Reconciling complexities: for a stronger integration of approaches to complex socio-technical systems

Juste Raimbault[1,2]

[1] UMR CNRS 8504 Géographie-Cités, Paris, France
[2] UMR-T IFSTTAR 9403 LVMT, Champs-sur-Marne, France
juste.raimbault@polytechnique.edu

Abstract. System engineering has developed a mature knowledge on how to design, integrate and manage complex industrial systems, whereas disciplines studying complex systems in nature or society also propose numerous tools for their understanding. Socio-technical systems, that situate at their intersection, could benefit from a higher integration between these. This position paper advocates for such integrated approaches. A bibliometric study through citation networks first illustrates the respective isolation of some of these approaches. We then produce a proof-of-concept of how the transfer of concepts from biology can be useful for the design of complex systems, in the particular case of transportation networks, using a biological network growth model to produce various optimal networks in terms of cost and efficiency. We finally discuss possible disciplinary positioning of such hybrid approaches.

Keywords: System Engineering; Complex Systems Science; Bibliometrics; Bio-inspired Network Design; Integrative Disciplines

1 Introduction

[1] recalls that several approaches to complexity do not

[2] actualize the metaphor of the Laplace Deamon, and develops three visions of complexity with progressive epistemological assumptions on the role of emergence.

[3] advocates for a stronger consideration of emerging properties in the engineering of complex systems, and claims for example that engineers and social scientists have much to exchange.

[4] suggests that agent-based systems are an interesting alternative for the design of control systems, in particular thanks to their increased flexibility and robustness.

These issues of integrating complexities is indeed not particular to system engineering, as [5] show that in the case of economics, policy-related benefits would be obtained by a more frequent use of agent-based approaches.

The rest of the paper is organized as follows: we first develop a bibliometric study, in order to illustrate through the exploration of citation networks the effective separation of some branches of system engineerings and of complex systems science. We then develop a modeling case study to give a proof-of-study of how complex systems concepts, in this case from biology, can be used for the design of systems.

2 A bibliometric insight

2.1 Context

Statements about disciplines, their positioning and their relations, must often be taken with caution, including ours, as they will depend on the perspective taken to enter the problem, on the information available, on possible higher contexts implying sociological issues [6]. They furthermore involve issues of reflexivity if they are done by researchers in the field themselves, implying to find what Morin calls a "meta-viewpoint" to construct an integrated knowledge [7]. However, a growing body of knowledge in bibliometrics, that can be understood as a *quantitative epistemology* [8]

[9]

2.2 Method

We use here the tool provided by [10] to reconstruct backward citation networks

[11] as the origin node for system engineerings

[12] for complex systems

2.3 Results

3 A proof-of-concept: biological network generation

3.1 Context

How can the transfer of concepts from other disciplines can inform system design ? Contributions giving elements of answer to this question are indeed not new, and the entire field of *Artificial Life*

[**?**] autopoiesis and cognition in the game of life

3.2 Network generation model

We detail here the model of type *slime mould* used to evolve a biological network, introduced by [13]. The network is composed by nodes characterized by their pressure p_i and by links characterized by their length L_{ij}, their diameter D_{ij}, an impedance Z_{ij} and the flow traversing them ϕ_{ij}. The topology of the network is assumed fixed, but the diameters of links can evolve in time.

The flows are characterized by a relation analogous to Ohm's law on links which writes

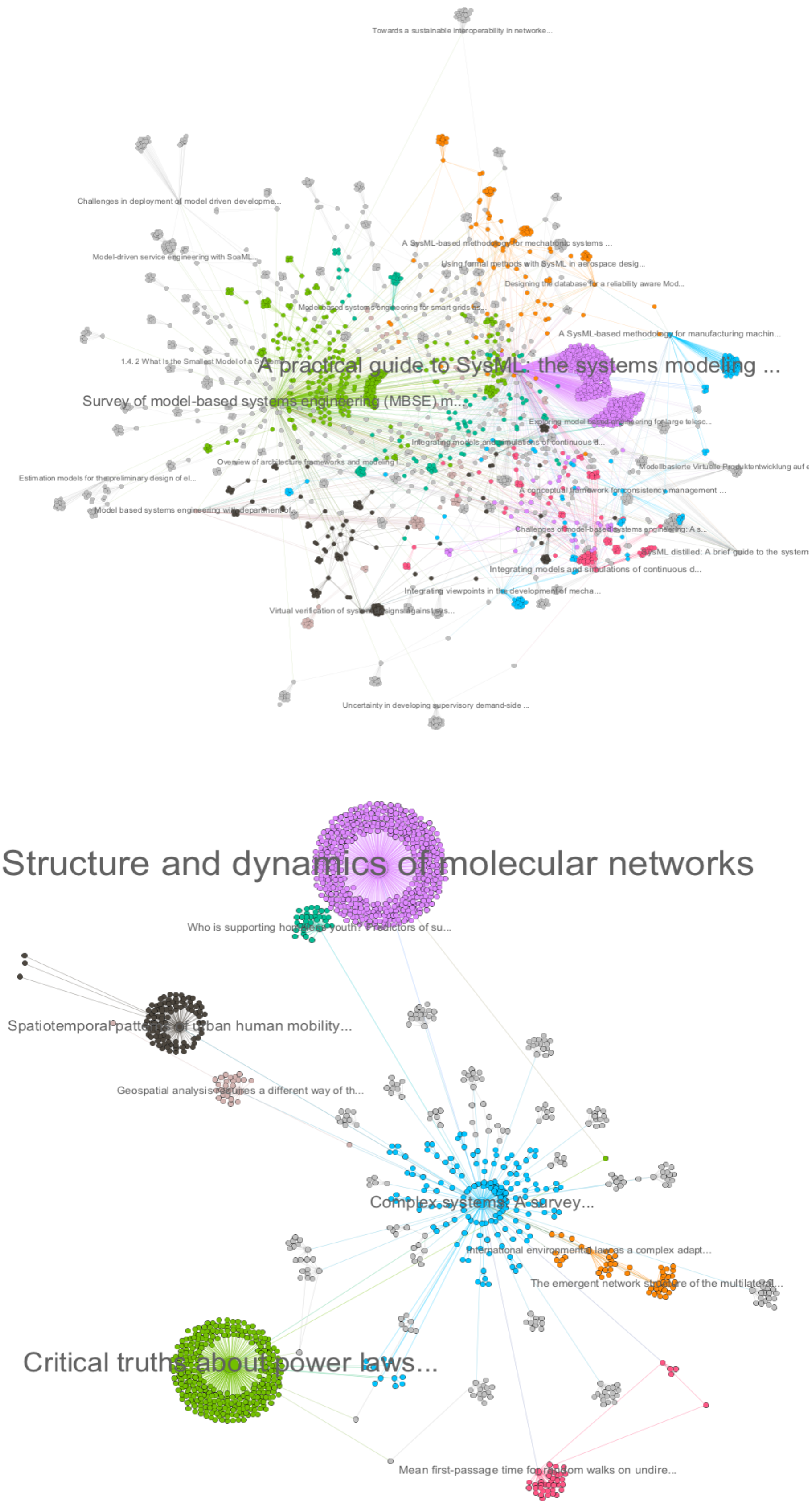

Fig. 1. Citation networks for each field. *(Top)* Citation network for the sample corresponding to system engineering approaches; *(Bottom)* Citation network for the sample corresponding to complex systems science approaches.

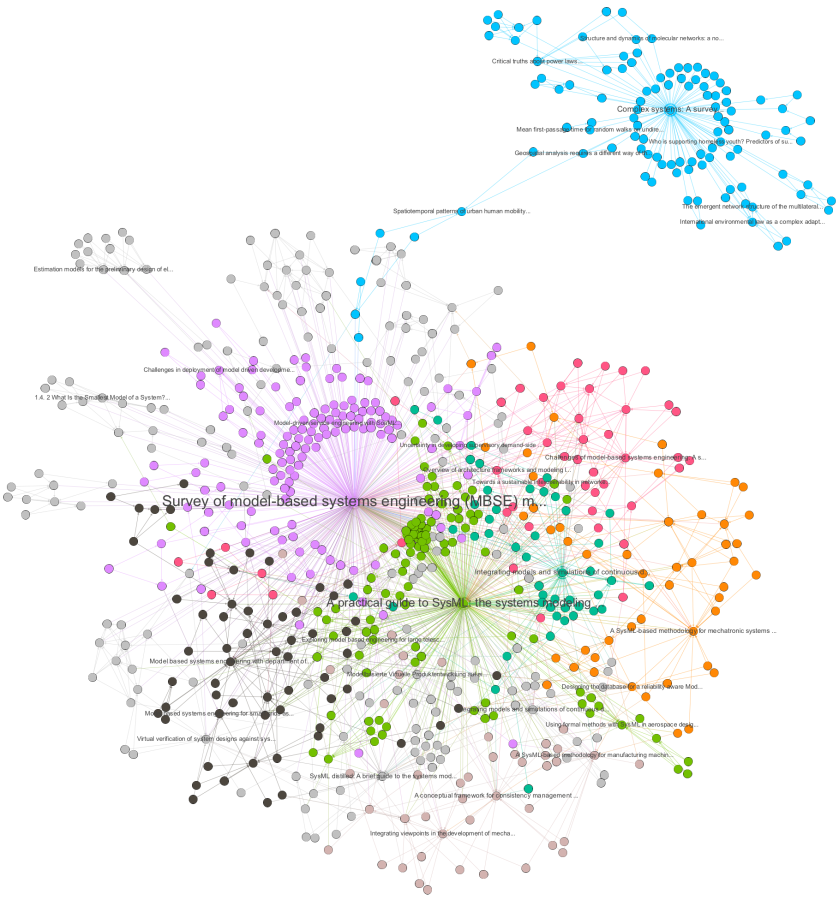

Fig. 2. Full citation network. We show the core of the full citation network, corresponding to nodes with a degree larger than one and corresponding edges, to ease readability. The two components shown in Fig. 1 are connected by a small bridge only.

$$\phi_{ij} = \frac{D_{ij}}{Z_{ij} \cdot L_{ij}} (p_i - p_j)$$

Furthermore, the conservation of flows at each node (Kirchoff's law) imposes

$$\sum_i \phi_{ij} = 0$$

for all j except the source and the sink, that we assume at indices j_+ and j_-, such that $\sum_i \phi_{ij_+} = I_0$ and $\sum_i \phi_{ij_-} = -I_0$ with I_0 initial flow parameter.

The combination of above constraints gives for all j

$$\sum_i \frac{D_{ij}}{Z_{ij} \cdot L_{ij}} (p_i - p_j) = \mathbb{1}_{j=j_+} I_0 - \mathbb{1}_{j=j_-} I_0$$

what simplifies into a matrix equation, by denoting $\mathbf{Z} = \left(\frac{\frac{D_{ij}}{Z_{ij} \cdot L_{ij}}}{\sum_i \frac{D_{ij}}{Z_{ij} \cdot L_{ij}}} \right)_{ij}$, and also $\boldsymbol{k} = \frac{\mathbb{1}_{j=j_+} I_0 - \mathbb{1}_{j=j_-} I_0}{\sum_i \frac{D_{ij}}{Z_{ij} \cdot L_{ij}}}$ and $\boldsymbol{p} = p_i$, what simplifies into

$$(Id - \mathbf{Z})\, \boldsymbol{p} = \boldsymbol{k}$$

The system admits a solution when $(Id - \mathbf{Z})$ is invertible. The space of invertible matrices being dense in $\mathcal{M}_n(\mathbb{R})$, by multilinearity of the determinant, an infinitesimal perturbation of the position of nodes allows to invert the matrix if it is indeed singular. We obtain thus the pressures p_i and as a consequence the flows ϕ_{ij}.

The evolution of the diameter D_{ij} between two equilibrium stages is a function of the flow at equilibrium, through the equation

$$D_{ij}(t+1) - D_{ij} = \delta t \left[\frac{\phi_{ij}(t)^\gamma}{1 + \phi_{ij}(t)^\gamma} - D_{ij}(t) \right]$$

We take to simplify $\gamma = 1.8$, following the configuration used by [14] for the generation of a network in a real configuration. We furthermore take $\delta t = 0.05$ and $I_0 = 10$.

The generation of a network can be achieved from an initial network, until reaching a convergence criteria, for example $\sum_{ij} \Delta D_{ij}(t) < \varepsilon$ with ε fixed threshold parameter. We will use this model with a criteria of a number of iterations, and proceed to an iteration to obtain final networks with a reasonable number of links.

3.3 Results

Designing public transportation lines

Generating optimal networks

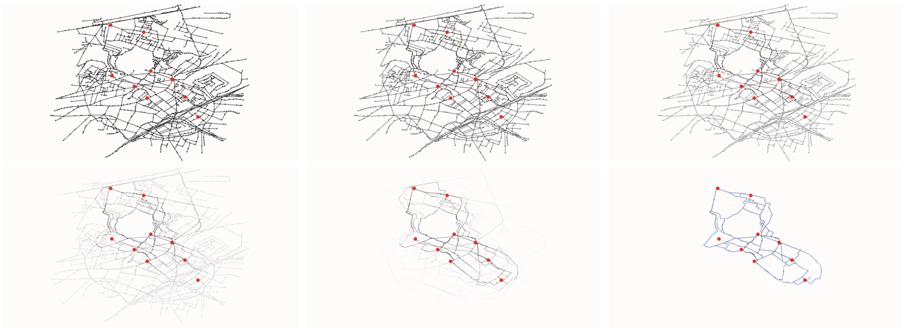

Fig. 3. Application of the slime mould model to design a robust public transportation network.

Fig. 4. Example of networks.

4 Discussion

5 Conclusion

Acknowledgments

References

1. Dominique Chu. Criteria for conceptual and operational notions of complexity. *Artificial Life*, 14(3):313–323, 2008.
2. Guillaume Deffuant, Arnaud Banos, David Chavalarias, Cyrille Bertelle, Nicolas Brodu, Pablo Jensen, Annick Lesne, Jean-Pierre Müller, Édith Perrier, and Franck Varenne. Visions de la complexité. le démon de laplace dans tous ses états. *Natures Sciences Sociétés*, 23(1):42–53, 2015.
3. Julio M Ottino. Engineering complex systems. *Nature*, 427(6973):399, 2004.
4. Nicholas R Jennings and Stefan Bussmann. Agent-based control systems: Why are they suited to engineering complex systems? *IEEE control systems*, 23(3):61–73, 2003.
5. J Doyne Farmer and Duncan Foley. The economy needs agent-based modelling. *Nature*, 460(7256):685–686, 2009.
6. Bruno Latour and Paolo Fabbri. La rhétorique de la science [pouvoir et devoir dans un article de science exacte]. *Actes de la recherche en sciences sociales*, 13(1):81–95, 1977.
7. Edgar Morin. La méthode 3. la connaissance de la connaissance. *Essais, Seuil*, 1986.
8. David Chavalarias and Jean-Philippe Cointet. Phylomemetic patterns in science evolution—the rise and fall of scientific fields. *Plos One*, 8(2):e54847, 2013.

Fig. 5. Optimality of simulated networks.

9. Ludo Waltman, Nees Jan van Eck, and Ed CM Noyons. A unified approach to mapping and clustering of bibliometric networks. *Journal of Informetrics*, 4(4):629–635, 2010.
10. Juste Raimbault. Exploration of an interdisciplinary scientific landscape. *arXiv preprint arXiv:1712.00805*, 2017.
11. Jeff A Estefan et al. Survey of model-based systems engineering (mbse) methodologies. *Incose MBSE Focus Group*, 25(8):1–12, 2007.
12. Mark EJ Newman. Complex systems: A survey. *arXiv preprint arXiv:1112.1440*, 2011.
13. Atsushi Tero, Ryo Kobayashi, and Toshiyuki Nakagaki. A mathematical model for adaptive transport network in path finding by true slime mold. *Journal of theoretical biology*, 244(4):553–564, 2007.
14. Atsushi Tero, Seiji Takagi, Tetsu Saigusa, Kentaro Ito, Dan P. Bebber, Mark D. Fricker, Kenji Yumiki, Ryo Kobayashi, and Toshiyuki Nakagaki. Rules for biologically inspired adaptive network design. *Science*, 327(5964):439–442, 2010.