# A Generic Model for Multidimensional Temporal Social Network

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***Abstract*—A comprehensive generic model for multidimensional, temporal social network is proposed in the paper. It covers three main dimensions: layers, time windows and social groups. All the dimensions share the same set of nodes corresponding to social entities, usually individuals. Layers correspond to different types of relationships between humans, e.g. social and semantic, that can be derived from different human activities in IT systems; time windows reflect temporal profile of the social network, whereas groups (social communities) are sets of similar humans. The intersection of all dimensions is called a view; it represents the statement of a single social cluster (group) with connections of only one type (from a single layer) and with the snapshot for a given period. Views can be aggregated by one, two or even all three dimensions simultaneously using filtering of dimension instances. Apart from description of the multidimensional model, also its applicability is considered in the paper..**

***Index Terms*—social network, multidimensional social network, multi-layered social network, temporal social network, network model, social groups modelling**

## 1. Introduction

Representation and analysis of the social interactions and activities of people have become recently a very important area of research which attracts people from many fields. Social network analysis is a set of tools that enable to investigate static and dynamic characteristics of both vertices and edges of networks. Although many of these techniques and methods have been developed for the last few decades, the research in this area was limited to small datasets about people and their interactions gathered by sociologists by means of surveys and questionnaires. Nowadays we have experienced rapid growth of social structures supported by communication technologies and the variety of Internet- and Web-based services. This results in opportunity to process data (gathered in computer systems) about interactions and activities of millions of individuals.

Due to scale, complexity and dynamics, social networks built based on gathered information from Internet, World Wide Web and other sources are very difficult to analyse in terms of traditional social network analysis methods being at our disposal. Each of those social networked system is a source of different information about people and their activities which are the source of different types of relations – layers – within a single network. This change has caused that new techniques which enable to analyse large datasets as well as methods that support investigation of different types of data are needed. All the extracted networks can be viewed as multidimensional structures, however what should be emphasized there is hardly any research reported with respect to multidimensional social networks models.

From the data gathered in different systems supported by communication technologies the information about both nodes and relations between them together with their characteristics can be extracted. This knowledge is the base to create social network. Nodes in such social networks are digital representations of people who use various services such as electronic mail, telecommunication systems, social networking sites, multimedia sharing systems, etc. Based on people activities the relationships of different types according to existing within a given service communication channels are extracted. The diversity of communication channels results in the networks that are multidimensional, i.e. these are networks that consist of more than one type of relationship. Based on each communication channel separate relation that can be also called a layer of a network is created. Each social network features also the high clustering coefficient which means that there exist many communities. This results in yet another dimension of each network. Moreover, there is one more element 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. Time factor in an analogous way as in physics can be treated as an additional dimension.

As it was pointed out earlier, although the social structures were extensively investigated in the past, there is no intense research in the area of modelling the multidimensional temporal social networks. The goal of this article is to build a model for multidimensional social network that will also be able to present the dynamics of this structure. The concept of multidimensionality needs to cover both different types of relations between nodes and communities existing within each relational layer.

The rest of the paper is structured in the following way: Section 2 outlines the research that has been already conducted in the field of social networks and their multidimensional aspect. In Section 3 the model of multidimensional temporal social network together with three dimensions (layer, time window and group) is described. Section 4 presents possible applications of developed model and finally Section 5 the conclusions are provided.

## 2. Related Work

Social networks and their analysis is one of the main streams in the complex networks research field and has its origins in 1950s. A general concept of social network is very simple and can be defined as the finite set of actors and relationships that link these actors. Different researchers developed their own variations of this concept as they analysed it from different perspectives [14], [26], [28], [29]. Each application domain of this concept has resulted in separate branch of research. The well-known networks that were analysed in the past are: scientist collaboration networks [24], movie-actor networks, friendship network of students [2], sexual contact networks [22], labour market [21], public health [5], psychology [25]. Data for the enumerated cases were mainly gathered based on surveys and questionnaires.

Nowadays based on data gathered in computer systems, a new type of social networks can be extracted and analysed. These networks are usually automatically extracted from such data sources as: bibliographic data [12], blogs [1], photos sharing systems like Flickr [16], e-mail systems [18], telecommunication data [3], [19], social services like Twitter [15] or Facebook [9], video sharing systems like YouTube [7], Wikipedia [6] and many more. Networks created based on these types of data are called online social networks [8], [11], web-based social networks [13] or computer-supported social networks [30].

Scientists focus their research efforts on investigating the structure and function of these networks; however they usually take into account only one type of relation between people. It should be emphasized that in most real-world social networks, there exist many different relationships as it was described in Section 1 and will be further described in more details. So far only few scientists have focused their research interests at multi-layer social networks.

The problem of multiple relations was investigated in [28] where the graphical, algebraic and sociometric notations for multiple relations are proposed. Wasserman and Faust proposed to use Image Matrices for Multiple Relations. This notation is a theoretical concept that has been found hard to implement in the environment with several different layers. Additionally, as authors emphasized interpreting each image 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 large-scale networks where there can exist many of relation types.

In another approach Kazienko *et al.* investigated Flickr photo sharing system and have distinguished eleven types of relationships between users [16]. A special type of social networks that allows the presentation of many different activities is called a multi-layered social network [4], [17]. It can be represented as a multi-graph [10], [28]. The network layers were created based on communication channels and there was no implementation of either time factor or communities concept, which authors of this article find to be crucial for the generic nature of the network concept. However, this research was an inspiration for the authors to propose a formal model that enable to encompass different network's dimensions under the umbrella of a single framework.

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, authors focus on developing a conceptual, generic model for multidimensional temporal social network that enables to capture information about different types of activities and interactions between users, the communities existing within each relation type as well as represent the dynamics of user's behaviour.

## 3. A Model of Multidimensional, Temporal Social Network

### 3.1 General Concept

The general idea behind the model for multidimensional temporal social network endeavours to provide the framework allowing the description of entirety of social interactions existing between network actors. As the social network represents interaction between users, it needs to be modelled respecting the type of relationship, its strength and relation dynamicity. Moreover, it is expected that the model also allows gathering additional customized description of all relations that may be easily concluded in order to provide informative presentation of networks and individuals characteristics.

The proposed model for multidimensional temporal social network is based on the principal profile of multidimensional and dynamic social networks. The basis 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.

Usually, social networks 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.

Additionally, the proposed model 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.

Summarizing, the general concept of the model considers three distinct dimensions of social networks: layer dimension, time-window dimension and group dimension, see Fig. 1a.

All the dimensions share the same set of nodes that correspond to social entities: single humans or groups of people.

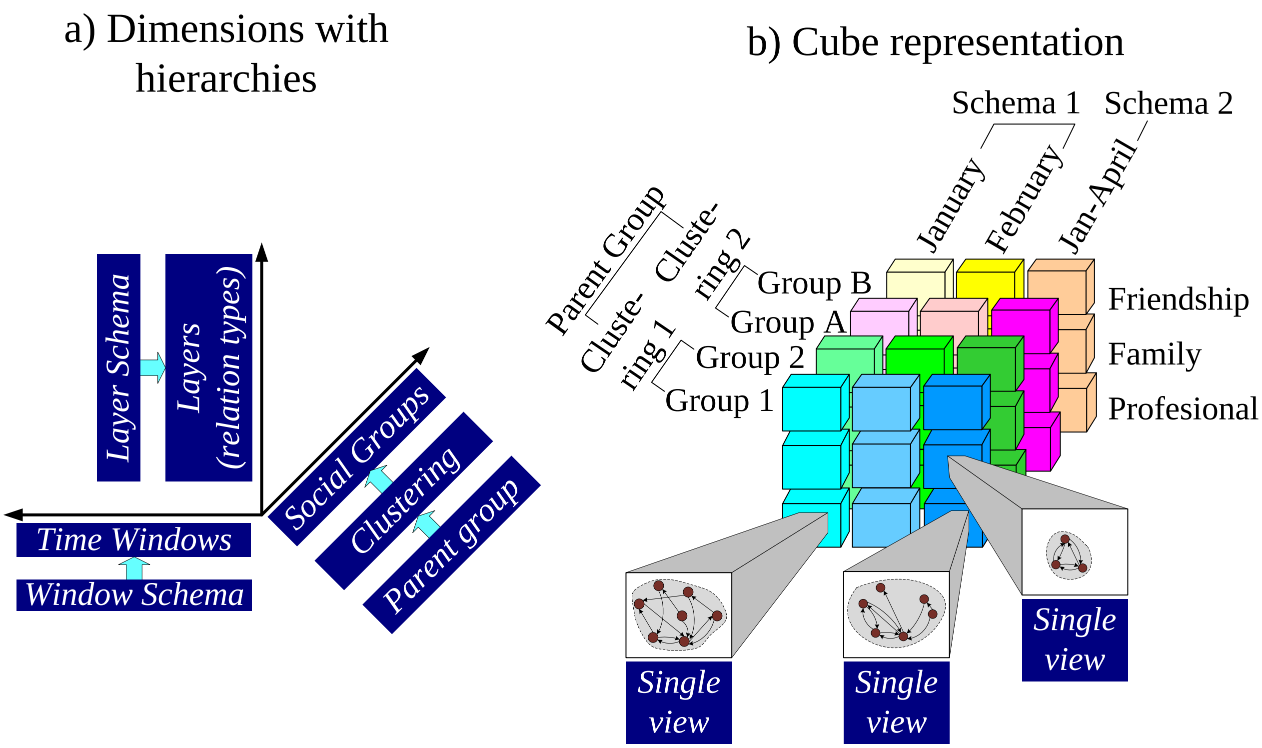


Figure 1. Three dimensions with hierarchies (a) and the cube representation of multidimensional social network (b)

### 3.2 Layer Dimension

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.

- Direct relation (Fig. 2) is a relation that connects directly two different users. Both participants are conscious of being in relation, e.g. in e-mail communication a sender as well as a receiver know that a process of information exchange takes place.

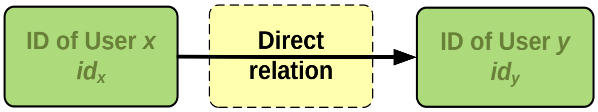

Figure 2. Direct relation between users *x* and *y*

- Pseudo-direct relation (Fig. 3) connects two different users via an intermediary object. The object is subjected to the activities of both users *x* and *y*. Activities of *x* and *y* may be the same or different. Referring to this pseudo-direct relation may occur in two forms: pseudo-direct relation with the same roles and pseudo-direct relation with different roles. First of them refers to situation when both of the users play the same role with respect to the object, e.g. commentator of a photo. Second type of pseudo-direct relation occurs when acting on the object one of the users plays different role than the other, e.g. user *y* reviews a paper written by user *x*. Note that in case of pseudo-direct relations users do not need to be directly engaged in creating and maintaining the relation, moreover one or both of them may not be conscious of its existence.

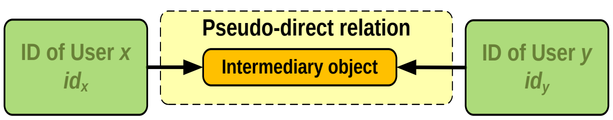

Figure 3. Pseudo-direct relation between users *x* and *y*

- Indirect relation (Fig. 4) occurs between two users who's profiles are similar. It is a kind of a demographic filtering that retrieves all the users with the same or similar profiles. None of users is conscious of the existence of the indirect relation.

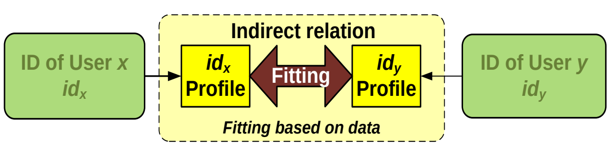

Figure 4. Indirect relation between user *x* and *y*

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.

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 $=\{R_1, R_2, \ldots, R_n\}$, where $R_i, i = 1, 2, \ldots, n$ is a type of relation. In turn, every $R_i, i = 1, 2, \ldots, n$ is a set of pairs $R_i = \{\langle user_x, user_y\rangle \mid user_x \in Users, user_y \in Users,\ user_x \neq user_y\}$.

Let *IDU* defines a finite set of users of one system. The layer dimension in the model of multidimensional, temporal social network is represented by a set $L = \{l_1, l_2, \ldots, l_n\}$, where *n* is a number of all the relationships that can be derived from data available in the system and $l_1, l_2, \ldots, l_n$ are the layers corresponding to the relations. Particular layers $l_1, l_2, \ldots, l_n$ 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. 5).

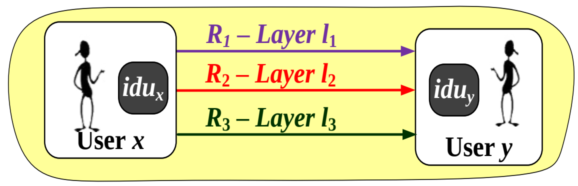

Figure 5. Three types of relationships $R_1$, $R_2$ and $R_3$ between users *x* and *y* that form three layers of multidimensional, temporal social network

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, 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 Time-Window Dimension

Temporal analysis of social network is possible thanks to time-window dimension. A time-window is a period of time with well-matched width. 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.

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. Comparing networks obtained in successive time-windows make it possible to complete missing information or predict changes that may occur in the future.

Fundamental problem of temporal SNA is time-window resolution, i.e. its width. If time-window is too narrow structural parameters of social network are not correlated. Besides, too narrow window introduces relatively big noise in parameter values. On the other hand, too wide time-window causes loss of information about temporal dependencies that occur between relations and nodes in social network. Moreover, the dimensions of time-windows for different structural parameters of social network may vary. So, for temporal analysis, it is necessary to apply a method - like presented in [27] - 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. 1.

### 3.4 Group Dimension

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.

In the model of multilayered, temporal 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.

### 3.5 Views

The above mentioned dimensionality of the model for multidimensional temporal social network is utilized to conclude the state of the network providing its static picture. The concept of views as a core of the model is introduced. Single 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 temporal social network may be compared with principal assumptions of logical architecture of data warehouses. As seen in Fig. 1b, a single cube is representing the view that encapsulates relations existing within a given layer, group and time-window simultaneously.

### 3.6 Aggregations by Dimensions

As the concept of views provides the atomic insight on the sub-network, there arises the natural expectation to provide 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.

Moreover, 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 exist 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.

Obviously, 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.

Moreover, aggregation operations may consider additional profile of relations – timeliness. As a result, older relations can be treated as less significant while strength calculation.

## 4. Model Applicability

### 4.1. Data Pre-processing and Loading

The first step of data pre-processing is data cleaning and validation, same as next step the way how data is treated depends on data type. In this step, all data that does not contain essential information are deleted. Those essentially information are message timestamp, message id, sender or recipient id/mail address in case of mails data, and in case of billing data important are phone call timestamp and duration or dialler and receiver id/phone number. Cleaned data is validated to check if the integrity of the data is preserved. For example, if a user email address is invalid, it is removed during the cleaning phase, and all messages from or to this person must be removed to preserve integrity. The next step is a transfer of the cleaned and validated data into unified structure: hierarchical pre social network. In data describing communication like billings or mail logs, where two or more peoples communicate with each other via an object (billings: phone call, teleconference; mail logs: mail, thread), each person can have a different role towards this object, through which they communicates (mail: sender, receiver; mail thread: thread creator, thread participant; phone call: dialler, receiver) [23]. Objects may even have hierarchical relationship. For example, in mail logs, a thread contains one or more mails. Thus, hierarchical pre-social network can be created by gathering all object-based relations between peoples and grouping those objects into hierarchy. The third step is flattening hierarchy of objects to one selected level, see [20] for details. During this phase, all object based relations are identified on different levels, then the selected one are copied to the object, with which they are directly or indirectly connected and which belongs to selected level. The network layers detection is started after flattening process. During layer detection the permutations of all role pairs are created and this pairs (*role a*, *role b*) are treated as layers. For each layer all connections between two people $x$ and $y$ are counted. Those connections must meet two conditions described below:

- The first person $x$ has the first *role a* from and another user $y$ has the second *role b*,
- Users $x$ and $y$ are not the same person.

The last phase of data pre-processing is multi-layered social network creation. In this step, layers which should be added, are selected and time windows are defined. The whole process is described in [20]. An additional unclassified group *Parent group* which covers all layers and windows is created in order to preserve intergroup edges. *Parent group* is at the top of the group dimension hierarchy.

## 4.2. Internal structures

Data structure for three-dimensional social network is presented in Fig. 7. Main element of this representation is network object, that describes the social network name, start and end date. Network object aggregates all nodes that belongs to social network. The first dimension is based on layers, the second are time windows , whereas the third one are social groups. Additionally, all groups, except the top one (*Parent Group*), have information about the top group – *Parent Group* aggregating the entire network. Each of three dimensions have information/description how the dimension hierarchy was created (Window - window_scheme, Layer - layer_scheme, Group - group_clustering - Parent Group) and name of this object. In addition, the time dimension has information about the period: when it starts and ends. Those three dimensions are related to a single view object (corresponding to a fact in the data warehouses model). A view object aggregates edge objects that describe relations between two nodes in one layer, window and group.

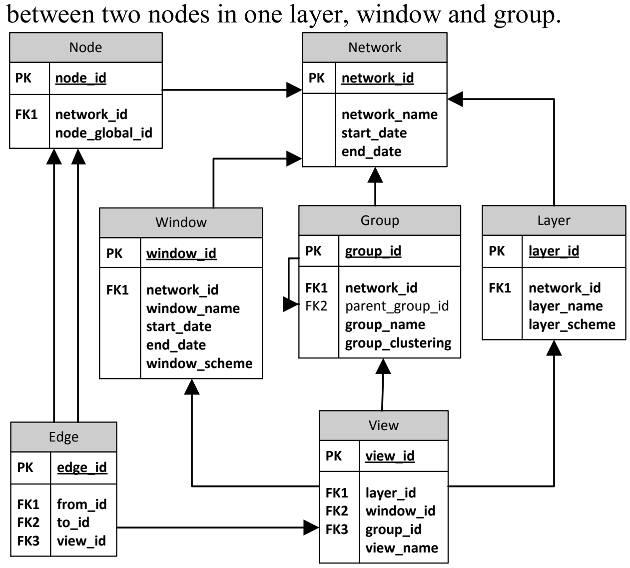

Figure 6. Data structures for the multidimensional social network

All mentioned above elements can have their own attributes which describe them in more details. One exception is the node element, whose attributes are grouped depending on how the element attribute was calculated, e.g. the node can have separate attributes calculated for the entire network, for single layer, window, group or view element.

## 4.3. Model Usage

The model and the representation of multidimensional temporal social network described above, can be utilized for analysing a large social networking system and big organizations (Fig. 7).

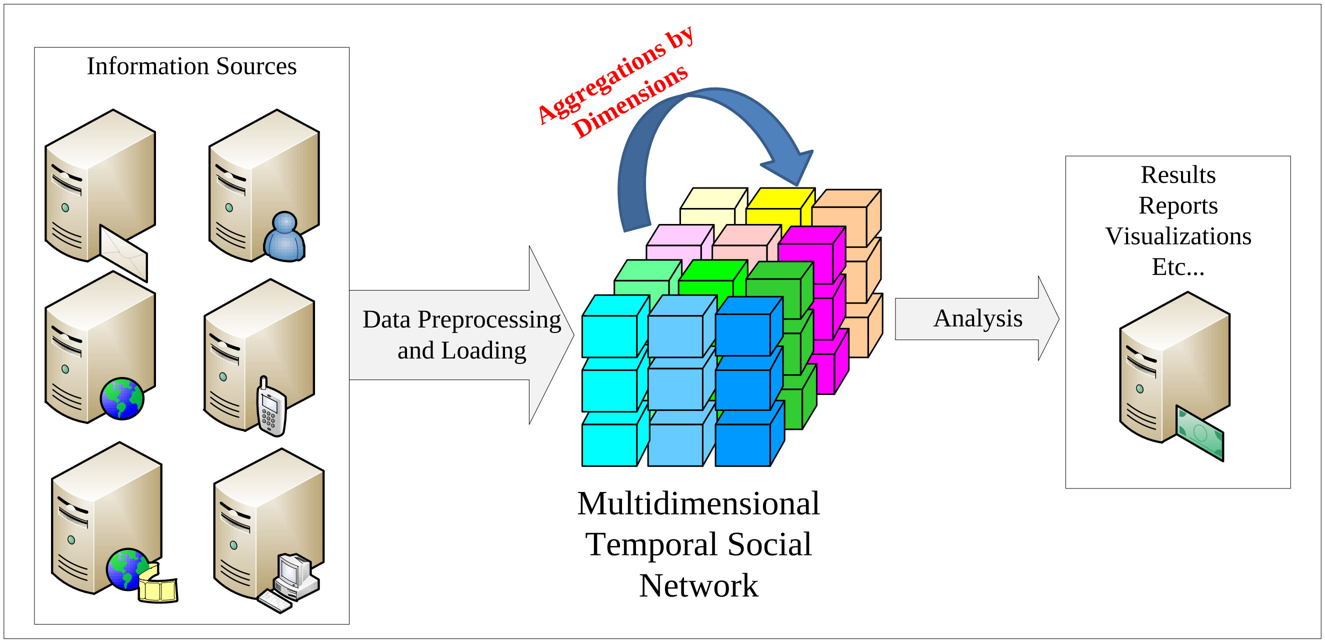


Figure 7. Example of the system which utilize Multidimensional Temporal Social Network

Layer dimension allows to analyse systems where people are connected by many different relationship like in complex social networking sites (e.g. Facebook), where people are linked as friends, via common games, “like it”, etc. or in regular companies: department colleagues, best friends, colleagues from the company football team, etc. Multidimensionality provides opportunity to analyse each layer separately and in the same time investigate different aggregations of layer dimension as well as compare them. For example, we have a network consisting of four layers, two from the real word: family ties, work colleagues and two from the virtual world, i.e. friends from Facebook and fiends from the MMORPG game. Now, one can analyse each layer separately, aggregate layers from the real world and compare it to the virtual world layers aggregation, and finally, aggregate all layers together.

Time dimension allows to investigate the network dynamics and how it evolves over time. For example, the analysis how adding or removing one network member affects the network in longer period of time, how particular group (e.g department or project team) changes over time, or how each network layer changes and how it affects the whole network.

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

Summarizing, the described model facilitates to analyse all three dimensions simultaneously, 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 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

As it was pointed out in the introduction to this paper, the multidimensional analysis of social networks is a new research field. This causes that in order to facilitate its development one needs a framework how to represent such structures. Such multidimensional analysis is especially important as the researchers try to understand the cause and effects of different phenomena such as information or diseases spread and these cannot be infer based on a single user activity.

The model proposed in this paper enables to combine data, perceives human interactions and activities in a broader view.

Layer dimension supports the investigation of different communication channels and people activities within each of them. Group dimension enables to detect and analyse communities within different layers of a network. This provides knowledge about within which relation types (activities) groups are more likely to form.

Combination of layer, group and time-window dimension in a form of view supports analysis of many types of relationships and groups that additionally change in time. This allows seeing what kind of relations form what types of groups and if these communities overlap between different relation layers. Such approach can be crucial for example when a company tries to introduce new offer for its customers. What communication channel should the company use? Who is the person to whom the offer should be sent? Answers to these questions can be found using multidimensional network analysis.

The developed model also enables to analyse the behaviour of groups, nodes and relations in time. This provides additional insight that helps to understand the dynamics of social structures. Due to the time-window dimension it is possible to find out which groups and relation layers are stable and which dynamically change over time.

The proposed model for multidimensional temporal social network is an original idea that enables to investigate complex social networks from many different perspectives.

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