Multidimensional Social Network: Model and Analysis

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Abstract. A social network is an abstract concept consisting of the set of people with relationships linking pairs of humans. A new multidimensional model, which covers three main dimensions: relation layers, time windows and groups, is proposed in the paper. The dimensions have a common set of nodes, typically, corresponding to human beings Layers, in turn, reflect various relation types coming from different user activities gathered in computer systems. The time dimension corresponds to temporal variability of the social network. Social groups are extracted by means of clustering methods and join people close each other. An atom component of the multidimensional social network are views – small social sub-networks, which are in the intersection of all dimensions. A view describes the state of one social group, linked by only one type of relationships (one layer), derived from within only one time period. The multidimensional model of the social network is similar to the general concept of data warehouses, in which a fact corresponds to a view. Aggregation possibilities and usage of the model is also discussed in the paper.

Keywords: social network, multidimensional social network, multi-layered social network, network model

1 Introduction

Each social networked system is a source of different information about people and their activities. Lately we have experienced rapid growth of social structures supported by communication technologies and the variety of Internet- and Web-based services. For the first time in the human history we have possibility to process data (gathered in our computer systems) about interactions and activities of millions of individuals. Communication technologies allow us to form large networks which in turn shape and catalyse our activities. Due to scale, complexity and dynamics, these networks are extremely difficult to analyse in terms of traditional social network analysis methods being at our disposal. Moreover, there is hardly any research reported with respect to multidimensional networked models models.

Nodes in such complex social networks are digital representations of people who use email services, telecommunication systems, multimedia sharing systems, access

blogosphere etc. Based on interactions between users their mutual relationships are extracted. Due to diversity of communication channels the analyzed networks are multidimensional, i.e. these are networks that consist of more than one type of relationship. Different relations can emerge from different communication channels, i.e. based on each communication channel separate relation that can be also called a layer of a network is created. Moreover, there is one more dimension that needs to be considered – time. The behaviour of all nodes in social network is time-dependent, i.e. time factor cannot be neglected during analysis.

Although different models of social networks have been developed and many ways of their representation, such as matrices, graphs or algebraic description, exist, there is hardly any research reported with respect to the modelling of multidimensional social networks. This article focuses on building a model for multidimensional social network that will also be able to present the dynamics of this structure.

2 Related Work

The research in the field of social networks has its origins in 1950s and since then is continuously developed by many scientists.

As it was mentioned before a social network can be defined as the finite set of actors (network nodes) and relationships (network edges) that link these actors. Although this concept appears to be quite obvious, different researchers describe it in a slightly different way and from different perspectives [11], [18], [20], [21]. These various approaches are the result of the fact that the social network concept has been simultaneously developed by scientists from many different domains.

Based on data gathered in computer systems, a new type of social networks can be extracted and analysed. These networks are named online social networks [5], [8], web-based social networks [10], computer-supported social networks [22] or virtual communities. They can be created from different data sources, e.g.: bibliographic data [9], blogs [1], photos sharing systems like Flickr [14], e-mail systems [16], telecommunication data [2], [17], social services like Twitter [12] or Facebook [6], video sharing systems like YouTube [4], and many more.

During analysis of social networks, researchers usually take into account only one type of connections between users while, in most real cases, there are many different relationships. Only few scientists have focused their research interests at multi-layer social network extraction from activity data.

The problem of multiple relations was investigated in [20] where the graphical, algebraic and sociometric notations for multiple relations are proposed. Wasserman and Faust proposed to use Image Matrices for Multiple Relations. However as authors emphasized interpreting each image (matrix a single relation) separately seems to be ad hoc. They suggest comparing pairs of images and investigating multi-relational patterns such as multiplexity or exchange. This solution does not solve the problem with networks where there can exist many of relation types.

Another approach was presented by Jung in [13] who proposed to combine social relationships with corresponding ontology and concept ties. In another approach,

which is not semantically-driven, Kazienko *et al.* investigated Flickr photo sharing system and have distinguished eleven types of relationships between users [14]. A special type of social networks that allows the presentation of many different activities is called a multi-layered social network [3], [15]. It can be represented as a multi-graph [7], [20]. Overall, due to their complexity, such networks are more difficult to be analyzed than simple one-layered social networks and no established methods have been developed.

In this paper, we focus on developing a conceptual, generic model for multidimensional social network that enables to capture information about different types of activities and interactions between users as well as represent the dynamics of user's behaviour. The proposed model encompasses information not only about different relations but also the groups that exist within a given relation layer and in a specific time window.

3 Multidimensional Social Network: A Model

3.1 Multidimensional Model of the Social Network

The expected nature of social network models should reflect interaction between users with respect to the all types of relationship existing between network's users accompanied by proper description, namely strength and dynamicity of relation. The representation of relations in the model should additionally allow gathering customized description to be easily concluded in order to provide informative presentation of networks and individuals characteristics. The general idea behind the multidimensional model of the social network endeavours to provide the framework allowing the description of entirety of social interactions existing between network actors.

Multidimensional model of the social network presented in the paper is based on the basic profile of multidimensional and dynamic social networks. The foundation of each social network is a structure made up of individuals, which are tied by one or more specific types of interdependency, such as friendship, kinship, common interest, financial exchange, likes and dislike, etc. In order to represent such entities, the model assumes the representation of nodes and edges, where nodes represent individuals (social entities) and edges – interconnections between them. Obviously, as there exist multiple numbers of interconnection types, the edges may represent distinct meanings of relation. Therefore, the model assumes they are contained in some semantic layer of relations of the same meaning.

Social networks usually are not a static structure and may comprise relations that change over time. Thereby, the set of network actors may vary over time. The dynamics of relations and nodes needs its representation and is modelled by time windows – a set of static pictures (snapshots) representing the state of network obtained in certain time interval.

The proposed model additionally encompasses information not only about dynamicity and different kind of relations but also the groups that exist within a given

relation layer and in a specific time window. It provides the opportunity to distinguish distinct sets of nodes with high density of internal edges and low density of edges between those sets.

Concluding, the general concept of the model considers three distinct dimensions of social networks: layer dimension, time-window dimension and group dimension, see Fig. 1. All the dimensions share the same set of nodes that corresponds to social entities: single human or groups of people.
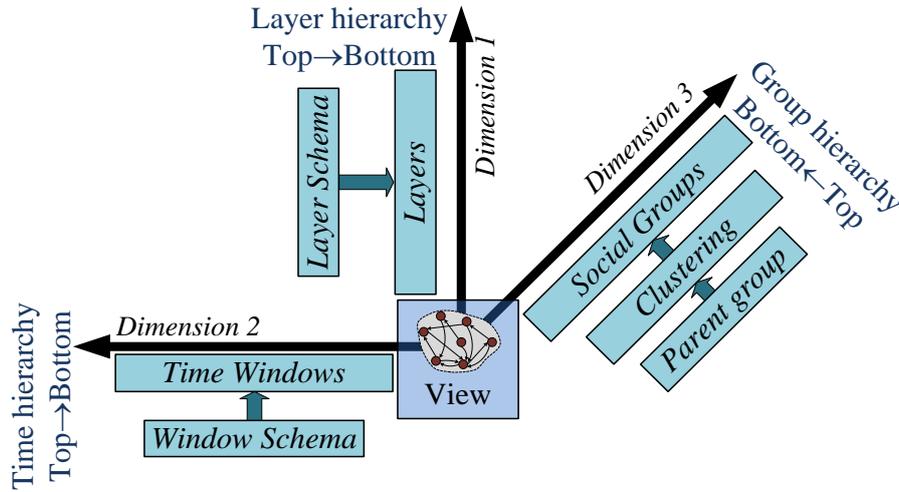

Fig. 1. Three dimensions with hierarchies in the multidimensional social network

3.2 Dimension 1: Layer Hierarchy

Layer dimension describes all the relationships between the users of a system. The relations may represent direct communication between users via e-mail or phone. But they also may result from human activities in IT system, e.g. sharing and co-editing documents in business intranet.

In general, three categories of relations are distinguished: direct relation, pseudo-direct relation and indirect relation, see [14] for details. A relationship between the users may be directed, when it takes place from one user to another, or undirected if a direction of the relation is not determined.

Besides, the relationships occurring between people have different nature. Going to the same school, shopping in the same e-magazines, being a friend of somebody, writing SMS to somebody, attending e-lectures are only a few examples of the relation types. Based on the data available in a given system it is possible to extract all the types of relationships that occur between its users, defining in this way a set $\{R_1,R_2,...,R_n\}$, where $R_i=\{\langle user_x,user_y\rangle \mid user_x,\ user_y \in Users,\ user_x \neq user_y\}$, $i=1,2,...,n$ is a type of relation. Let *IDU* defines a finite set of users of one system and $L=\{l_1,l_2,...,l_n\}$ – a set of layers corresponding to the relations from the set $\{R_1,R_2,...,R_n\}$. Particular layers $l_1,l_2,...,l_n$ consist of the same *IDU* set (nodes in graph

representation) connected by relations (edges) of the types: R_1 in layer l_1, R_2 in layer l_2, and R_n in layer l_n respectively.
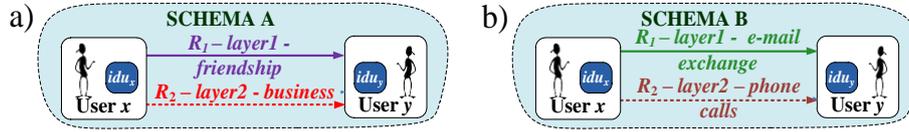

Fig. 2. Two dimensional social networks with layer dimensions created according to two different schemas: a) layer1 – friendship relationship, layer2 – business relationship, b) layer1 – e-mail exchange, layer2 – phone calls

Note that single layer l_i represents simple social network including all the users of the system connected each other by relationship R_i, whereas two or more layers gives multi-layered social network with the same set of nodes connected by more than one relationship.

Layer dimensions could be created according to one or another Layer Schema (Fig. 2), e.g. Schema A: layer1 – *friendship*, layer2 – *business*, or Schema B: layer1 – *email exchange*, layer2 – *phone calls*. Schemas form an additional upper level in the layer dimension hierarchy. As a result, the social network may be analyzed with respect to any simple (single relation) or different complex (multi-relation) layer schemas.

3.3 Dimension 2: Time Hierarchy

Temporal analysis of social network is possible thanks to time-window dimension. A time-window is a period of time with well-matched size. It may be a snapshot at given time stamp, i.e. relation existing at that time, but also relations extracted for a given period, i.e. based on human activities within time-window, see Fig. 3.

Time-window limits social network analysis to those users (nodes) and relationships (edges) that have existed in a period defined by time-window size. Resulting social network may be simple (one-layered) or multi-layered. Missing information or changes prediction is then possible by comparing networks from successive time-windows, e.g. time-windows 1, 2 and 3 in Fig. 3.
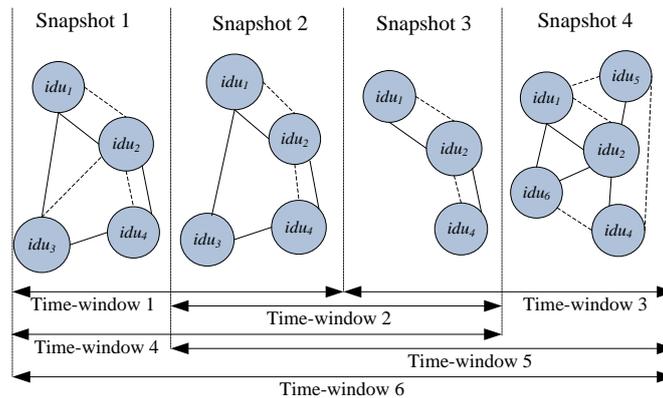

Fig. 3. Time window schemas and hierarchy

Basic problem of temporal SNA is time-window resolution. If time-window is too narrow structural parameters of social network are not correlated and the window itself introduces relatively big noise in parameter values. In turn, too wide time-window entails loss of information about temporal dependencies occurring between relations and nodes in social network. To solve this problem it is necessary to apply a method - like presented in [19] - that enables a choice of time-window optimal size.

Similarly to layer dimension, time-window dimension comprises time-windows with different sizes, moving windows, etc. that correspond to various Window Schemas, see Fig. 3.

3.4   Dimension 3: Group Hierarchy

Concept of group is not precisely define in social network environment. In general, it is considered that group assembles similar peoples. Frequently, instead of definition we can find conditions (criteria) that should be fulfilled for the group to exist. Most of these conditions derive from an idea, that a group is a social community which members more often cooperate within the group than outside. So, in social network context, a group may be defined as a subset of users who are strongly connected with the other members of the group and loosely with members of other groups, see Group 1 and Group 2 in Fig. 4.

In the model of multilayered social network, group dimension is supposed to contain all the social groups possible to obtain in the clustering processes. However, different clustering algorithms may be applied. Clustering create the second level in the hierarchy of group dimension. In addition, a *Parent Group* concept is introduced. It is a virtual object - a root of a group hierarchy, which preserves information about inter-group relations used further in the aggregation process. A single social group may include a subset of social network users connected by single relation or more than one relation in a given period of time. Thus it may be considered as multilayered structure in time-window. A group may also evolve in time. Its temporal changes and their dynamics give valuable information.
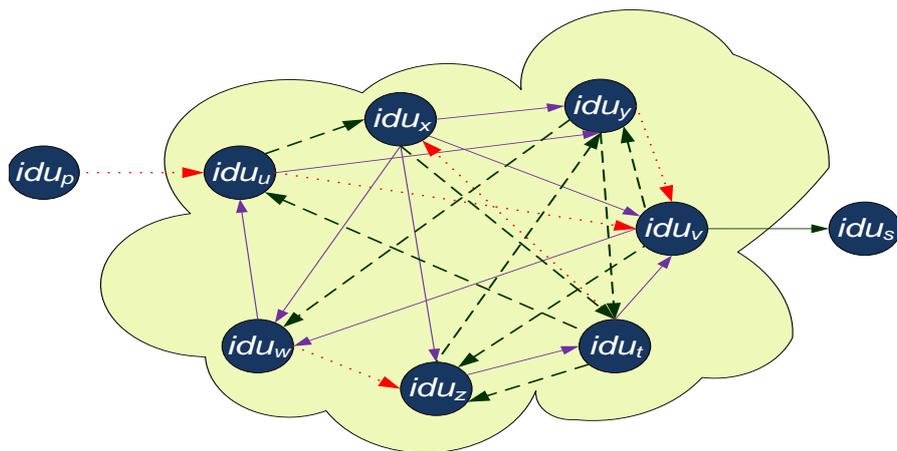

Fig. 4. Group hierarchy

3.5 Views – Dimensional Intersection

The dimensionality of the multidimensional model for the social network, that is presented in the paper, is utilized to conclude the state of the network providing its static picture. Therefore, the concept of views as a core of the model is introduced. The view is a sub-network consisting only of nodes and edges that belong to particular layer, time window and group. It means that the single view describes the state of the sub-network composed of nodes tied by edges representing the same type or relation between nodes, from the same time and that are in the same group of nodes. Thus, the concept of the model for multidimensional social network may be compared with principal assumptions of logical architecture of data warehouses.

4 Multidimensional Social Network: Analysis

4.1 Aggregations by Dimensions

The proposed concept of atomic insight in the sub-network stated by views does not allow performing queries to more sophisticated structures composed of several views. There is a strong expectation to provide the possibilities to operate on multiple views in order to consider not only a single view but more compounded patterns from the entire network. Therefore, some aggregation operators working on dimensions are required. Aggregations should offer ability to analyze such sub-network structures like accumulated network activity from particular layers, time-windows or groups. For instance, one can perform analysis of the network, considering activity from selected time-windows aggregating a given single hour of the day for all the days in the week only.

What is more, views can be aggregated by one, two or even all three dimensions at the same time. The aggregation creates a new social network object composed of nodes and edges from the considered views but with recalculated relation strengths. This recalculation is accomplished by taking into account only those relationships that occur in the selected views.

There might be considered several approaches of views' aggregation. Among others, typically, the relation strengths may be aggregated by:
- sum of relation strengths,
- mean of relation strengths,
- weighted sum of relation strengths,
- weighted mean of relation strengths.

All above mentioned aggregations are performed on edges existing between the same pair of nodes but in distinct views. Additionally, another aggregation for set of nodes appearing in distinct views may be performed by union of sets of nodes. Aggregation operations may consider additional profile of relations – timeliness. As a result, older relations can be treated as less significant in strength calculation.

4.2 Usability of the Model

In Figure 4, the simple system which utilize multidimensional social network described above to analyse a large social networking system and big organizations is presented.
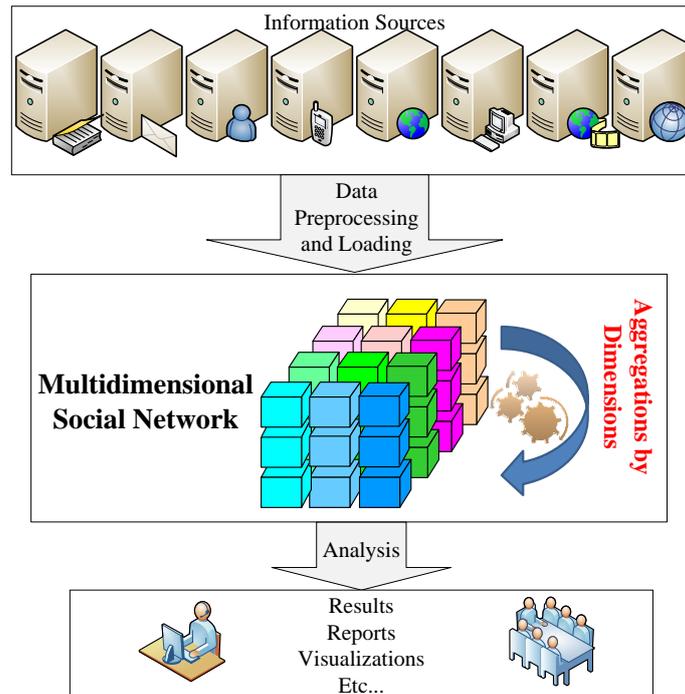

Fig. 4. Usage of Multidimensional social network

Systems, where people are linked by many different relationship types like in complex social networking sites (e.g. Facebook), where people are connected as friends, via common groups, "like it", etc. or in regular companies: department colleagues, best friends, colleagues from the company trip, etc., can be analysed using layer dimension. Multidimensionality provides a chance to investigate each layer separately and at the same time investigate different aggregations of layer dimension. For example, we have a network consisting of six layers, three from the real word: family ties, work colleagues and gym friends and three from the virtual world, i.e. friends from Facebook and fiends from the MMORPG game and friends from Stargate forum. Now, one has three different possibilities to analyse such network: (i) analyse each layer separately, (ii) aggregate layers from the real world and compare it to the virtual world layers aggregation, and finally, (iii) aggregate all layers together.

Time dimension provides possibility to investigate the network evolution and its dynamics. For example, the analysis how users neighbourhoods changes when one of the neighbours leave the network and how it affects the network in longer period of time, how group leaders (e.g project team leaders) changes over time, or how changes on one layer affects the other layers.

Finally, the group dimension. It allows to study groups existing within the social network. Using multidimensionality not only the usual social groups can be analysed (friend family, school, work, etc.) but also groups created upon various member features like gender, age, location etc. Moreover, the model allows to compare the results of different community extraction methods, e.g. by means of social community extraction or typical data mining clustering.

To conclude, the multidimensional social network enables to analyse all three dimensions at the same time, e.g. how interaction on different layers of two social groups changes over time. Moreover, any measure can be calculated separately for view, layer, window, group, or any aggregation of the above and next, compared to each other to find the specific characteristics of each dimension, or the network can be analysed as a whole. Thus, the network multidimensionality opens new possibilities for social network analysis.

5 Conclusions and Future Work

Large amount of data about users and their activities has created a need for multidimensional analysis as one can observe many types of relationships that additionally change in time.

The proposed model of multidimensional social network enables a comprehensive and detailed description of social interactions among individuals as well as the profiles of users and their relationships. Such model could be used to investigate the relationships based on their features and also to analyse different ways of communication in the context of social science. For example one can analyse which modes of communication are jointly used or whether one mode of communication supports another one. Moreover, the model that includes the information about different types of connections between users facilitates the development of new and redefinition of existing characteristic features describing users and networks.

The proposed model also includes the information about the communities that exist at each relation layer. This provides knowledge about within which relation types (activities) groups are more likely to form.

Both different relation layers and communities existing within these layers can be investigated in different time windows. It means that their evolution and dynamics can be examined.

To sum up the development of a formal model for multidimensional social network is a novel and interesting idea that enables to investigate each complex social network from different perspectives.

References

[1] N. Agarwal, M. Galan, H. Liu, and S. Subramanya, "WisColl: Collective Wisdom based Blog Clustering", Information Sciences, 180 (1), 2010, pp. 39-61.

[2] V.D. Blondel, J-L. Guillaume, R. Lambiotte, and E. Lefebvre, "Fast unfolding of communities in large networks", J. Stat. Mech., P10008, 2008.

[3] P. Bródka, K. Musial, and P. Kazienko, "A Method for Group Extraction in Complex Social Networks", WSKS 2010, Communications in Computer and Information Science, CCIS 111, Springer, 2010, pp. 238-247.

[4] X. Cheng, C. Dale, and J. Liu, "Statistics and social networking of YouTube videos", in Proc. the 16th International Workshop on Quality of Service, IEEE, 2008, pp. 229-238.

[5] P.Y. Chiu, C.M.K. Cheung, and M.K.O. Lee, "Online Social Networks: Why Do "We" Use Facebook?", The First World Summit on the Knowledge Society, Communications in Computer and Information Science, vol. 19, Springer, 2008, pp. 67-74.

[6] N.B. Ellison, C. Steinfield, and C. Lampe, "The benefits of Facebook "friends:" Social capital and college students' use of online social network sites", J. of Computer-Mediated Communication, 12 (4), art. 1, http://jcmc.indiana.edu/vol12/issue4/ellison.html, 2007.

[7] C. Flament, Application of graph Theory to Group Structure, Englewood Cliffs, NJ: Prentice-Hall, 1963.

[8] L. Garton, C. Haythorntwaite, and B. Wellman, "Studying Online Social Networks", Journal of Computer-Mediated Communication, 3 (1), 1997, pp. 75-105.

[9] M. Girvan, and M.E.J. Newman, "Community structure in social and biological networks", The National Academy of Sciences, USA, 99 (12), 2002, pp. 7821-7826.

10] J. Golbeck, and J. Hendler, "FilmTrust: movie recommendations using trust in web-based social networks", in Proc. Consumer Communications and Networking Conference, IEEE Conference Proceedings, vol. 1, 2006, pp. 282-286.

[11] R. Hanneman, and M. Riddle, Introduction to social network methods, online textbook, Riverside, U. of California, 2005, Available: http://faculty.ucr.edu/~hanneman/nettext/.

[12] B. Huberman, D. Romero, and F. Wu, "Social networks that matter: Twitter under the microscope". First Monday, 2009, pp 1-5.

[13] J. J. Jung, "Query transformation based on semantic centrality in semantic social network," Journal of Universal Computer Science, 14 (7), 2008, pp. 1031-1047.

[14] P. Kazienko, K. Musial, and T. Kajdanowicz, "Multidimensional Social Network and Its Application to the Social Recommender System", IEEE Transactions on Systems, Man and Cybernetics - Part A: Systems and Humans, 41 (4), 2011, in press.

[15] P. Kazienko, K. Musial, and T. Kajdanowicz, "Profile of the Social Network in Photo Sharing Systems", AMCIS 2008, Association for Information Systems (AIS), 2008.

[16] P. Kazienko, K. Musiał, and A. Zgrzywa, "Evaluation of Node Position Based on Email Communication", Control and Cybernetics, 38 (1), 2009, pp. 67-86.

[17] P. Kazienko, D. Ruta, and P. Bródka, "The Impact of Customer Churn on Social Value Dynamics". Int. J. of Virtual Communities and Social Networking, 1 (3), 2009, pp. 60-72.

[18] J Scott, Social Network Analysis: A Handbook, SAGE Publications, London, UK, 2000.

[19] R. Sulo, T. Berger-Wolf, R. Grossman, "Meaningful Selection of Temporal Resolution for Dynamic Networks", MLG '10, ACM, 2010.

[20] S. Wasserman, and K. Faust, Social network analysis: Methods and applications. Cambridge University Press, New York, 1994.

[21] D.J. Watts, and S. Strogatz, "Collective dynamics of 'small-world' networks", Nature, vol. 393, 1998, pp. 440-444.

[22] B. Wellman, J. Salaff,, D. Dimitrova, L Garton, M. Gulia, and C. Haythornthwaite, "Computer Networks as Social Networks: Collaborative Work, Telework, and Virtual Community", Annual Review of Sociology, 22 (1), 1996, pp. 213-238.