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Information and material flows in complex networks

Dirk Helbing[a,b,*], Dieter Armbruster[c,d], Alexander S. Mikhailov[e], Erjen Lefeber[d]

[a]*Institute for Transport & Economics, Dresden University of Technology, Andreas-Schubert-Street 23, 01062 Dresden, Germany*
[b]*Collegium Budapest - Institute for Advanced Study, Szentháromság utca 2, 1014 Budapest, Hungary*
[c]*Department of Mathematics, Arizona State University, AZ 85287-1804 Tempe, USA*
[d]*Department of Mechanical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600 MBEindhoven, Netherlands*
[e]*Department of Physical Chemistry, Fritz Haber Institute of the Max Planck Society, Faradayweg 4-6,14195 Berlin, Germany*

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Abstract

In this special issue, an overview of the Thematic Institute (TI) on Information and Material Flows in Complex Systems is given. The TI was carried out within EXYSTENCE, the first EU Network of Excellence in the area of complex systems. Its motivation, research approach and subjects are presented here. Among the various methods used are many-particle and statistical physics, nonlinear dynamics, as well as complex systems, network and control theory. The contributions are relevant for complex systems as diverse as vehicle and data traffic in networks, logistics, production, and material flows in biological systems. The key disciplines involved are socio-, econo-, traffic- and bio-physics, and a new research area that could be called "biologistics".
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This special issue of Physica A presents the scientific outcome of the Thematic Institute on Information and Material Flows in Complex Networks and some invited contributions by other experts in the field. Inspired by Centers of Excellence in the area of complexity science, Thematic Institutes intended to get scientists of diverse background, e.g., physicists and economists, to engage into active collaboration for an extended period of time. They were supported within the program Information Society Technology—Future and Emerging Technologies by the European Union.

The Thematic Institute on Information and Material Flows in Complex Networks took place at Goldrain Castle (Italy) from June 15 to 2005 July 15. Its participants were an interdisciplinarily oriented group of researchers from physics, mathematics, traffic science, production engineering, biology, and economy. The partially overlapping and cross-country author lists of many contributions to this special issue reflect the large number of collaborations that the TI has initiated. This is also the reason why some participants have co-authored several papers. The Thematic Institute has obviously managed to establish a new research

*Corresponding author. Fax: +493514636809.
E-mail address: helbing@trafficforum.org (D. Helbing).

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community. It will certainly continue to grow, to tackle the numerous challenges in information and material flow networks, and to develop fundamental methods in the field of interdisciplinary physics.

1. Production networks and factory physics

Classical production systems and supply networks are typically designed and operated in a stationary, pre-planned and centralized manner. In reality, however, consumption varies, fashions and markets change, machines can break down, and workers may fail, quit their job, be ill or on holidays—i.e., the systems are evolving dynamically and in a stochastic environment. Today, most traditional models and optimization algorithms neglect some essential features of production systems or do not represent them well. This includes

- a huge variation in the demand,
- a competition for scarce resources (space, time, materials),
- nonlinear effects and interactions,
- congestion,
- unpredictable dynamics,
- stochasticity,
- heterogeneity,
- local failures or breakdowns, and
- network structures.

These features make logistic and production systems highly complex, hard to describe, and challenging to optimize. Scenarios with fluctuations in demand, changes in production programs, breakdowns of machines, or variations in production capacities have been typically addressed by event-driven Monte-Carlo simulations. However, these are extremely time consuming and cannot be scaled up to deal with the large networks representing real production systems and their supply chains. Similarly, stochastic queuing theoretical models turn out to be unsuitable for the simulation and control of large nonstationary logistic or production networks. Recent "fluid-dynamic" production models are independent of individual production steps and production units [1]. They manage to capture the nonlinear interactions due to capacity constraints, allow to simulate dynamics, and study network effects. These equations treat production systems as dynamic queuing networks [2] and are promising to lead to a better understanding, design and optimization of logistic and production systems. The fluid-dynamic approach is so general that it can also be applied to a broad class of other problems, including information and work flows in social organizations or companies, and the simulation of traffic networks.

Even though progress has been made on simulating these large systems, there are still no general rules how to operate these systems optimally. The optimization problem is dominated by nonlinearities and algorithmically NP hard, i.e., the numerical effort explodes with the number of network nodes and cannot be managed in a satisfactory way. Approximate, heuristic optimization methods such as genetic/evolutionary algorithms are too time consuming. Therefore, new optimization approaches are needed. A possible approach argues for decentralized interactions leading to collective or swarm intelligence. In principle, it is known that suitable local interaction rules can lead to coordination and optimization throughout the overall system. However, in contrast to systems close to equilibrium, there is no general theory for the evolution of stochastic, nonlinear, dynamic systems with network effects. Therefore, most algorithms based on local interaction rules tend to be trapped in local (potentially quite bad) maxima. Moreover, dynamical effects based on network interactions may cause instabilities and breakdowns (see, e.g., the intermittent behavior of the TCP/IP internet protocol, stop-and-go waves in freeway traffic, or the bull-whip effect in production systems).

It is obvious that physics has many powerful tools to offer here. Driven many-particle models and their extensions to multi-agent models have not only succeeded in understanding the dynamics and patterns observed in vehicle and pedestrian traffic [3]. They are also a promising approach to supply and production networks [4–6]. In particular, many-particle models offer an interpretation of the statistics of various observed arrival and departure time distributions based on nonlinear interactions between the components of the system [7]. Moreover, the aggregated, "fluid-dynamic" description of material flow networks turn out to be quite successful in capturing the dynamics, nonlinear interactions, and adaptation processes in production systems [8–11].

Similar to traffic systems, supply and production systems can be abstracted as many-particle or multi-component systems with delays, fluctuations, and nonlinear interactions, which facilitates a statistical physics approach. Consequently, one can find similar phenomena as in traffic systems. For example, congested streets and stop-and-go traffic are analogous to congested buffers and bullwhip effects. Furthermore, it turns out that the network structure of a production network not only determines the robustness of production with respect to local failures, but also the dynamics of the production system [12–14]. This is where the physics of networks [15,16] comes into play. In fact, recently developed dynamical models of queuing networks promise closer insights into various problems, such as the traffic dynamics in street networks [17,18], functioning of production systems [2,19], the reasons for business cycles [20], and biological supply networks from the cell to the body [21–25].

The competition for limited resources (time, space, energy, materials) and the resulting conflicts in usage connects logistics and production systems with the problem of social dilemmas and other subjects in game theory, which have recently found an increasing interest among physicists [26–31]. Conflicts of usage (e.g., in intersection areas) require priority rules and scheduling strategies which are adaptive to a varying demand. Therefore, management and control strategies for supply or production systems have a lot in common with traffic light scheduling [32,33]. In fact, buffers in production systems correspond to road sections, cycle or production times to travel and delay times, processing units to junctions, different product flows to different origin–destination flows, machine breakdowns to accidents, etc.

We should underline that all of the above systems may show complex spatio–temporal patterns. For example, in production systems one can find nonstationary and nonperiodic solutions, unpredictable dynamics, and a large sensitivity to small parameter changes. It appears that production systems are often characterized by a complex (e.g., fractal) phase space. The possible dynamic solutions include unstable and chaotic solutions [34–37], which are particularly well understood in switched arrival or departure systems [12,38,39]. Moreover, (phase) transitions from one dynamic behavior to another one can occur at critical parameter thresholds. For these reasons, methods developed to describe complex systems are required to understand and optimize the dynamics of production processes. Note that the optimization potential of the physics-based approach is considerable. For example, applying the slower-is-faster effect [40], which is found in many logistic and production systems [11], has facilitated to increase production throughputs by 30% and more. Considering machine investment costs of the order of 1 to 20 million EUR, this allows companies to save a lot of money.

2. Biological networks and biologistics

The human body is one of the most complex logistic systems. It manages to deliver billions of different substances to billions of different locations in the body. This material transport is quite specific and very efficient: the basic body functions consume energy at the rate of a 100 W light bulb only. This incredible efficiency is the result of an evolutionary optimization process and the competition over millions of years.

Consequently, we expect considerable optimization potentials by bio-inspired approaches to logistic and production problems. This applies not only to ant algorithms, which have been successfully used for search problems, data routing, or shop floor logistics [41–45]. One can also learn from systems biology [46,47], cellular traffic [48–51], and protein machines [52–54]. In fact, research is already seeking ways to produce nanostructures based on a control of intracellular processes. Conversely, production and logistic processes are typically studied with highly advanced tools from Operations Research (OR): optimization, scheduling, control and discrete event simulations are just of few of the most important ones. As the study of biological molecular machines and the dynamics of their interacting networks moves to a stage where these networks are manipulated, controlled and organized to perform certain functions, those tools from OR will become more and more relevant. Therefore, it is time to explore the potentials of *biologistics*. By biologistics we mean both, the production of artifacts by biological systems and the transfer of biological organization principles to production plants and logistic processes.

Reviewing organization principles of biological production, information and material flows, we notice that many processes seem to function in a decentralized manner [24,41,55]. Collective intelligence solutions (e.g. in the immune system), stability with respect to undercritical fluctuations and transitions to other modes of operation in cases of overcritical perturbations are common: while living systems must tolerate small fluctuations, large variations tend to trigger adaptation processes. The robustness of biological systems is reached by attractive states ("attractors"), while transitions at bifurcation points allow for flexible adjustments. The success principle in biology seems to be a gentle control of an otherwise self-organized system [56,57] (see also a recent review [58] on control of self-organization in chemical systems). A classical, completely predetermined control logic would require a lot more resources for the encoding of information and the implementation of control. It would also tend to generate rigid rather than flexible solutions. Moreover, it would potentially destroy the self-organized dynamics and structures.

As in physical systems, in biological systems one can find hierarchical organization principles. While the strongest control is on the lowest level, the more centralized functions operate on slower time and length scales based on weaker (residual) interactions. Strong interference in the system tends to mix up or even destroy the self-organization of a biological system [58].

The management of production processes seems to be quite differently organized today: the most central levels appear to take a strong influence on the system on a relatively short time scale. This not only requires a large amount of resources (administrative overhead), but also makes it difficult for the lower, less central levels of organization to adjust themselves to a changing environment. This complicates large-scale coordination in the system and makes it more costly. Therefore, bio-inspired organization principles appear to be promising for the future design of logistics and production systems. As a consequence, the organization principles of biological systems should be extended and employed in engineering and industrial production [55].

3. Contents and organization

While we have outlined some of the future challenges in the fields of biologistics and factory physics [59] relating to material flows, this special issue covers numerous additional aspects of information flows in complex systems: Schönhof et al. study the propagation of traffic information in ad-hoc networks of intervehicle communication systems, i.e., coupled traffic and data flows. Helbing, Ammoser, and Kühnert discuss the reliability of information flows in hierarchical organizations challenged by failures, crises, or disasters. The paper by Draief addresses epidemic spreading, which can also be used for information diffusion.

We have grouped the contributions of this special issue of Physica A into 5 sections:

(1) manufacturing systems,
(2) control of network flows,
(3) traffic flows and supply networks,
(4) biologically inspired approaches, and
(5) social networks.

The papers on manufacturing systems cover the so-called equation-free approach to the multiscale analysis of production lines and discuss measures to counteract the bullwhip effect (i.e., increasing oscillations in production rates and stock levels). The paper on robust control of demand-driven supply networks build the link to network dynamics. Two contributions tackle phase synchronization as an emergent phenomenon and as a means to control production and traffic flow networks, respectively. The interaction-based interpretation of the inter-arrival time statistics in queuing systems bridges to the subject of traffic flows. Gourley and Johnson discuss the effects of decision-making on the transport costs across networks, while the subsequent contributions discuss empirical scaling laws in urban road and supply networks. Remarkably enough, although road networks typically do not display a self-similar structure or power-law scaling, the distribution of traffic in the network shows an interesting scaling behavior.

Armbruster et al. attempt to transfer a biological approach to a manmade system: they propose a pheromone-based control of production networks. Tero, Koayashi, and Nakagaki suggest a *Physarum solver* for road-network navigation, while Draief analyzes epidemic spreading processes. Moreover, Buzna et al.

study a model for disaster spreading, which has mathematical similarities with some models of brain dynamics. Finally, this special issue closes with two contributions on social networks: one on information flows in organizations and another one on pair-formation processes in multi-agent populations.

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References

[1] D. Armbruster, D. Marthaler, C. Ringhofer, K. Kempf, T.-C. Jo, A continuum model for a re-entrant factory, Oper. Res. (2006), in press.
[2] D. Helbing, New J. Phys. 5 (1) (2003) 90.
[3] D. Helbing, Rev. Mod. Phys. 73 (2001) 1067.
[4] C. Daganzo, A Theory of Supply Chains, Lecture Notes in Economics and Mathematical Systems, vol. 526, Springer, New York, 2003.
[5] D. Armbruster, D. Marthaler, C. Ringhofer, SIAM J. Multiscale Model. Simulation 2 (2004) 43.
[6] D. Helbing, S. Lämmer, T. Seidel, P. Seba, T. Platkowski, Phys. Rev. E 70 (2004) 066116.
[7] D. Helbing, M. Treiber, A. Kesting, Physica A (2006), doi:10.1016/j.physa.2006.01.048, this issue.
[8] D. Armbruster, in: G. Radons, R. Neugebauer (Eds.), Nonlinear Dynamics of Production Systems, Wiley, New York, 2004, p. 5.
[9] K. Peters, J. Worbs, U. Parlitz, H.-P. Wiendahl, in: G. Radons, R. Neugebauer (Eds.), Nonlinear Dynamics of Production Systems, Wiley, New York, 2004, p. 40.
[10] E. Lefeber, in: G. Radons, R. Neugebauer (Eds.), Nonlinear Dynamics of Production Systems, Wiley, New York, 2004, p. 71.
[11] D. Helbing, in: G. Radons, R. Neugebauer (Eds.), Nonlinear Dynamics of Production Systems, Wiley, New York, 2004, p. 85.
[12] B. Rem, D. Armbruster, Chaos 13 (2003) 128.
[13] M.W. Braun, D.E. Rivera, W.M. Carlyle, K.G. Kempf, Simulation: transactions of the society for modeling and simulation international 79 (2003) 139.
[14] D. Helbing, S. Lämmer, in: D. Armbruster, A.S. Mikhailov, K. Kaneko (Eds.), Networks of Interacting Machines: Production Organization in Complex Industrial Systems and Biological Cells, World Scientific, Singapore, 2005, p. 33.
[15] R. Albert, A.-L. Barabási, Rev. Mod. Phys. 74 (2002) 47.
[16] S. Bornhold, H.G. Schuster (Eds.), Handbook of Graphs and Networks, Wiley, Weinheim, 2003.
[17] C. Daganzo, Transport. Res. B 29 (1995) 277.
[18] D. Helbing, J. Phys. A 36 (2003) L593.
[19] D. Helbing, in: S.P. Hoogendoorn, S. Luding, P.H.L. Bovy, M. Schreckenberg, D.E. Wolf (Eds.), Traffic and Granular Flow '03, Springer, Berlin, 2005.
[20] D. Helbing, U. Witt, S. Lämmer, T. Brenner, Phys. Rev. E 70 (2004) 056118.
[21] B. Hess, A.S. Mikhailov, Science 264 (1994) 223.
[22] B. Hess, A.S. Mikhailov, J. Theor. Biol. 176 (1995) 185.
[23] P. Stange, D. Zanette, A.S. Mikhailov, B Hess, Biophys. Chem. 72 (1998) 73.
[24] A.S. Mikhailov, V. Calenbur, From Cells to Societies: Models of Complex Coherent Action, Springer, Berlin, 2002.
[25] D. Armbruster, A.S. Mikhailov, K. Kaneko (Eds.), Networks of Interacting Machines: Production Organization in Complex Industrial Systems and Biological Cells, World Scientific, Singapore, 2005.
[26] N.S. Glance, B.A. Huberman, Sci. Am. 270 (1994) 76.
[27] G. Szabó, C. Hauert, Phys. Rev. E 66 (2002) 062903.
[28] F. Schweitzer, L. Behera, H. Mühlenbein, Adv. Complex Syst. 5 (2/3) (2002) 269.
[29] F. Schweitzer, in: M. Gallegati, A.P. Kirman, M. Marsili (Eds.), The Complex Dynamics of Economic Interaction, Lecture Notes in Economics and Mathematical Systems, vol. 531, Springer, Berlin, 2004, p. 303.
[30] D. Helbing, M. Schönhof, D. Kern, New J. Phys. 4 (1) (2002) 33.
[31] D. Helbing, M. Schönhof, H.-U. Stark, J.A. Holyst, Adv. Complex Syst. 8 (2005) 87.

[32] D. Helbing, S. Lämmer, P. Lebacque, in: C. Deissenberg, R.F. Hartl (Eds.), Optimal Control and Dynamic Games, Springer, Dortrecht, 2005.
[33] D. Helbing, S. Lämmer, Patent DE 10 2005 023 742.8 (2005).
[34] T. Beaumariage, K. Kempf, in: Proceedings of the Fifth IEEE/SEMI Advanced Semiconductor Manufacturing Conference, 1994, p. 169.
[35] I. Diaz-Rivera, D. Armbruster, T. Taylor, Math. Oper. Res. 25 (2000) 708.
[36] I. Katzorke, A. Pikovsky, Int. J. Bifurcat. Chaos 13 (2003) 1343.
[37] L.A. Bunimovich, Discrete and Contin. Dyn. Syst. B 1 (2001) 209.
[38] C.J. Chase, J. Serrano, P. Ramadge, IEEE T. Automat. Contr. 38 (1993) 70.
[39] K. Peters, U. Parlitz, Int. J. Bifurcat. Chaos 13 (2003) 2575.
[40] D. Helbing, I. Farkas, T. Vicsek, Nature 407 (2000) 487.
[41] S. Camazine, J.L. Deneubourg, N.R. Franks, J. Sneyd, G. Theraulaz, E. Bonabeau, Self-Organization in Biological Systems, Princeton University Press, NJ, 2003.
[42] M. Dorigo, L.M. Gamberdella, IEEE Trans. Evol. Comput. 1 (1997) 53.
[43] G. Di Caro, M. Dorigo, Vivek Quart. Artif. Int. 12 (1999) 2.
[44] M. Dorigo, E. Bonabeau, G. Theraulaz, Future Gener. Comp. Syst. 16 (2000) 851.
[45] P. Valckenaers, H. Van Brussel, M. Kollingbaum, O. Bochmann, in: Lecture Notes in Artificial Intelligence, vol. 2086, Springer, Berlin, 2001, pp. 317.
[46] L.H. Hartwell, J.J. Hopfield, S. Leibler, A.W. Murray, Nature 402 (1999) c47.
[47] H. Kitano, Nature 420 (2002) 206.
[48] J. Howard, Mechanics of Motor Proteines and the Cytoskeleton, Sinauer Associates, 2001.
[49] R. Lipowsky, S. Klumpp, Physica A 352 (2005) 53.
[50] C. Wittenberg, Nature 434 (2005) 34.
[51] D. Chowdhury, A. Schadschneider, K. Nishinari, Phys. Life Rev. 2 (2005) 318.
[52] B. Alberts, Cell 92 (1998) 291.
[53] A.L. Barabasi, Z.N. Oltvai, Nat. Rev. Genet. 5 (2004) 101.
[54] A.S. Mikhailov, B. Hess, J. Biol. Phys. 28 (2002) 655.
[55] A.S. Mikhailov, Artificial life: an engineering perspective, in: R. Friedrich, A. Wunderlins (Eds.), Evolution of Dynamical Structures in Complex Systems, Springer, Berlin, Heidelberg, 1992, pp. 301–312.
[56] H. Haken, A.S. Mikhailov (Eds.), Interdisciplinary Approaches to Nonlinear Complex Systems, Springer, Berlin, Heidelberg, 1993.
[57] A.S. Mikhailov, Foundations of Synergetics I. Distributed Active Systems, 1994, 2nd revised ed., Springer, Berlin, Heidelberg, 1990.
[58] A.S. Mikhailov, K. Showalter, Phys. Rep. 425 (2006) 79.
[59] W.J. Hopp, M.L. Spearman, Factory Physics, McGraw-Hill, Boston, 2000.