Socioeconomic Development and Stability: A Complex Network Blueprint

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ABSTRACT: Complex networks provide flexible and powerful resources for characterizing, modeling and simulating a wide range of real world complex systems. The current work discusses how such a versatile new area can be applied in order to aid economical development and stability at several scales and contexts. The following activities are involved: (a) compilation of several types of data related to socioeconomic development, including several types of transportation systems, availability of human and natural resources, communication and energy networks, climate and geographical features, as well as endemic diseases, to name but a few; (b) representation of such data in terms of multilayer interacting complex networks registered geographically; (c) application of traditional and new methods for complex networks characterization and analysis. Such an approach allows the identification of bottlenecks and deficits/surpluses, simulation of system development under varying constraints and perturbations, as well as the application of optimization methods in order to help identify the most effective strategies leading to social and economic wealth and stability. In addition to its practical implications, such an approach also emphasizes several issues of substantial theoretical interest, including the integration of networks of different natures, the interplay between the dynamics of topological and node state evolution, the effects of geographical constraints, community finding, as well as the interesting problem of how to optimize such systems with respect to network topology and dynamics in order to achieve specific objectives expressed by merit figures. The discussed methodology is particularly interesting for applications in developing countries because of the greater potential for economic evolution in such nations. This manuscript also includes a brief review of complex networks approaches to socioeconomics modeling.
"... it is hard to turn ideas into wealth in the absence of social connectedness, which in the age of the Internet still requires something more than bandwidth and high-speed connectivity."

(F. Fukuyama, The Great Disruption)

1 Introduction

The main activity in science is the art of model building. Good models require sound representation of the phenomenon of interest in terms of a reduced set of most relevant variables and parameters. Because all models are necessarily incomplete, it is important to obtain particularly effective representations, which should be able to account for the relevant variables under constraints imposed by the chosen parameters. By being naturally oriented to representing connections and relationships, graph theory stands out as particularly general and suitable for model representations. Indeed, almost all discrete data structures can be understood as a particular instance of graphs. As the relationships between variables and parameters typically change with time, it is also necessary that the adopted representations be capable of expressing dynamical changes in both network topology as well as the dynamics undergone by the states of the nodes. With this respect, the seminal works by Flory [1], Rapoport [2], Erdös and Rényi [3] on random networks have been substantially expanded in the recent years mainly through the consideration of principles from statistical physics and dynamic systems, especially regarding the characterization and modeling of scale free network models [4].

A direct indication of the impressive success of complex network research is the large and ever increasing related scientific production, accounting for about 1 or 2 new arxiv manuscripts per day (http://arxiv.org/archive/). Indeed, the catalysis of scientific investigation, interaction and dissemination allowed by the WWW and internet resources as arxiv provides further evidence of the impact of immediate wide dissemination of data, results and knowledge. One particularly interesting portion of the developments in complex network has been aimed at applying concepts, measurements and models in order to mimic and predict the behavior of real complex systems including the internet (e.g. [5] [6] [7] [3]), WWW (e.g. [9] [10]), protein and metabolic interactions (e.g. [11] [12]), transportation systems (e.g. [13] [14] [15]), opinion formation (e.g. [16] [17] [18] [19]), epidemiology (e.g. [20] [21]), among many other relevant issues. Because of its flexibility and power for developing good integrative models of complex systems, it becomes particularly interesting to consider the systematic application of this new area as means to represent, model, predict and optimize the behavior of socioeconomic systems.

Socioeconomics environments rank among the most complex systems known to humanity, involving a whole range of entities and relationships. By selecting a set of reference entities (e.g. institutions or cities), it is possible to obtain a series of integrated complex networks [22] registered by geography, each representing specific types of relationships. Several concepts, measurements and modeling approaches derived from the area of complex network research can then be applied in order to characterize several topological and dynamical features of such systems, allowing the prediction of the
response of the system to modifications, the identification of promising development strategies, the enhancement of the stability of the whole system, optimization in order to achieve specific objectives, as well as its resilience to disruptions (e.g. epidemics and catastrophes), to name but a few possibilities.

This text describes a possible blueprint for such investigations, which are relevant not only for their immediate implications and potential for optimizing commonwealth, but also for poising several interesting theoretical issues arising from the integration of networks and optimization of topology-dynamics under pre-specified optimality indices. It should be emphasized at the outset that it is the broad integrative perspective of considering several types of evolving geographically registered geographical networks, with emphasis on applications to third-world socioeconomics, which provides the main motivation for the present work. It should also be noted that any result arising from such a type of simulations need to be treated with the greatest caution because of the several non-linear and unpredictable effects which are known to operate in socioeconomics. However, it is expected that the systematic and integrative use of concepts and methods from complex network research, itself a very dynamic research area, can provide valuable means for optimizing socioeconomic development and stability.

This article starts by briefly reviewing some of the main complex network approaches to socioeconomics and follows by discussing the representation of the modeled systems in terms of multi-layer, geographically registered networks, as well as simulation and optimization possibilities.

2 A Brief Review of Complex Network Approaches to Socioeconomics and Related Issues

Previous developments involving complex network approaches to socioeconomics reported in the literature are briefly reviewed in the following. One of the first socioeconomics related applications of complex networks was reported by Guardiola et al. [23], where the web of trust scheme between users of PGP was considered as a model for trust networks, leading to good resilience to intentional attack. The use of small-world models for socioeconomic systems was investigated by Elgazzar [16] through simulation of the Sznajd dynamics [24, 17] on small-world networks. The issue of geographical embedding of networks [25, 26, 27] as a constraint to U.S. Internet infrastructure and its implications for economy and politics was considered in [28]. Spatial constraints have also been found to affect networking and internet architectures [29], in the sense that computing resources would tend to be placed as close as possible to the source of data in order to avoid expensive network traffic. The network topology of the Austrian Interbank market was investigated by Boss and collaborators [30], indicating that the contract size distribution follow an extensive power law. The issue of grid computing has been addressed in terms of resource allocation and regulation [31, 32] as well as by adopting complex network interconnections [33]. Bonanno et al. [34] investigated the possibility to extract meaningful economic information from portfolio of stocks and its implications for comparison of the topological properties of networks. A model of wealth dynamics and transactions among economic agents by considering dif-
ferent network connectivities was investigated by Garlaschelli and Loffredo [35]. The effect of information cascades over economic recessions in the U.S., assuming a random network model was described by Cook [36], while studies of cascades of failures as a consequence of attacks have been covered in [37]. The possibility of representing economic variables of different nature in terms of multiple interconnected networks, called Solomon networks, have been considered for Ising simulations of the dynamics of economic systems [22]. Bipartite network models have been used to simulate relationship between countries and currencies in world exchange arrangements web [38], considering assortativity aspects. The stability in supply/production networks has been investigated by Helbing [39] who analysed, by considering different network topologies, how networks of damped oscillators tend to be subject to increasing oscillations. Topological investigations of networks defined by traders exchanging goods have been considered by Reichardt and Bornhold [40], who analysed the 2004 pre-Christmas season and identified high modularity. A review of econophysics has been presented by Di [41], and a review of quantitative modelling of financial markets has been reported by Farmer and Lo [42].

3 Representation

One of the first important decisions while modeling a socioeconomic system is to define and represent in a careful way its most representative components. Such components can be divided into two categories: states and relationships. In socioeconomics networks, local states correspond to properties of the main considered sites or places (e.g. cities, institutions, etc.). Examples of states include but are not limited to:

(a) Human resources: The involved individuals, possibly subdivided into workers, consumers, experts, etc.

(b) Natural resources: The existing (or prospected) energy sources, organic and inorganic assets, rivers and lakes, climatic features, etc.

(c) Storage capabilities: The local potential for storing raw and processed materials.

(d) Industrial resources: The facilities available locally which can be used to process raw materials as well as high technological means for obtaining more sophisticated goods.

(e) Financial resources: May include the bank and finance systems which can be found in the locality.

(f) Endemic diseases: The epidemics and pathologies which continuous or periodically affect humans and animals in the region.

(g) Cultural and social features: The cultural traditions and social features and values.

(g) Scientific and technological assets: The level of scientific and technological development at each locality.

Note that several of such states are not straightforward to be quantified, implying some degree of arbitrariness.
Figure 1: Socioeconomics complex network models may involve several geographical networks characterized by the fact that the nodes have definite spatial positions. Each network \( \gamma_i \) represents one of the considered types of relationship. Note that the registration between these networks is accomplished through the spatial congruence of the nodes position. The interactions between the several layers are not represented in this diagram.

Global states are typically maps of local states into overall properties of the modeled system, such as overall production, debt or surplus, total birth/death rates, etc. The relationships between the localities follow naturally, defining a complex network for each considered type of interaction \([22]\). A particularly interesting possibility is to integrate such networks geographically, i.e. each site is represented as a node with geographical position and several types of edges are defined between such common nodes, yielding an integration of several geographical networks in a way that reminds the topographical connections between cortical layers \([43]\). Figure 1 illustrates a simple hypothetical socioeconomic model involving six cities and \( p \) relationship networks.

Examples of relationships relevant for socioeconomic systems are listed in the following:

(A) *Transportation*: Essential for economic integration, allowing human, raw materials, and processed goods displacement. Each type of transportation (e.g. railway, motorways, airways) can be represented as a specific complex network, facilitating the analysis of the complementarity between such resources.

(B) *Energy distribution*: The existing network allowing access to several types of en-
ergy (e.g. electrical and gas).

(C) **Communications**: The interconnections allowing information exchange between the considered localities, possibly subdivided into networks for cell and fixed telephony, satellite, optic fibers, etc.

(D) **Financial and political trusts and alliances**: Corresponding to the network of government and private financial agencies.

(E) **Borrow/Loan relationships**: The directed network defined by borrowing and debts between the involved localities.

(F) **Cultural and social links**: Networks established by common share of common beliefs and traditions.

(G) **Distributed computing**: Including wide range distributed computing facilities, such as grid computing.

Observe that most such networks are typically dynamical (in the sense that their topology will vary with time) and weighted. Flow or resources conservation may eventually be observed. Except for communications networks, all the above networks are typically represented as digraphs (i.e. involving oriented edges).

### 4 Characterization and Simulation

Once a part of a socioeconomic system has been represented in terms of geographically integrated networks, a series of measurements can be used to characterize and analyse their topology. The choice of measurements should be performed with basis on the specific issues of interest. For instance, in the case of transportation systems, statistics of shortest paths are of special relevance. The reader is reported to a recent survey \[44\] for a comprehensive review of complex network measurements. Of special interest are the specific demands implied for the topological characterization of the geographically registered coexisting networks, motivating new measurements capable of expressing the topological interactions between the several layers (e.g. \[43\]). Another particularly relevant issue is the identification of communities in the integrated networks. A particularly interesting possibility is to consider the identification of well-defined communities in one of the layers as a subsidy for identification of communities in the remainder layers, as well as the analysis of overlaps and divergences between such clusters. Perspectives of special interest also include the development of models describing the topological evolution of the networks at each layer and as a whole.

The simulation of the dynamics of the network states can be performed by assuming several methods including spin dynamics (e.g. \[22\]), cellular automata, and systems of coupled differential equations. Global feedback can also be considered in such formulations \[22\]. Important related aspects involve the synchronization of events in the networks as well as the appearance of instabilities and oscillations \[39\]. A particularly interesting possibility is to link the dynamics of the network individual states with the dynamics of topological changes in the network structure (e.g. \[19\]).
While the simulation of the dynamical evolution of the network states can lead to valuable insights about socioeconomic development and stability, it is also interesting to consider the optimization of the network architecture and constraints in order to achieve specific goals. Provided merit figures are clearly established in terms of properties of the modeled system, a series of optimization approaches ranging from linear programming to genetic algorithms can be applied in order to identify improvements to the topology of the network or its dynamical evolution. For instance, once a government have decided to explore a recently discovered source of raw material or to find the best way to protect indigenous fauna and flora, optimization of the topology of the network under constraints imposed by its states can be performed in order to evaluate possible development strategies. Of course, such approaches are inherently limited by the suboptimality (i.e. convergence to local minima) characterizing most non-linear optimization methods.

5 Concluding Remarks

This article has discussed how complex network concepts and methods can be extensively used to model socioeconomic systems. After reviewing briefly the main related literature, a blueprint has been proposed and discussed. Such a model involves multi-layer networks whose nodes are registered in terms of the geographical positions of the entities which they represent. Several interesting issues are motivated regarding the characterization and simulation of such networks. As far as the analysis of the topological features of the multiple networks are concerned, adaptations of traditional measurements and new features capable of taking into account and quantifying the interconnections between different layers are of special interest. Two mains possibilities are defined regarding the dynamics of state evolution: (i) the simulation of the dynamics on static diverse topologies; and (ii) the simulation of state dynamics on networks whose topology undergoes dynamic evolution.

Several are the difficulties constraining such investigations. To begin with, it is important to gather reliable, uptodated and representative data related to each socioeconomic features considered in the model. A particularly challenging issue concerns the definition of the merit figures used for the optimization of the topology and weights of the network, which often implies political, ethical and/or arbitrary nature (e.g. should transgenic products or abortion be allowed?). Also, the high complexity of the involved systems severely constrains the time window for predictions, implying that the greatest caution should be taken when analysing characterization and simulation results. Despite such difficulties, it should still be possible to adopt a progressive approach starting with only a few layers and gradually increasing complexity. An example of a particularly feasible and interesting starting point is to investigate the efficiency of coexisting transportation networks (e.g. railways, motorways, airport systems) while trying to identify how such systems can be improved (e.g. minimize the average shortest path) by small topological modifications (e.g. the inclusion of a new railway link). Such models can be easily upgraded by including the availability of natural and human resources, consequently defining interesting problems of optimizing flow and production-consuming interactions.
The author is currently conducting related efforts considering the Brazilian economy and would highly appreciate to receive comments and suggestions and to consider collaborations in any theoretical or practical related aspects.

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