy demands within households and companies.

PEOPLE 主要人员

SINGAPORE-ETH CENTRE GOVERNING BOARD

Prof Dr Pin Lim (Co-Chair)
National University of Singapore, Singapore
University Professor, School of Medicine

Prof Dr Lino Guzzella (Co-Chair)
ETH Zurich, Switzerland
President

Prof Dr Bertil Andersson
Nanyang Technological University, Singapore
President

Prof Dr Detlef Günther
ETH Zurich, Switzerland
Vice President for Research and International Relations

Prof Dr Eng Chye Tan
National University of Singapore, Singapore
Deputy President (Academic Affairs) and Provost

Prof Dr Ralph Eichler
ETH Zurich, Switzerland
Former President & Emeritus Professor

Prof Dr Teck Seng Low
National Research Foundation, Singapore
Chief Executive Officer

SINGAPORE-ETH CENTRE DIRECTORS

Prof Dr Peter Edwards
SEC Director
ETH Zurich
Singapore-ETH Centre
edwards@env.ethz.ch

Dr Remo Burkhard
SEC Managing Director
ETH Zurich
Singapore-ETH Centre
remo.burkhard@sl.ethz.ch

FRS MANAGEMENT COMMITTEE

Prof Dr Hans Rudolf Heinimann (ETH)
FRS Programme Director
hans.heinimann@frs.ethz.ch

Prof Dr Tso-Chien Pan (NTU)
Executive Director
Institute of Catastrophe Risk Management
NTU

Prof Dr Teck Hua Ho (NUS)
Deputy Vice President for Research and Technology

FRS SCIENTIFIC ADVISORY COMMITTEE

CHAIR

Prof Dr Jerome Apt
Professor of Technology & Director of Carnegie Mellon Electricity Industry Center
Carnegie Mellon University

MEMBERS

Prof Raissa D'Souza
Professor of Computer Science and Mechanical and Aerospace Engineering
University of California, Davis

Sim Cheng Hwee
Director
Integrated Decision Systems Consultancy Pte Ltd

Dr Wilhelm Krull
Secretary-General
Volkswagen Foundation

Prof Dr Enrico Zio
Director of the Chair on Systems Science and the Energy Challenge
Ecole Centrale Paris and Supelec

CORE RESEARCH TEAM CLUSTER 1

Prof Dr Sulfikar Amir (NTU)
School of Humanities and Social Sciences
sulfikar@ntu.edu.sg

Prof Dr Stefan Bechtold (ETH)
Department of Humanities,
Social and Political Sciences
stefan.bechtold@ip.gess.ethz.ch

Prof Dr Sai Hung Cheung (NTU)
School of Civil and Environmental Engineering
shcheung@ntu.edu.sg

Prof Dr Hans Rudolf Heinimann (ETH)
ETH Risk Center and Department of Environmental Systems Sciences
hans.heinimann@frs.ethz.ch

Prof Dr Gerard Hertig (ETH)
Department of Humanities,
Social and Political Sciences
gerard.hertig@recht.gess.ethz.ch

Prof Dr Edmond Lo (NTU)
Institute of Catastrophe Risk Management
cymlo@ntu.edu.sg

Prof Dr Tsan Sheng Ng (NUS)
Department of Industrial & Systems Engineering
isentsa@nus.edu.sg

Prof Dr Tso-Chien Pan (NTU)
Institute of Catastrophe Risk Management
cpan@ntu.edu.sg

Dr. Dorsa Sanadgol (ETH)
Department of Management, Technology and Economics
dsanadgol@ethz.ch

Prof Dr Melvyn Sim (NUS)
NUS Business School,
Department of Decision Sciences
melvynsim@nus.edu.sg

Prof Dr Didier Sornette (ETH)
ETH Risk Center and Department of Management, Technology, and Economics
dsornette@ethz.ch

Prof Dr Defeng Sun (NUS)
Department of Mathematics
matsundf@nus.edu.sg

Prof Dr Chung Piaw Teo (NUS)
NUS Business School,
Department of Decision Sciences
dschead@nus.edu.sg

Prof Dr Kim-Chuan Toh (NUS)
Department of Mathematics
mattohkc@nus.edu.sg

Prof Dr Peng Wang (NTU)
School of Electrical & Electronic Engineering
epwang@ntu.edu.sg

Prof Dr Kevin Gaoxi Xiao (NTU)
School of Electrical & Electronic Engineering
egxxiao@ntu.edu.sg

Prof Dr Huan Xu (NUS)
Department of Mechanical Engineering
mpexuh@nus.edu.sg

CORE RESEARCH TEAM CLUSTER 2

Dr Peter Burgherr (PSI)
Laboratory of Energy Systems Analysis
peter.burgherr@psi.ch

Dr Stefan Hirschberg (PSI)
Laboratory of Energy Systems Analysis
stefan.hirschberg@psi.ch

Prof Dr Michel-Alexandre Cardin (NUS)
Department of Industrial & Systems Engineering
macardin@nus.edu.sg

Dr Luca Podofillini (PSI)
Laboratory for Energy Systems Analysis
luca.podofillini@psi.ch

Prof Dr Nan Chen (NUS)
Department of Industrial and Systems Engineering
isecn@nus.edu.sg

Prof Dr Kim Leng Poh (NUS)
Department of Industrial & Systems Engineering
isepohkl@nus.edu.sg

Dr Vinh Dang (PSI)
Laboratory of Energy Systems Analysis
vinh.dang@psi.ch

Dr. Matteo Spada (PSI)
Laboratory for Energy Systems Analysis
matteo.spada@psi.ch

Prof Dr William B. Haskell (NUS)
Department of Industrial and Systems Engineering
isehwb@nus.edu.sg

Prof Dr Loon Ching Tang (NUS)
Department of Industrial & Systems Engineering
isetlc@nus.edu.sg

CORE RESEARCH TEAM CLUSTER 3

Prof Dr Youngho Chang (NTU)
School of Humanities and Social Sciences
isyhchang@ntu.edu.sg

Prof Dr Jochen Reb (SMU)
Lee Kong Chian School of Business
jreb@smu.edu.sg

Prof Dr Georgios Christopoulos (NTU)
Nanyang Business School
cgeorgios@ntu.edu.sg

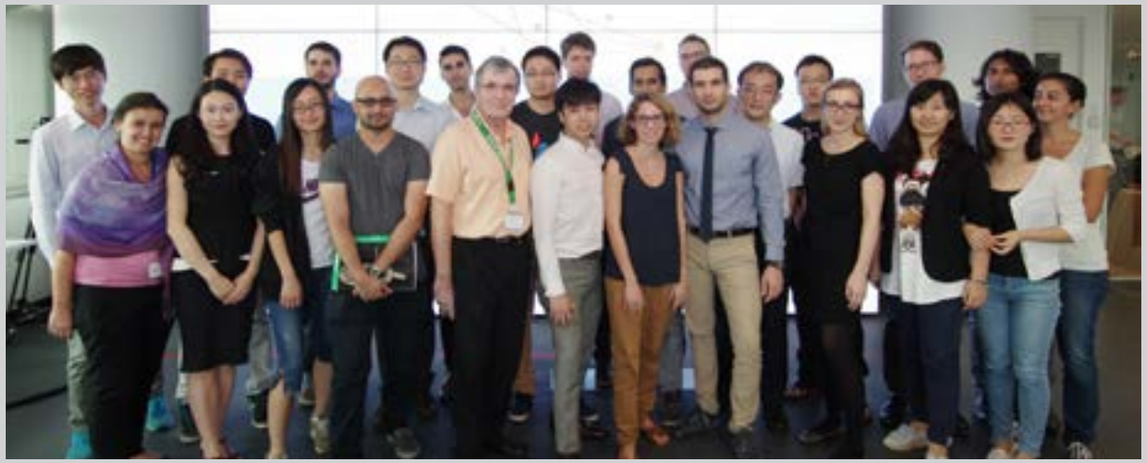
Prof Dr Yohanes Eko Riyanto (NTU)
School of Humanties and Social Sciences
yeriyanto@ntu.edu.sg

Prof Dr Teck Hua Ho (NUS)
NUS Business School,
Department of Marketing
dprhoth@nus.edu.sg

Prof Dr Renate Schubert (ETH)
Department of Humanities, Social and Political Sciences
schubert@econ.gess.ethz.ch

Prof Dr Euston Teong Ewe Quah (NTU)
School of Humanties and Social Sciences
ecsquahe@ntu.edu.sg

Prof Dr Walter Edgar Theseira (UniSIM)
School of Humanties and Social Sciences
waltertheseira@unisim.edu.sg



Bird's eye view of the CREATE campus and CREATE tower accommodating the Singapore-ETH Centre on the 6th and 7th floors.
(Photography by Tim Griffith, Design/Planning Architect: Perkins+Will)

Singapore-ETH Centre
Future Resilient Systems
1 Create Way
#06-01 CREATE Tower
Singapore 138602

www.frs.ethz.ch

For general enquiries, please write to **info@frs.ethz.ch**
For media enquiries, please write to **ee@arch.ethz.ch**