A Systems Approaches for Critical Decisions

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Summary. In this paper three types of system analysis are considered at a conceptual level which are relevant for decision making, namely: (a) breakdown in connected transport or other networks, when a change in modelling may be needed during critical transitions; (b) systems with dynamical boundary processes in smooth and sudden transitions; (c) critical transitions and sensitivities of the throughput and behaviour of systems depending on the relation between their 'speeds' of operation and response to external influences.

1 Description of General Systems Dynamics (GSD)

Natural and artificial entities, or systems, from molecules all the way through to whole societies, consist of many disparate elements operating simultaneously but with some level of connection between them [1]. In models of many environmental, engineering, social and economic/financial systems [2] a choice is made between statistical and quasi-deterministic methods. But an exclusive choice between these two approaches may not be necessary [3]. For example, in seasonal weather forecasts (www.metoffice.gov.uk) the two methods are currently used simultaneously. Some applications are described below for the conceptual application of a systems approach in making critical decisions particularly when systems are undergoing significant transitions. They can, perhaps, guide us how to operate systems so as to minimise the adverse effects of external or unexpected internal influences.

2 Applications of GSD for critical decisions

Breakdowns in connected networks: Studying patterns of restricted paths in idealised mathematical networks is a powerful method of studying the operation of real and virtual networks. They are particularly revealing when elements of the networks are changed, for example, by disruptions or improvements.

Following Euler, the key quantity describing paths is the connectedness matrix A_{ij} between n nodes, the magnitude of whose elements define the quality of the connection (or lines), e.g. probability between 0 and 1, between nodes i and j. For example, this defines the total number of significant connections N_i at node i (the sum of all the values of j for which $A_{ij} \neq 0$ and $i \neq j$). Consider the effects of N_b breakages in the connections of the network (see fig.1). An assumption has to be made about whether the nodes at either ends of the broken connections also fail. If each of these has an average of $< N_i >$ connections (e.g.=5 for central London tube nodes), it means that the total number of connections affected is about $2N_b < N_i >$. So a certain number of deliberate or accidental breakages (disconnections) can affect a high proportion of the central part of a network [4].

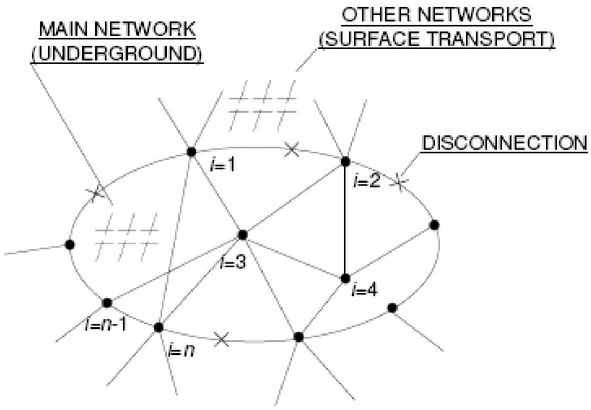

Fig. 1. Breakdown in connected networks-showing the effect of a few disconnections near nodes in a main network (e.g. underground) diffusing into other networks (e.g. surface transport).

However, the operation of the underground network with a finite number of high capacity lines is closely connected to a much larger more diffuse network, consisting of surface transportation and walkers etc. There are parallels with movement of oil and water through porous rock and through connected cracks in the rock, or urban networks of fractured water mains. For planning changes, responding to breakdowns, one form of simplification is to reduce the complexity the networks to fewer edges by averaging over many elements.

Or in a city with dense transport networks we represent the movement of people as a diffusive flux F_p equal to the spatial variation (or 'gradient') of the number of people per unit area, and the diffusivities of the coupled networks D_1 and D_2 for flow. These diffusivities vary greatly across the city especially with breakdowns. The variations of the fluxes depend on local sources and sinks in the network (i.e. the numbers of people entering and leaving unit area S, e.g. people entering or leaving activity areas (S_A) and overwhelmingly in emergencies by the movement of people away from areas of danger (S_D) as communicated and/or perceived. In dynamic situations the decision takers can vary all these parameters through physical controls (e.g. road blocks reducing the value of D_2) and communication. Simulations can solve the diffusion equation and rapidly display results as different scenarios are tried.

Systems with dynamical boundaries: Many systems are defined in relation to a finite physical, or non-physical, space which has boundaries (B) (e.g. a static organisation such as a city, or moving human/animal groups, or abstract boundaries, such as defined by 'areas' of activity and their scales in businesses or academia). Just as with networks, analysis can provide guidance about these systems when the boundaries and boundary processes undergo significant changes - drawing on the recent general theories of complex evolving and disrupting surfaces in turbulent fluid flow [5], and new concepts about how flooding patterns can change [6].

Richardson first showed the power of applying these concepts to social systems in his analysis of the frequencies of conflicts between nations, which he correlated with the lengths L of the boundaries B that separated them [7]. This led him to the famous conclusion that the smaller the scale l of the wiggles of the boundary shape the greater the length, according to the fractal relation $L \propto [l]^{-d}$, where $0 < d < 1$).

Consider a space within a continuous closed boundary B (fig.2). Outside B the key variable A, say, is A_0. Inside B, $A = A_0 + \Delta$. This changes when the surface undergoes severe disruption. With an evolving boundary, B moves outwards at an average boundary (or entrainment) 'speed' V_b. In many cases the boundary is porous, so that there is a flux of external 'activity' that crosses B in proportion to the flux (entrainment) 'speed' V_f.

One class of confined system with evolving boundaries is where the activity within the boundary is changing as the boundary spreads and exchange processes occur across the boundary. In other types of system Δ protects the system within B against an external activity A_0, e.g. the reduced flood hazard or lower wind damage in an urban area produced by deflection of water/wind by the buildings, or the reduced threat or competition to people, animals or organisations produced by joint defence against adversaries. In both cases $\Delta < 0$.

Within these boundaries, as the magnitude of the flux V_f of external activity crossing B (e.g. of fluid flow or of external bodies) grows, the protection within B might decrease (e.g. greater competition) or increase (e.g. economic advantage of immigration) in proportion to V_f and inversely with the length L_B of the boundary. The number of exchanges between insiders and outsiders would increase with L_B and this might trigger conflict [7].

Above a critical threshold, typically defined by the external action A_{crit}, the external and internal processes inter-mingle. Typically the mean differential activity Δ decreases while the fluctuations A' and flux speed V_f increase. This might be associated with change in the activity within a fixed boundary

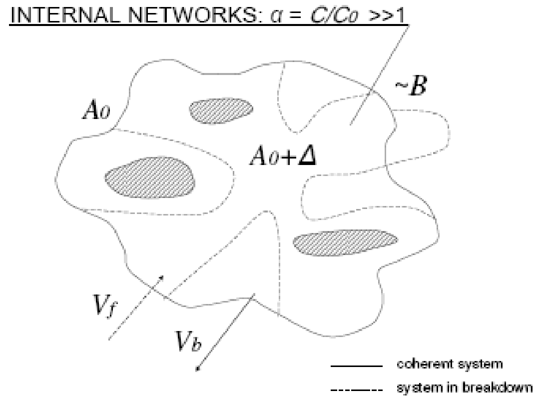

Fig. 2. A system with dynamical boundary processes undergoing transitions. A distortion and break up of the boundary produces large fluxes in and out, and large fluctuation A'.

(e.g. water/wind flow rising to high enough levels within an urban area that it becomes more hazardous inside B with infrastructure collapse than outside B). Or changes occur associated with the shape of the surface B becoming highly distorted as it breaks up into smaller areas each with surfaces denoted by dashed line, e.g. as a diseased population spreads or as spatial systems (as clouds and organisations break up).

These are also generic features of systems defined within multiple, interacting boundaries, such as when they merge or split, which applied to flow systems and adjoining nations [7].

Critical dynamics of system-processes affected by non-local influences: In many physical and non-physical systems there are various kinds of throughput, Q say, which are made up of 'movements' or transfers of quantities A (objects, activity, ideas etc). In changing conditions, the rate of accumulation always has to be considered at the same time as throughput. The systems involve large numbers of moving and evolving elements, which may include A and also extend beyond A, such as frameworks, external controls etc. Typically the throughput is controlled by local interactions between elements (as in transport/flow systems and in social organisations) and other 'non-local' influences or signals (Σ) coming from elsewhere in the system. Σ can be considered to be distinct from the quantity A. But Σ may be affected by large changes in A, such as when sudden changes and 'shocks' occur. A system dynamics approach also has to take into account its response process in order to estimate the speed (c) at which A is affected by the 'signals'.

The processes of accumulation and throughput with varying external influences have characteristic patterns of gradual and sharp variations that are common to many systems. Fluid flows provide a good example which show

how similar behaviour occurs in different liquid and gaseous systems. These concepts have already been used to analyse and control non-fluid systems. In fluids non-local signals are waves moving with a speed c that in general differs from the speed of the flow V, though it may be affected by the flow at distant points. The equation for the change of A affected by the wave moving in one dimension shows how any arbitrary 'activity' moves at speed c. In river flows or on water surfaces, A could be the flow speed or the heights of waves, and c is 'wave' speed at which the current changes or the wave height moves. Its magnitude depends partly on the form of A, as well as on the particular system. In gases, which are compressible, c is proportional to the density - for air this is the familiar sound speed of 300 m/s, very fast compared to long waves of 3 m/s in a typical shallow river.

Where the flow has a speed $V < c$, it responds immediately to the any variations elsewhere in the system (e.g. along a river). However when the critical ratio V/c (the Froude number for liquids or Mach number for gases) exceeds 1, the flow is faster than the speed of the waves or signals from elsewhere and are less dependent of non-local influences (e.g. what happens downstream). The responses to influences are quite different to those in sub-critical systems. Typically the throughput is locally obstructed (e.g. a fast flow of traffic being blocked) followed by a sudden change in the local and the overall flow occur, such as a hydraulic jump (a frothy wave on a stream) or shock wave (in front of an aircraft) in which there are intense local agitations [8]. Downstream of the 'shock', the river level rises, and in gases the density rises as in traffic density ('waves') on highways. As is well known there is a bumper-to-tail slow flow where $V/c < 1$ and free flowing supercritical traffic where $V/c > 1$. As V/c increases, the throughput of traffic increases gradually, as the traffic responds to non-local influences e.g. controls or obstructed flow. This understanding has led to traffic controls that maximise Q and reduce the chance of large waves or shocks, by ensuring that V/c is below its critical value. The patterns of mass movements of people in streets and buildings have many of the same smooth/shock transitions, often with deadly results.

There are also social and intellectual systems with non-local influences where the variation of throughput Q have similar characteristic variations depending on the relation between the speed at which the system operates (V) and the speed (c) with which information is considered or at which changes to the system propagate through it. For example, organisations in a sub-critical mode ($V/c < 1$) operate smoothly, but probably not very sensitively, in response to external and non-local influences. In a super-critical mode ($V/c > 1$), they have to respond quickly to external influences, but they are at greater risk of the whole organisation experiencing sudden changes in its activity A, that are similar to shocks in flow and traffic systems. These ideas might also guide research into how individuals operate in the modern world where a certain imposed 'speed' V is required to deal with their activities (which they can choose to some extent). Their effectiveness is affected by how this imposed speed V relates to each individual's innate speed c of processing information and responding to external influences. Probably greatest contentment comes from operating close to the critical ratio; they might also be one component of happiness [9].

3 Conclusions

Wilson [10] has commented that science is rich in concepts that have wide potential application through the methodology of complex systems analysis. But detailed modelling and measurement can greatly increase the value of system studies for decision making, because component models differ considerably between different systems. However, there are some of the generic issues of complex modelling that need to be discussed and teased out before non-technical policy makers will begin to use systems thinking and techniques more widely, and use the results intelligently.

4 Acknowledgments

We acknowledge the financial support of the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission, under the FET-Open grant agreement GSD, number 221955. JH acknowledges support of the 5th European Conference on Complex Systems in Jerusalem 2008 and funding from Midi-Pyrenees Innovation for the preparation of this paper.

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