NGI101x - Physical Complexity part I

In this course we have introduced the notion of infrastructure systems as complex systems, and the notion of infrastructure systems as socio-technical systems.

Both in their physical dimension and in their social dimension, infrastructure systems behave as complex systems.

As Professor Eve Mitleton explained, complex systems are characterized by emergent behavior. The system behavior at macro-level emerges from the behavior of system elements at the micro-level. Emergent behavior often cannot be predicted.

The engineers among us may be puzzled here. Since all the technical parts of the system are designed according to functional and performance specifications, and since we put controls in place to make sure that the system behaves as intended, how can it be that we cannot predict the behavior of the overall system?

The answer is in the interactions. That's where the complexity is. When many simple systems are interconnected in a network, they interact with each other, across different scale levels, and across different time scales.

In doing so, the system may reconfigure itself and show behavior that you had not anticipated.

The emergent behavior of the overall system may be predictable, but it may also be unpredictable.

Emergence is everywhere around us.

In nature, emergent behavior can be seen in flocks of birds, shoals of fish, swarms of bees or termite mounds.

Their shape and behavior are emergent properties resulting from interactions between the individual entities. Free-market theories understand economy as an emergent feature of psychology , and psychology can be understood as an emergent feature of the neurobiological processes happening in our brains.

Biology can also be viewed as an emergent property of the laws of chemistry which, in turn, can be viewed as an emergent property of particle physics.

In the built environment, cities can be viewed as complex systems, functioning like a living organism, consuming energy, water and food, and excreting waste and waste water, with infrastructure systems representing their metabolic pathways.

Infrastructure systems themselves are complex systems. The complexity of infrastructure systems has many causes.

We have already explained how continental electricity networks emerged from the interconnection of neighborhood networks into city networks, followed – over decades - by regional, national and cross-border interconnections.

The legacy infrastructures of the industrialized world are a patchwork of local, regional and national networks, with a vast number of decentralized controls at all levels of the system.

The patchworked nature of our multinational transport, energy and communication networks can be recognized from the national standards that still persist in many physical infrastructure systems.

If you travel a lot, you will know that you need to bring a set of adapter plugs, so that you can connect your mobile phone and laptop rechargers to different sockets abroad. Another example:

Railway systems in different countries use different railway gauges. Moreover, different countries selected different standards for railway electrification, with different voltage levels, with some countries using alternating current, and others using direct current.

Legacy infrastructures are also a patchwork of old and new technologies. Some parts of the electricity infrastructure in Europe and the US date back more than 50 years. The exact technical specifications of old parts of the infrastructure and records of the exact location of underground cables and pipelines may have been lost.

Obviously, in ageing infrastructures, wear and tear will play a role. Very often we do not know enough about the aging behavior of infrastructure components to predict when and how they will fail.

Local conditions, such as mechanical load, soil humidity and acidity, will differ between locations, causing different aging behavior of for example underground cables and pipelines.

The management of infrastructure assets has become a new field of scientific study since the privatization of drinking water infrastructure in the United Kingdom.

In the early 1990's, the newly privatized Yorkshire Water company discovered that they were losing more than 40% of their precious drinking water on the way between the drinking water plant and their customers, as a result of leakage from old pipelines.

It therefore comes as no surprise that Yorkshire Water had a keen interest in improving its distribution system, and ensuring its long term robustness. Their efforts played a big role in the development of asset management standards, which are now being adopted worldwide by operators of capital intensive infrastructure assets.

Another cause of complexity is changing functionality. The cross-border interconnectors between the national electricity systems in Europe were originally intended as back-up facilities to be used only if the system stability at the national level needed support.

Nowadays, these interconnectors need to accommodate massive flows of electricity that result from electricity trading.

This raises the question if, and how much, of their capacity should be reserved for the original technical stability support function.

Another example: the nature of electric power generation is changing. More and more power is being generated from intermittent renewable energy sources, such as wind.

In the past, electricity supply could easily be adapted to fluctuations in electricity demand, since coal and gas fired power plants can be controlled: they are so-called dispatchable generators. The power generated by wind turbines cannot be controlled – it just depends on the wind.

Generally, fossil and nuclear power plants are strategically located in the vicinity of the electricity demand centers, the load centers, as they are called by electrical engineers, such as big cities and energy-intensive industrial sites.

Wind parks, however, not only need wind - they also require much more physical space than a traditional power plant.

Therefore, wind parks are usually located far from the load centers.

Let us have a look at the consequences.

In Germany for example, wind parks are largely located in the northern part of the country, both on and offshore. The load centers are largely located in the southern part of the country, and they used to be served by hydropower, nuclear and fossil fuel based power plants are also located in the southern part of the country.

With the sudden closure of a large number of its nuclear power plants, in reaction to the Fukushima disaster in Japan, the German load centers have become more dependent on wind power supplies from the North.

There is, however, a lack of interconnection capacity between the northern and the southern part of the country, so that the electricity flows generated by the wind farms in the north need to find their way to the German south via neighboring countries.

In other words, the flow patterns in the European system are drastically changing, and, since the amount of electricity generated from intermittent renewable energy sources is increasing, the risk of the system becoming unstable is increasing.

Electricity infrastructure differs from other infrastructure systems in the sense that the system has little storage capacity in proportion to its overall size.

At this point in time, the only option to store electricity on a commercial scale is in hydropower reservoirs.

In times of excess electricity supply, electricity is cheap and can be used to pump up water to refill hydroelectric reservoirs.

At times of peak demand, when electricity is expensive, the hydroelectric plant can then produce more electricity.

However, this type of storage capacity is relatively scarce and geographically unevenly distributed.

Electricity differs in another significant aspect from most other infrastructures: the velocity of electricity flows approaches the speed of light.

In a system with little storage capacity, this implies that the balancing of supply and demand needs to be managed in real-time.

If only the demand fluctuates, while generation can be controlled, the balance can quite easily be maintained by adjusting power generators.

However, as more and more power is generated from intermittent renewable energy sources, the share of controllable generators in the generation mix is dwindling, and balancing the supply and demand becomes far more challenging

In comparison with electricity infrastructure, water and gas infrastructures are far more inert systems.

The flows in these systems are relatively slow, and since there is ample storage capacity, including the storage capacity in the pipelines themselves (the so-called line pack), the balancing of supply and demand is far less critical than in the electricity system.

Thank you for your attention, see you in the next part.