# Nature inspired robustness of networks

Rüdiger Brause, J.W. Goethe-University,
Department of Informatics and Mathematics,
Institute for Informatics,
60054 Frankfurt am Main, Germany
RBrause@informatik.uni-frankfurt.de

In uncertain and hazardous times, robustness may be a key to survival. The effects on ecosystems of disturbances big or small; the responses of cells to environmental or genetic change; the performance of computer software in the event of input errors, disk failures, network overload, or purposeful attack; the viability of a technological product in wildly changing markets; the resilience of a political institution during societal flux – in all these cases, it is **robustness** (rather than optimization or evolvability or stability *per se*) that is the determining factor [1].

In social and economical sciences, interactions are rarely modelled in a robust way. Since the dynamics of interaction are often described in a qualitative, not quantitative manner, robustness is often not quantified. Nevertheless, some questions about ecosystems and social changes can only be answered in the light of robustness, called *resilience* in this context [2]. It is the ability of a system to undergo disturbances and still maintain its function and controls. The robustness of ecosystem processes, such as nutrient cycling, varies across different types of ecosystems and is related to structural properties such as the strength of interactions among species. Here, many questions are open:

- What are the organizational principles (possibilities include spatial structure, redundancy, modularity, diversification, and hierarchy among others) that characterize highly robust entities?
- Why do they change after long periods of stability, e.g. the society of the former soviet union?
- How do non-robust ecosystems look like and how they evolve?

In socio-economic networks, all relations are dynamical and subject to historical changes. Only the most robust interaction networks will survive and build the core of the social network.

Another area of robustness is the construction of robust VLSI design. All electronic circuits are subject to variations due to the fabrication process. Current efforts try to reduce the influences by introducing special mathematical operations (affine arithmetics) into the system description of circuits [3]. Beside these methods new ways are needed for the goal of self-healing, self-configurating computers in *organic computing* [4]. Here, additional methods for introducing robustness are welcome.

One of the most recent applications of enhanced robustness design is in bioinformatics the modelling of biochemical pathways as networks of interacting genes, metabolites or molecular signals, based on experimental findings. The traditional dynamic approach tries to model the time dynamics of the expression data, e.g. [5]. A fuzzy clustering stage is performed for a fixed number of clusters and the dynamical interaction of the clusters is modelled by a system of linear differential equations based on the expression data of selected genes. As selection criterion in the huge search space of possible networks, the most simple network is chosen which fits the data. We think that this choice is not appropriate: the aspect of robustness is not taken into consideration, although the networks have been exposed to a long evolutionary development. Small genetic

mutations may influence the production rate of the proteins, but are likely not to cause a significant, fatal change in the metabolism; otherwise, the individual will not have the possibility to pass his or her genes to the following generation [6]. Therefore, we claim that modelling of biological networks have also to include the proportion of robustness as selection criterion of the target system.
For the case of gene expression networks, by comparing the robust network with documented pathways in literature, one should be able to predict new signalling pathways, identify previously unknown members of documented pathways and identify relevant groups of interacting proteins.

With this motivation in the background, let us take a closer look on the nature of robustness. There are several aspects of “robustness”:

1. One major aspect is **fault tolerance**. This means that random faults or accidents in the considered system should not propagate and should not impede the desired system functions too much.
2. The second important aspects is **stability** in a system inherent way. This means that the system should not deviate by noise or random input, even if its internal components slightly change.

All these properties can be observed in a variety of biological systems. They are both involved for the case of mutations or accidents of the biological subjects and are essential for the survival of the genes. In contrast to this, the analytical description of the natural system lacks the important property of robustness. The main reason for this lies in the principle of describing all systems by the most simple way (“Occams razor”). This idea has been successful for the task of abstracting all implementation details from the system description in order to keep it as simple as possible. Nevertheless, the robustness of a system (and not the stability) is often not tested and therefore not modelled. Hence, the engineered synthesized system does not offer the robustness property: Including those aspects might lead to a more complicated, but more realistic system description.

In contrast to robustness observed in natural systems, human engineered systems are mostly not robust. Here, system failure after only one faulty component is common. Now, given a system, how can we improve its robustness? Nature inspired heuristics might lead to some new ideas:

a) If there are multiple similar influences in the system in parallel, if one fails, the others may continue to work. This can be compared to parallel redundancy in classical fault tolerance theory [7]. An example for this are the muscle fibers all effecting in parallel on one bone. If one cracks, the others will continue to function.
   Another example for robust parallel action is the group encoding of muscle enervation: Here, the fibres receive almost the same input, but slightly deviate compared to the neighbour. This results in a very precise mechanical control which continues, even when some of the muscle fibres are degraded. The control resolution of the muscle fiber bundle will be smaller, but the movement will continue.

b) There is an adaptive feedback in the system which allows a broad range of the parameters involved without changing system behaviour too much. An example for this is the human walking cited above. Here, the intrinsic system behaviour compensates the large varying effects of bone and tissue growth.

All heuristic propositions have to be judged in the light of a mathematical framework. Generally, the social, economical and biological systems can be described by interacting components. The interactions can be modelled either by graphs or networks, or by a corresponding system of differential equations. For the latter system view, robustness is related to the three mathematical aspects

- stability (qualitative aspect),
- sensitivity (quantitative aspect),
- redundancy,

of differential equations. There are many ideas about enhancing stability by feedback controllers ("robust control" [8]). Nevertheless, the connection between "robustness" introduced above and the aspects above is not well developed until now.

The computation of robustness depends heavily on the amount of uncertainty in the system, i.e. on the information available for the system. This corresponds to the descriptional complexity used in computer science: the more we have to know about a system in order to describe it the more complex it is. The more degrees of freedom we have in the differential equations for network control, the more complex is the system [9].

The identification of parameters in such systems by numerical methods has been investigated by many researchers, but many questions are still open. One of these questions is the stability of numerical methods (*illposedness, regularization*). Another question is how to treat the uncertainties in the design of models.

Here we notice a broad gap of knowledge which have to be bridged by research. Nature might give us hints by investigating robustness in the light of system evolution for improving the corresponding differential equations. The results should help us to develop technical and social mechanisms for robust systems.


[1] Gunderson L,Holling C (eds.): Panarchy: Understanding Transformations in Human and Natural Systems. Island press, Washington D.C., 2001

[2] S. Levin, B. Walker, D. Erwin: section "Robustness in Ecosystems", in: Jen E, (Ed.) Robust Design: A Repertoire of Biological, Ecological, and Engineering Case Studies, Santa Fe Institute Studies on the Sciences of Complexity, Oxford University Press, Oxford 2003

[3] C. Grimm, W. Heupke, and K. Waldschmidt. Analysis of Mixed-Signal Systems with Affine Arithmetic. *IEEE Transactions on Computer Aided Design of Circuits and Systems*, (1), 2005

[4] www.organic-computing.org

[5] Guthke R, Möller U, Hoffmann M, Thies F, Töpfer: Dynamic network reconstruction from gene expression data applied to immune response during bacterial infection. Bioinformatics 2005, 21: 1626-1634

[6] Andreas Wagner: Robustness and Evolvability in Living Systems, Princeton Studies in Complexity,

[7] M. Shooman: Reliability of Computer Systems and Networks: Fault Tolerance, Analysis, and Design, Wiley, 2001

[8] Kwakernaak H: Robust Control and $H_\infty$-Optimization- Tutorial paper. Automatica, 1993, 29(2):255-273

[9] Doyle J, Carlson J: Robustness and Complexity. In Jen E, Ed. Robust Design, Oxford University Press, Oxford 2003