NGI101x - Physical Complexity part II

Welcome back!

So far we have been talking mainly about legacy infrastructure systems.

You may have started to wonder about new infrastructure systems. They do not yet suffer from wear and tear, and you may expect them to be well documented, in each and every detail.

Surely you would expect such a system to behave more predictably?

I am sorry to disappoint you.

For a small system at a very local level it may be possible to model the system accurately and to predict its behavior. However, most infrastructure systems are much larger, and have a tendency to grow continuously, as a result of economies of scale and network externalities.

Many technologies applied in infrastructure systems are characterized by decreasing cost per unit of output with increasing scale, until a certain optimum size of operation. That is why electricity infrastructures are still dominated by large scale thermal power plants.

The growth of infrastructure networks is largely explained by the economic driver to exploit economies of scale, thus making the service more and more affordable for increasing numbers of users.

The other driver for network growth, the phenomenon of network externalities, is the phenomenon of increasing user value with an increasing number of users being connected to the network.

Let me give you an example.

A telephone connection would be of little value if only a few other people have a phone.

Anyone connecting to the telephone network or the internet increases the value of the network to other users.

Anyone buying a smart phone increases the usefulness of such phones to other people already using a smart phone.

It is due to network externalities that, once a new infrastructure service takes off, the system tends to grow until the usage of that service is universal – or near-universal.

Economies of scale and network externalities explain why infrastructure systems for energy, transport, telecommunication and information services have a natural tendency to grow into huge systems, comprising a huge number of subsystems, links and nodes, all of which are interdependent in several ways. If one subsystem is not functioning well, this may have farreaching repercussions on the functioning of the overall system. The interdependence of the subsystems can take various forms, from simple linear dependencies to multiple, non-synchronous relationships.

The non-linearities caused by feedbacks between subsystems, across system levels and time scales, are the main cause of emergent behavior of the aggregated system, that is the system as a whole

As the number of subsystems and interrelationships increases, and as those interrelationships become more diverse, it becomes more difficult to gain an overall view of the system and to know all the feedback loops. Eventually, the system will become so complex that the analyst can no longer recognise or model it at all.

Fortunately, the emergent behavior of infrastructure systems shows remarkably consistent patterns.

Even if I do not come home at exactly the same time every day, and though my individual use of electric devices in my home differs from day to day, the aggregated pattern of road congestion and electricity demand during the day is very similar, with slight variations between working days and weekends, and with seasonal variations. These recurrent patterns play a crucial role in the operation of infrastructure systems.

Infrastructure operators recognize these patterns and know how to deal with them. They use models that predict how their control actions influence the aggregate behavior of the system, even if they cannot model how this behavior emerges from the interacting elements at the micro-level of the system.

As a user, I do not care, since the value of the infrastructure for me is determined by the system’s performance at the aggregate level.

What difference does it make for me what cables or switches are used, as long as I can make a phone call and watch television in a comfortably heated home?

Another factor contributing to the predictability of infrastructure system behavior is path dependency.

Since most infrastructures use technologies that are characterized by strong economies of scale, they include many large scale, capital intensive installations with an economic lifetime of decades.

This feature implies that the physical system is fairly stable. Also the transportation and distribution networks are capital intensive.

They represent huge sunk costs. Sunk costs are past costs that have already been incurred and that cannot be recovered.

Even in a small country like the Netherlands (only 37,350 km^2), the distribution networks for electricity, natural gas, drinking water and sewage each represent more than 100,000 km of underground cables or pipelines to serve its 17 million inhabitants. The high voltage and high pressure transmission networks each reach a length of approximately 10,000 km.

The cost of these networks cannot be recovered if we were to decide today that it would be smarter to use an entirely different technology.

We call this sunk costs.

It is highly unlikely that we would adopt that smart new technology, if it would entail the need to build a new network requiring billions of Euros investment. The sunk costs represented by the existing system make it more likely that we will stick to the established system.

In other words, technological choices that we made a long time in the past, have created a certain path dependency: they dictate many of the choices we make today about expanding and innovating our infrastructure systems.

The path dependency created by past technology choices and capital investments does not mean that established infrastructure systems will never become obsolete. If a new technology comes around which promises far better performances or a new service, it is likely to be adopted if it can compete with the established infrastructure.

A prime example is mobile telephony, that requires comparatively small "network" investments, while bringing unprecedented flexibility in telecommunication, and revolutionary new services.

Many developing economies around the world have embraced mobile telephony, while leapfrogging the copper wired fixed telephone infrastructure.

Developed economies have been slower to adopt the mobile phone and the new services it enables, such as mobile money transactions, than, for example, African countries like Kenya.

Studies on complex systems often use the concept of agents for interacting elements in the system. In general, an agent is a model for any entity in reality that acts according to a set of rules, depending on input from the outside world.

An agent can be an automatic on-off switch in a local control system, it can be a sophisticated software entity that is capable of intelligent control actions, it can be a human controller or any other decision maker, somewhere in the infrastructure system.

By now, it should be clear that our definition of infrastructure does not only refer to the physical network.

In our view, an infrastructure system includes – besides the transport and distribution networks – the carriers, conversion and storage facilities as well as the governance, management and control systems that are needed to make the system meet its functional specifications and its social objectives.

In all parts of the system, social agents or actors as we call them, are making big and small decisions that influence the behavior of the system.

The complexity of infrastructure systems in the social domain is the subject of the next video lecture.

Thank you for your attention.