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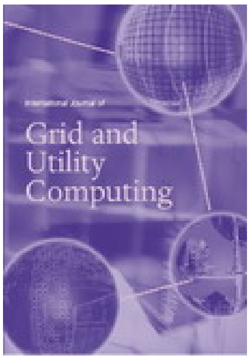

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Complex networks applied to the analysis of the dynamics of social systems

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Abstract: Social systems' inherent structure has an impact on how they act. The system's internal structure is determined by the parts that make it up and the connections that link them. The system's behaviour dynamics through time are determined by interactions among its components, and determining the internal structure of a social system in order to analyse its behaviour over time is a very complex process. The analysis of the system is complicated due to the numerous variables whose behaviour is challenging to quantify through functional relationships, which also contributes to the complexity of the network or graph that must be constructed to represent the system. The best data structure for modelling complex systems is a network or a directed graph, which can be used to analyse and study the dynamics of the system in order to make decisions.

Keywords: complex networks; social dynamics; Vensim PLE; decision making.

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1 Introduction

1.1 Complex network models

During the second half of the 20th century, models for modelling real systems in graphs, complex networks, were introduced in the literature. The first model was suggested by Lima et al. (2008), which became known as random graphs or the ER model. In Fortunato (2010), this model has two parameters: the total number of vertices *n* and a probability *p*. Each pair of vertices is connected according to this probability *p* independent of the other vertices (Enbeyle et al., 2022). In Newman (2003), he expected number of edges for this model is $pn(n-1)/2$ and the average connectivity $\langle k \rangle = p(n-1)$. The distribution $p(k)$ of this type of model follows a Poisson distribution, which can be represented by $p(k) = \langle k \rangle e^{-\langle k \rangle} / k!$ (Newman et al., 2003), in which all vertices have a degree close to $\langle k \rangle$. The shortest average path in this type of network tends to be very small, growing proportionally to the logarithm of *n* (Costa et al., 2011).

This paper offers a review of these measurements. It also presents the most important measurements currently in use and discusses some general ideas about complex network characterisation (Boccaletti et al., 2006).

When the probability of link formation is zero, $p = 0$, the network will be completely disconnected. If $p = 1$, the network will be a complete graph; therefore, the average value of the clustering coefficient will be maximum, $\langle cc \rangle = 1$ (Milgram, 1967). A network may have a very small mean path shortest characteristic. This effect is known as small-world, introduced in Milgram (1967). Shrinivas et al. (2010) conducted an experiment where they sent hundreds of letters to randomly chosen people in the USA, and in the letter, they asked if the person knew a certain final recipient by their first name. If so, the person should send the letter to the final recipient, if not, the person should send the letter to an acquaintance who was more likely to know the recipient. Before sending the letter, the person should sign their name on it. At the end of the experiment, the final recipient should send the letter back to Milgram. The result of the experiment was that Milgram realised that the letters were on average signed by only six people before they were sent back, that is, there was on average only 6° of separation between any two randomly chosen people in this Shrinivas et al. (2010).

Jian and Dandan (2016) presented investigation applies the theory of the data structure of the type of directed graphs or network and its theoretical foundation to carry out the analysis of the social systems in which we human beings interact. Currently, the theory of Complex Networks is being applied to the study of different branches of knowledge (Yang and Suh, 2021). In our case, we direct the investigation towards the complexity of the organisation of social systems and the behaviour that is observed according to the structure of the networks in Yang and Suh (2021).

There are random networks, scale-free networks and networks of small worlds. Each of them has its own characteristics and structures. In the investigation, the corresponding analysis of these networks is made to analyses social systems that fit one of these network topologies. The data present as a result of different interactions of the elements of the social systems allow the construction of hypotheses regarding the elements and interactions between the elements of the system and carry out the analysis of the system's dynamics.

1.2 Dynamic complex networks

The framework for two common topological network architectures' relative network reactions is investigated many of the classic studies, Nicola et al. (2011) in complex network theory are based on static graphs, which are graphs that do not change over time. Nowadays, thanks to technological advances, it is possible to study large social, biological networks or even the web with precise temporal information regarding the appearance, duration and frequency of objects in the network (vertices and edges), Roy and Vemuri (2018). In Lunkenheimer et al. (2007), complex networks are networks that change over time. From an initial network, vertices and edges can be added and new connections between existing vertices can appear. Just as vertices can die, connections can be broken, a connected graph can become disconnected and any consequence derived from any action suffered by the network is possible. Social interactions and human activities are intermittent, and as time progresses, it is inevitable that a network that represents a real phenomenon does not undergo structural changes (Lunkenheimer et al., 2007; Al-Hamad et al., 2022).

When considered, the evolution of the network is normally studied by creating a series of static graphs, each containing the entire transformation that took place in the network during a certain period. Several changes that occurred in the network over time are aggregated, and the 'result' of the changes is displayed in a static graph, without additional information about which structures underwent transformations in Al-Obeidi et al. (2021).

1.2.1 Elements of system dynamics

For the study of the dynamics of the systems it is important to know the existing methodologies for this analysis. The complex network's approach is based on graph theory that allows modelling the interactions of the different elements that make up the system. These interactions are a function of the system's internal structure; that is, how the different elements that make up the system are related.

1.2.2 Notion of dynamic system

The model of the dynamic behaviour of a system is called System Dynamics.

A system is an abstract system in which the interacting elements are abstract concepts and the relationships between them are formalised.

Under the System Dynamics point of view, the dynamic behaviour of a system is determined by its structure rather than by the very nature of its component elements, Abidin et al. (2014).

A) *System limits*:

- The limits of the system must be determined so that the elements that allow the system's behaviour to be reproduced are within it, and all those elements that do not intervene directly are outside it.
- The concept of limit seeks to explain that the system's behaviour of interest occurs within defined limits, and is not determined from the outside. This does not mean that the system will not be affected from outside the limits, rather the action of the environment on the system is considered as a disturbance that affects the autonomous behaviour of the system.
- When building a model to study a system, one must first estimate which components interact to produce the behaviour under investigation.
- The elements outside the boundaries of the system are related to those inside in a very different way than the elements inside are interrelated with each other.
- CAUSE-EFFECT relationships between the environment and the system are unidirectional; on the other hand, the elements inside the system are structured by means of feedback loops that determine a strong interaction between them.
- The same attribute of the medium cannot affect and be affected by the system. If this happens, this attribute will be included in the system.

The concepts that we point out in the theoretical foundations are based on the theory of Javier Article and published in his book System Dynamics.

B) *Elements and relationships in the models*: A model as an abstract representation of a real system is composed of:

- A set of definitions that will help identify the elements that makes up the model.
- A set of relations that specify the interactions between the elements of the model.

Different models can be established from the same real system, depending on the different elements or variables that intervene in the model, they can be classified as exogenous and endogenous. Exogenous variables, they serve to describe those effects on the system that can be modified from outside the system. They represent the medium in which the system under study is immersed, they serve to characterise those elements whose behaviour is completely determined by the structure of the system, without the possibility of direct modification from the outside.

For example: In the study of a regional economy, the amounts of the General Sales Tax will represent an exogenous variable since the national government sets this amount; while the consumer price index would be an endogenous variable, since it is set by supply and demand within the regional economic system.

1.3 Problem statement

Currently in our country there are problems of social interaction of people. Therefore, it is necessary to develop research that analyses and seeks to explain these phenomena. In our specialty, we seek to apply network theory to analyse models represented in the computer and evaluate changes in behaviour according to the manipulation of the system's internal structure.

1.4 Problem formulation

All of the above leads us to support the need to formulate the following problem:

- To what extent can the dynamics of social systems be analysed by applying the theory of Complex Networks?
- Justification or importance of the investigation.
- The different specialties of the university must contribute to society with research that applies the knowledge acquired for the analysis, study and solution of the problems that arise.
- With this research we intend to contribute with the application of the theory of complex networks to the analysis of social systems and their dynamics based on the network's topology.

1.5 Aim of the study

The objective is to evaluate the effects of network topology variation on the dynamics of social behaviour with respect to a certain aspect. For this, metrics are established that allow evaluating the behaviour of the network according to its topology.

1.5.1 Objectives of the study

- Analyse the theory of Complex Networks and its usefulness for modelling social systems.
- Study the behaviour of networks according to their topology or structure.

1.6 Research hypothesis

If the internal structure defines the dynamics of the systems, then it is possible to evaluate the behaviour of the Complex Network according to its structure or topology.

Specific hypothesis

- It is possible to analyse the theory of Complex Networks and its usefulness for modelling social systems.
- It is feasible to study the behaviour of Complex Networks according to their topology or structure.

2 Methodology

The method that we apply in the present investigation is the scientific method. The research is qualitative and descriptive level. Based on Jay Forrester's theory, the tests were carried out from system simulation models.

Firstly, we work with causal diagrams, which are the networks that abstract the relevant elements of the social systems and the relationships between them. The result of these relationships determines the behaviour of the system over time. Jay Forrester's diagrams are built from these graphs, which allow computer simulation based on the functional relationships between these elements. These models were implemented in the Vensim PLE software and it enables constructing a model from the client's needs and ensuring that it adheres to them throughout the creation process, which is uncommon with other tools to carry out the necessary runs to determine changes in the behaviour of the systems over time based on changes in the internal structure of the system.

3 Results and discussion

3.1 Case study 1

Simulation of the propagation of a rumour, comment or news in a population is carried out. Initially, 12 people knew about the rumour out of a total of 712 people. The spread rate is 3% and the spread factor is 5%. Population A is the population that already knows the event. Population B is the medium's total population, and the difference is the number of people who still do not know the news as shown in Figures 1 and 2. The observed dynamics are shown below.

3.1.1 Spreading a rumour to a group of people

3.2 Case study 2

In this case, we study and simulate production systems related to the dynamics of social systems.

The production capacity of the employees determines the inventory of products in a production system. In turn, the production capacity will be a function of the observed inventory level. Social system related to production systems Delay Information.

Figure 1 Complex network diagrams for the simulation of a rumour or news propagation in a social system (see online version for colours)

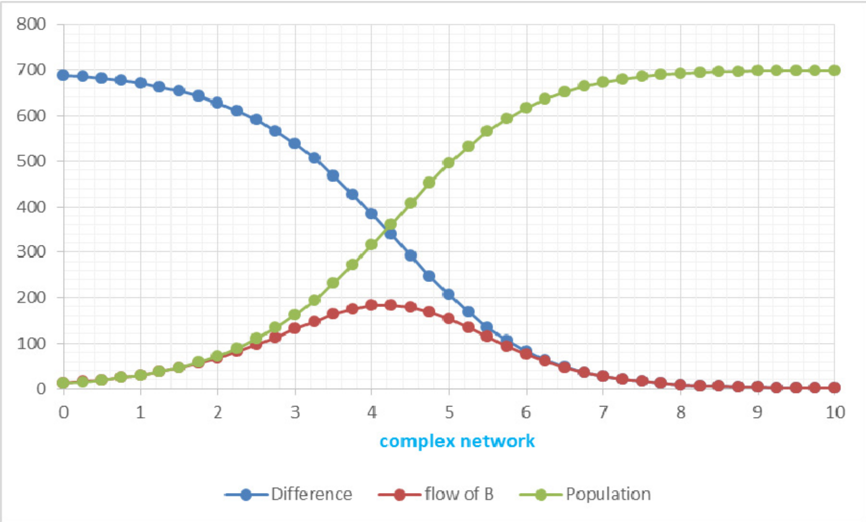
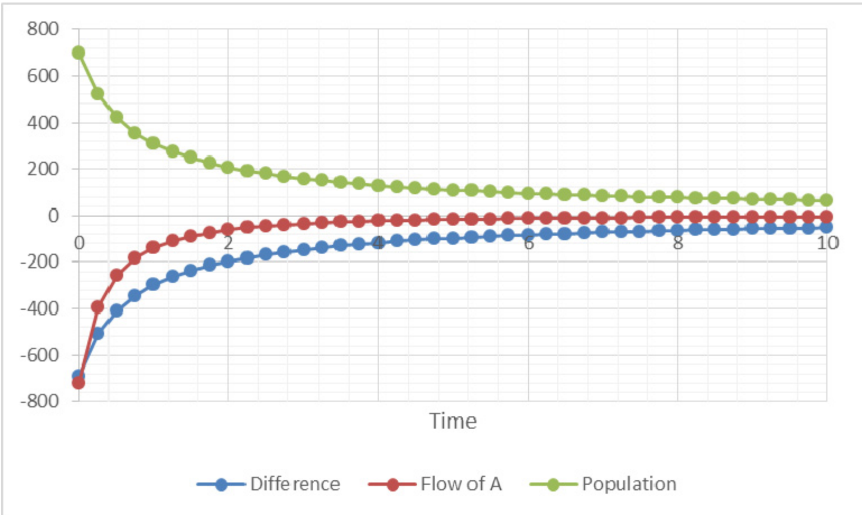


Figure 2 Results of simulation runs in Vensim PLE (see online version for colours)



3.2.1 Social systems related to production systems

- The simulation was run with the parameters:
- Desired inventory: 12,000 units
- consumption rate: 1000 units
- Production capacity: 1000 units
- Desired coverage: 12 units
- Constant demand: 1000 units
- Gap Factor = (Capacity Change Delay*Desired Inventory)/Desired Capacity Production
- Capacity Change Index = (Desired Inventory-Inventory)/Gap Factor
- Consumption Index=Demand
- Production Index=Production Capacity/Correction Factor
- Desired Inventory=Demand*Desired Coverage

3.3 Analysis of results

The analysis of the results of the simulation of social systems applying the study of networks or directed graphs translated to a Forrester diagram shows that the system's structure determines its dynamics over time.

In case 1, it is observed that the propagation of a social phenomenon changes according to the system's structure according its functional relationships or equations that determine it shown in Figure 3. When the population that knows about the event that is part of the social phenomenon is smaller than those that do not know about the phenomenon, a growth in *S* is observed in the system's behaviour related to the event's propagation. In the other case, when the number of people who do not know the phenomenon is less than those who do know the phenomenon, an asymptotic behaviour tending to the total population B is observed, as shown in Figure 4.

Figure 3 Social system related to production systems (see online version for colours)

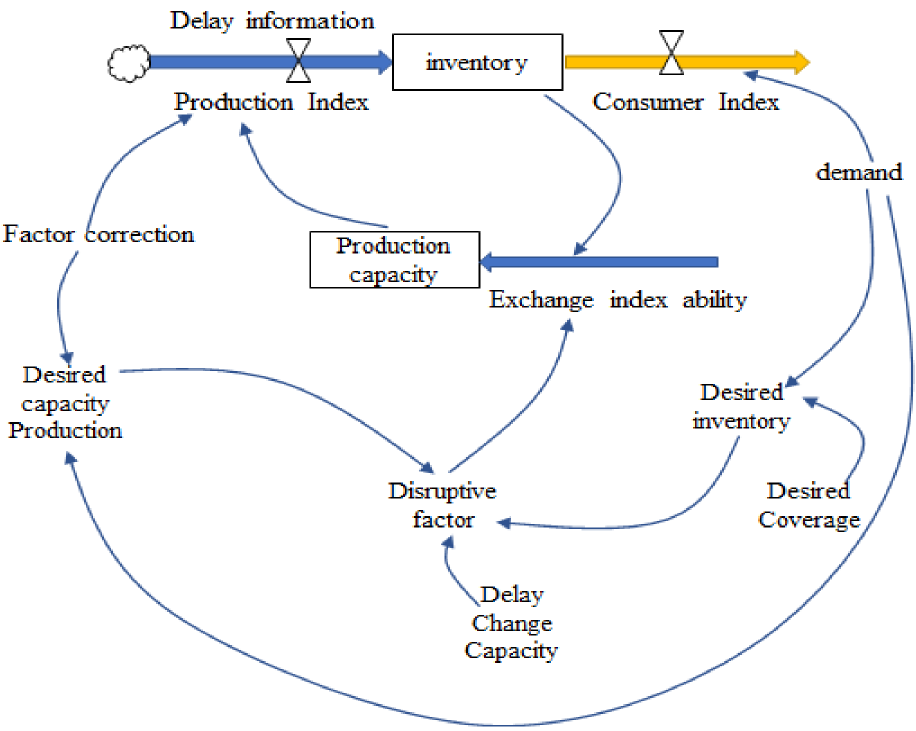
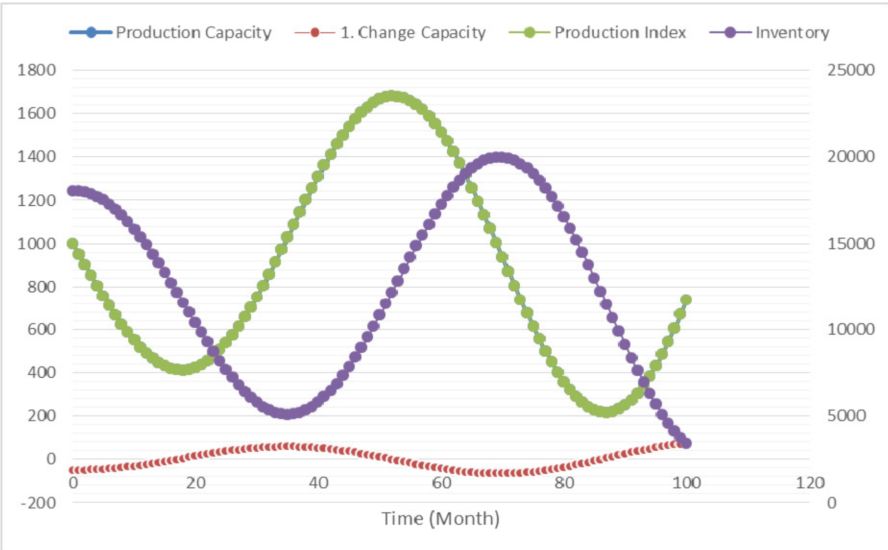


Figure 4 Result of the interaction of social systems with production systems (see online version for colours)



In case 2, it is observed that the social production systems are directly related to the growth of the production capacity, which in turn varies according to the company's inventory.

The way the systems are structured internally, which for computational purposes of analysis, are represented in data structures such as networks or graphs, determines the dynamics of the systems over time.

4 Conclusions

The analysis of the system is complicated due to the numerous variables whose behaviour is challenging to quantify through functional relationships, which also contributes to the complexity of the network or graph that must be constructed to represent the system. The best data structure for modelling complex systems is a network or a directed graph, which can be used to analyses and study the dynamics of the system in order to make decisions.

The topology of the network or directed graph represents the system's internal structure. The variation of this structure determines the variation of the behaviour of the system, as it was obtained as a result of the simulations of the two test cases on the computer by means of the simulation technique using the specific purpose software Vensim PLE.

- The analysis of complex networks was carried out to model social systems that were later implemented on the computer using Jay Forrester's diagrams.
- The behaviour of these social systems related to phenomena that are present in the system in which they are immersed was evaluated. It was observed that by varying the structure and its simulation parameters, the result of the behaviour also changes over time, which shows that networks allow the internal structures of systems to be modelled for analysis purposes by means of the computer simulation technique.

4.1 Recommendations

As the systems surrounding us are innumerable, there will always be the possibility of conducting analysis and study through complex networks. Then, it is recommended to deepen knowledge on the subject of modelling social systems for analysis in the computer in order to make decisions looking for desired behaviours in systems based on their internal structure.

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