Spatio-Temporal Geographic Information Systems: A Causal Perspective

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Abstract. In this paper approaches to conceptual modeling of spatio-temporal domains are identified and classified into five general categories: *location-based*, *object* or *feature-based*, *event-based*, *functional* or *behavioural* and *causal* approaches. Much work has been directed towards handling the problem from the first four view points, but less from a causal perspective. It is argued that more fundamental studies are needed of the nature of spatio-temporal objects and of their interactions and possible causal relationships, to support the development of spatio-temporal conceptual models. An analysis is carried out on the nature and type of spatio-temporal causation and a general classification is presented.

1 Introduction

Much interest has been expressed lately in the combined handling of spatial and temporal information in large spatial databases. In GIS, as well as in other fields [Sil97], research has been accumulating on different aspects of spatio-temporal representation and reasoning [Sto97]. The combined handling of spatio-temporal information allows for more sophisticated application and utilisation of these systems. Developing a Temporal GIS (TGIS) leads to a system which is capable of tracing and analysing the changing states of study areas, storing historic geographic states and anticipating future states. A TGIS could ultimately be used to understand the processes causing geographic change and relating different processes to derive patterns in the data.

Central to the development of a TGIS is the definition of richer conceptual models and modelling constructs. Several approaches have been proposed in the literature for conceptual modelling in a TGIS. These have been previously classified according to the type of queries they are oriented to handle, viz. What, Where and When, corresponding to feature, space and event respectively [PD95]. Other classifications of these approaches were identified on the basis of the modelling tools utilised, e.g. relational, semantic or object-oriented models, etc.

In this paper, a taxonomy of conceptual models for a TGIS is presented with the aim of representing the different dimensions and complexity of the problem domain.

Very few works have been directed to studying causal modelling in spatio-temporal databases. Yet this issue is important in many application domains. The reason is possibly attributed to the lack of systematic and thorough analysis of spatio-temporal causation to enable a semantic classification in a fashion similar to that carried out for process classification [CT96]. Spatio-temporal causation is studied in the second part of this paper and a general taxonomy of possible classes and properties are identified to be used in conceptual modelling.

In section 2, the dimensions of the problem domain are identified. Section 3 presents a framework with which conceptual modelling approaches for a TGIS can be categorised and studied. Models are classed as basic, composite and advanced. A study of spatio-temporal causation is given in section 4 and conclusions and discussions are given in section 5.

2 The Problem Space and Data Space

In spatio-temporal applications of GIS, the main entities of concern are *States* of objects or features, their relations with space and time, and their inter-relations in space and time. In what follows, these notations are first defined, followed by an analysis of the problem dimensions.

Definition 1. A **State** of a spatio-temporal object st_i can be defined by a triple $\langle o_i, s_i, t_i \rangle$ where o_i is an instance of the feature class defining the object, s_i is the extension of the space occupied by the object and t_i is a time point at which o_i existed in s_i.

A spatio-temporal data set is defined here as the collection of all possible States of objects of interest in the domain studied and is denoted ST.

Definition 2. **Change** in a spatio-temporal domain object, Ch, can be defined as an ordered set of States $\{st_1, st_2, \cdots, st_n\}$, each of which belongs to the set ST and which collectively define the transformation of a spatial object between two time instances.

The problem space of a TGIS can be modelled on three axes as shown in figure 1(a).

The problem space defined by the three axes is infinite reflecting the infinite nature of space and time and all possible semantic classifications. For specific application domains, the problem space is reduced to a finite *Data Space* limited to considering specific object types, and space and time extensions.

Each object state occupies a unique point in the *Data Space*. *Change* in the *States* of objects is represented by two or more points. In a rich data environment where *States* or *Changes* are monitored continuously, *Change* would be represented by a line connecting point states.

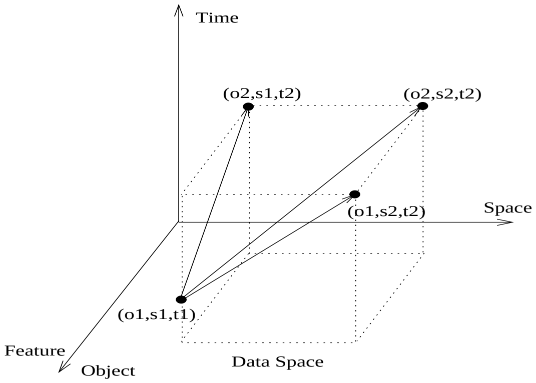


Fig. 1. Problem space and Data space and possible types of Change in object States.

3 Conceptual Modelling in a Temporal GIS

Conceptual modelling is essentially a process of identifying semantic classification and relations between data elements. The process of classification is one which identifies distinguishing properties, relations and distinguishing operations for a certain group of entities. In general three possible types of relationships can be distinguished between entities in a TGIS, namely, *Spatial*, *Temporal*, and *Causal*.

Levels of conceptual models may be distinguished by the semantic classifications used and types of relations that are explicitly defined. In this section, conceptual models for a TGIS are categorised by analysing their ability for representing and classifying entities in the Data Space.

3.1 The Basic Models: Where, What and When

Basic conceptual models for a TGIS are built around the principal axes of the problem space: *Space*, *Feature* and *Time*.

Location-Based Models: The Where view In this view, classifications are based on locations on the *Space* axis. A grid is used to divide up the space into locations. For each location, *Changes* are recorded in a list representing successive changes in the features of specific location, when they occur. This approach can be defined as a set of n parallel Feature-Time planes in the data space, $\{(o, s_j, t)\}, 1 \leq j \leq n$. An example of this model is given by Langran [Lan93].

Object or Feature-based Models: The What view In this view, classifications are based on geographic features or objects on the *Feature* axis. *Changes* are recorded by updating stored instances and reflecting the change of their spatial extent, e.g. the incremental change over time of the extent of polygonal or linear geometries.

The feature-based approach can be represented by a set of m parallel Space-Time planes, $\{(o_i, s, t)\}, 1 \leq i \leq m$, in the Data Space. This approach was first proposed by Langran [Lan93] and is the basis of the works in [RYG94,VBH96] [RMD96,TJ99,KRH00]. Hazelton [Haz91], and Kemelis [Kel91] suggested extending the model of Langran by using an extended feature hierarchy. Guting et al [GBE$^+$00] proposed a set of spatio-temporal abstract data types for moving objects. Their classification can be considered to be object-based as it is based on extending the basic spatial data types by a temporal dimension to become moving points, lines and regions.

Time-based Models: The Snapshot View In this view, classifications are based on the temporal axis, where snapshots of the *State* of the world at specific times are captured. Raster and vector data sets can be represented in this model. The main limitation here is the un-avoidable redundancy in the data recorded where objects or locations do not change in a step-like fashion. The approach is equivalent to a series of l parallel Space-Object planes, $\{(o, s, t_k)\}, 1 \leq k \leq l$, in the data space. This is the most common approach used in many works [PD95].

As can be seen, a *State* is the main entity type in all of the above basic models. Their main limitation is the inability to view the data as sets of events, to represent the changes of different objects which makes it difficult to handle queries about temporally related events, e.g. “which areas suffered a land-slide within one week of a heavy rainfall?”.

Event-based Models: The When View In this model, temporal relations between two successive *States* of objects or locations in space are defined explicitly, and *Change* is represented by an *Event*. Hence, an *Event* is defined as the line joining two *States* in the data space in this model.

This model deals with more abstracted relations than the previous ones. It has the advantage of dealing equally with both locations and objects. Queries involving temporal relations between *Changes* can be efficiently handled. The works of [Lan93,EGB93,Yua94,SW95,PD95] fall into this category.

Integrated Event Model Events can refer to space locations or to objects and features. The TRIAD model presented in [PQ96] uses pointers to link location, feature and time views. It stores successive changes at locations (as in the location-based view) which gives the full history of grid cells and stores two spatial delimiters of features.

Space-Composite Models In this model intersection relations are explicitly defined between states of different objects at different times from the snapshots. Hence, the space is decomposed or reclassified as units of a coherent history. The approach was proposed by Langran and Chrisman [Lan93] where the method can be classified as Space-Time composite.

3.2 Advanced Models: How and Why

In all the previous views the main concern was to retrieve *States* and *Changes* based on location, object or feature type and temporal properties. A more advanced modelling exercise is to retrieve *Changes* based on their underlying processes and on their interaction. These type of models can be broadly classified into the How and Why views.

Process-oriented Models: The How View In this approach, spatial relations between successive states of objects are explicitly defined and classified into specific processes. This is equivalent to defining a new axis in the Data Cube with *Change*, and not *State*, as variable.

Three models in the literature can be classified as *Process-oriented.* Gagnon et al [GBE92] presented taxonomies to define three types of *Change*: those involving one entity, two entities and n entities. Claramunt and Theriault [CT96,CT95] proposed a conceptual process-oriented model where changes are classified into three categories. These are: a) evolution of a single entity, b) functional relationships between entities and, c) evolution of spatial structure involving several entities.

Finally, Renolen [Ren97] classified six basic types of changes or processes of creation, alteration, cessation, reincarnation, merging/annexation and splitting/deduction. His types are a subset of the types classified by Claramunt [CT96], except for alteration which groups all possible spatial relations between object states. Seven processes, namely, *shift, appear, disappear, split, merge, expand,* and *shrink* were defined by Cheng and Molenaar in [CM98]. Those processes are a subset of those defined by Claramunt et al [CT96].

Causal Models: The Why View Causal relations are the third type of distinguishing relations in a temporal GIS. A specific temporal relation always exist between Cause and effect. Cause always either precedes, or coincides, the start of its effect. Few models exist which addresses casual modelling in GIS. These are the works of Allen et al [AEB95] and Edwards et al [EGB93]. Allen differentiates between the effects caused by other events or an intentional agent (e.g. a person, an animal or an organisation). The uncertainty of the introduction of some attributes was also presented in his work.

The lack of a comprehensive treatment of causal modeling may be attributed to the lack of work which identifies semantic classifications and distinguishing properties of different spatio-temporal causal relations. In the rest of this paper, spatio-temporal causation is analysed and different types of causal relations are classified. Similar to process classification [CT96], this work is aimed at identifying a causal axis upon which categories and types of causal relations may be presented.

4 Spatio-Temporal Causation

Increased consumption of fossil fuel and global warming are examples of phenomena which can be analysed by studying the relations between cause and effect (causal relations) in a geographic database. The identification of those relations is crucial in many application domains, such as, in ecology, epidemiology, etc. Several works in AI have been directed to studying temporal causality, [Ter95,Sch91,TT94]. However, this is not the case in the spatial domain, where the issue of analysing and classifying spatio-temporal causal relations has not been addressed. In this section, a qualitative analysis of spatio-temporal causation is carried out and a classification of its different patterns is presented.

General Assumptions

1. Cause and effect are considered between spatio-temporal *Changes* and not between object *States*.
2. *Change* is considered to be finite.

Definition 3. Let O_c and O_e denote the objects of cause and effect respectively, O_e is considered to be a function of O_c as follows.

$$O_e = f(O_c)$$

O_c is considered to be a function of time only, i.e. $O_c = f_{(t)}$.

4.1 Relative Relations in Spatio-Temporal Space

Here the spatial and temporal relations between the causal change and effect are studied.

Causal Temporal Relations Allen [All83] defined a set of 13 possible temporal relations between two time intervals. The basic 7 relations are shown in figure 2. If the cause or effect, or both occupy time points instead of intervals, then relationships between time points and between intervals and time points need to be considered. The main constraint on the intervals of cause and effect is that the start of the cause must be before or equal to the start of its effect. The time point contains both its start and its end.

Hence, causal temporal relations can be classified into two main categories: those satisfying the condition $cause_{start} < effect_{start}$ and those satisfying the condition $cause_{start} = effect_{start}$.

I. $Cause_{start} < Effect_{start}$ Two main reasons may be attributed to why the effect may start after its cause. These are denoted here, *threshold delay* and *diffusion delay*.

Threshold Delay: Two cases can be identified. In the first case the change may not be able to deliver its effect before reaching a certain level over a certain period of time, e.g. flooding will not occur before the water in

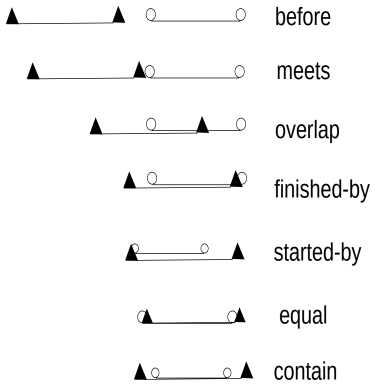


Fig. 2. Temporal relations between intervals.

the river increases beyond a certain level. In the second case, the affected object is not able to show change before a specific threshold is reached. For example, vegetation on the banks of polluted rivers will start to be affected only after a certain concentration of accumulated pollutants is reached, that is without an increase in the level of pollutants in the river itself.

Diffusion Delay: This is the case where the cause and effect are not spatially co-located. Hence, the delay is the time take by the cause to reach its effect. For example, there will be a delay for pollutants affecting the river upstream to reach vegetation located on the river banks downstream.

The diffusion delay is dependent on two factors, namely, the distance between the cause and its effect and the speed of diffusion which in turn depends on the resistance of different objects to transmit this diffusion.

Note that it is possible for both types of delays to coexist.

Figure 3 represents different scenarios which illustrate the effect of various factors. V_{c1} and V_{c2} are different diffusion speeds and $V_{c2} > V_{c1}$. D_{c1} and D_{c2} are different distances between cause and effect and l_c and l_e are threshold delays by cause and effect respectively. V_{c1} and V_{c2} are represented by a space-time cone.

Different scenarios for the delay are possible as follows.

1. O_e and O_c are adjacent or are in close proximity with the threshold delay of the cause l_c, then the start of the effect will be t_e.
2. O_e and O_c have a distance D_{c1} between them and,
   (a) V_{c1} is the speed of diffusion, the start of the effect is t_{e1}.
   (b) V_{c1} is the speed of diffusion and l_e is the threshold delay for O_e, the start of the effect will be $t_{e1''} > t_{e1}$
   (c) $V_c 2$ is the speed of diffusion, $V_{c2} > V_{c1}$, the start of the effect is at $t_{e2} < t_{e1}$.
3. O_e and O_c have a distance $D_{c2} > D_{c1}$ between them and,

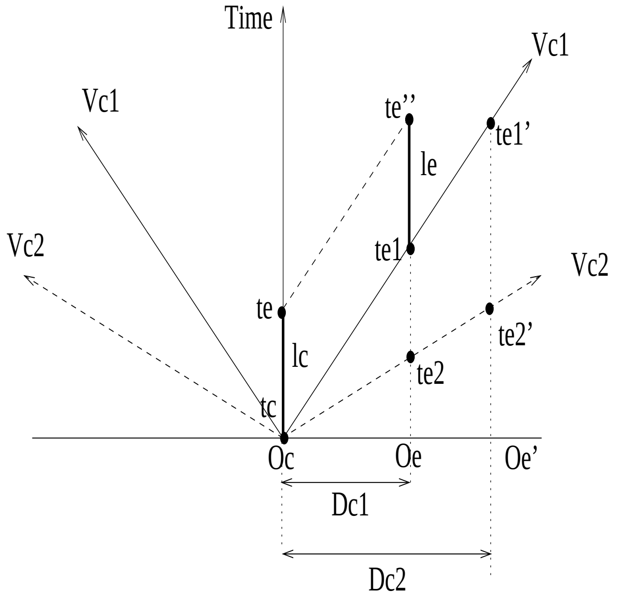


Fig. 3. Representing distance, diffusion and threshold delay of the start of the effect.

(a) V_{c1} is the speed of diffusion, the effect will start at $t_{e1'} > t_e1$.

(b) V_{c2} is the speed of diffusion, the effect will start at $t_{e2'} < t_{e1}$.

The difference in time between the start of a cause and the start of its effect Δt_s can be expressed by the following relation.

$$\Delta t_s = \left(\frac{D_c}{V_c}\right) + l_c + l_e$$

II. $Cause_{start} = Effect_{start}$ When the cause and effect start together, $\Delta t_s \approx 0$, i.e. $l_c \approx= 0$ and $l_e \approx 0$. Also, $\frac{D_c}{V_c} \approx 0$ where $D_c \approx 0$ or $V_c \approx \infty$, (or $\frac{D_c}{V_c} = t$ where t is the basic time unit used in the domain),

For most geographic phenomena the speed of diffusion is usually finite, which leaves the main factor to be $D_c \approx 0$, i.e. O_c and O_e are either adjacent or in close proximity with respect to the type of phenomena under investigation. When the cause and effect start concurrently, it is significant to study the relationship between their ends. A possible classification between causal relations in this case is as follows.

1. Synchronised causal relations, if the change in cause and effect both end at the same time.
2. Prolonged effect, if the change in the cause ends before the end of the change in the effect.
3. Short effect, if the change in the cause ends after the end of the change in the effect.

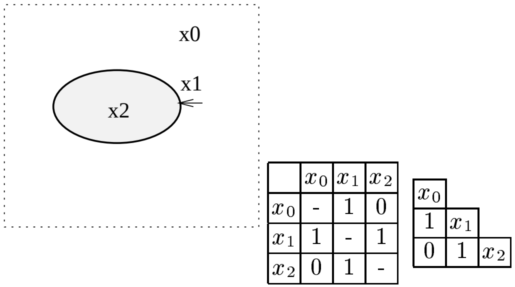
4.2 Causal Relative Spatial Relations

Similar to the general temporal constraint governing the relationship between the start of the cause and effect, a general spatial constraint can be defined between the causing object and the affected one. That is, the causing object must be spatially connected to its affected object in either of two ways.

1. Undirected connection, where a path of spatial objects exists between cause and effect. This path must be permeable to the causing property, e.g. the lake is not permeable to the spread of fire.
2. Directed connection, where the path of spatial objects between cause and effect is permeable to the causing property in one direction and not permeable in the opposite direction. For example, an object upstream in a river has a directed path into the river down stream to transmit the pollutants

In what follows, a method of representing the connectivity of objects and space is presented to guide the process of relating the spatial aspects of cause and effect, in a similar fashion to relating their temporal aspects.

Causal Adjacency Matrix One way of representing the connectivity of objects in space is by using the adjacency matrix developed in [BA00] to capture the topology of space and its containing objects. An example is shown in figure 4(a) and its corresponding adjacency matrix is in (b). The fact that two components are connected is represented by a (1) in the adjacency matrix and by a (0) otherwise. Since connectivity is a symmetric relation, the resulting matrix will be symmetric around the diagonal. Hence, only half the matrix is sufficient for the representation of the object's topology and the matrix can be collapsed to the structure in figure 4(c).



	x_0	x_1	x_2
x_0	-	1	0
x_1	1	-	1
x_2	0	1	-

x_0		
1	x_1	
0	1	x_2

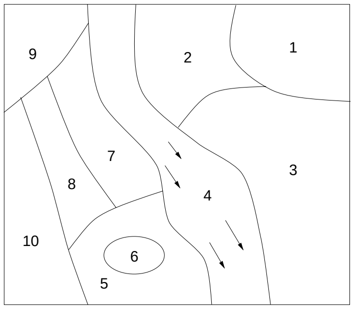
(a) (b) (c)

Fig. 4. (a) Possible decompositions of a simple convex region and its embedding space. (b) Adjacency matrices corresponding to the two shapes in (a) respectively. (c) Half the symmetric adjacency matrix is sufficient to capture the object representation.

The adjacency matrix above captures only the topology of objects and space. It needs to be modified to account for the permeable of objects to different causes.

The modified matrix shall be denoted, Causal Adjacency Matrix and an instance of the matrix need to be defined for every cause studied.

Consider for example the problem of studying the effect of fire spreading in the region in figure 5(a). If object 1 is a lake, object 5 is sand land and object 4 is a river, i.e. all are objects which are not permeable to fire. Hence, these constraints can be reflected in a causal connectivity matrix by assigning a value of 0 to all the cells in their corresponding raw and column (except with x_0) as shown in 5(b).



(a)

S										
1	1									
1	0	2								
1	0	1	3							
1	0	0	0	4						
1	0	0	0	0	5					
0	0	0	0	0	0	6				
0	0	0	0	0	0	0	7			
0	0	0	0	0	0	0	1	8		
1	0	0	0	0	0	0	1	1	9	
1	0	0	0	0	0	0	0	1	1	10

(b)

Fig. 5. (a) Example map with different object types. (b) Causal adjacency matrix for the fire-spread cause, as explained in text.

A fire starting in object 10 will not reach objects 6, 2 or 3, as there is no connecting path between those objects. Note that powered adjacency matrix can be used to check for multiple-step (both) connectivity[3].

Directed connectivity is defined to express connectivity via a gradient or a vector such as force. In this case the causing property can travel only down the gradient or the force vector. For example, in figure 5, if we are studying pollution traveling downstream in river (object 4), then if object 3 was the source of pollution, objects 2 and 9 will not be affected, i.e. objects 3 is not connected to either objects in the pollution causal adjacency matrix.

Another example is studying the effect of rainfall taking the height of the terrain into account. If object 7 is higher than 8, and 8 is higher than 10, then rainfall in 7 may cause flooding in 8 and 10. This constraint can be reflected in a directed causal adjacency matrix as shown below.

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[3] Two step connectivity can be represented by squaring the matrix, three step adjacency, by tripling the matrix, and so on.

	7	8	9	10
7	0	0	0	0
8	1	0	1	0
9	1	0	0	0
10	0	1	1	0

Proximity and directional spatial relationships are also important in studying causal relations. Proximity indicates the expected delay between cause and effect. Directional relationships would be taken into account in studying the effect of the wind or the sun. South-westerly winds will not affect regions south-east of its location. Vegetation on the east slopes of a steep mountain will not get the sun in the afternoon.

The above temporal and spatial constraints can be used to classify the different types of causes and effects as shown in figure 6.

They can also be used in checking the consistency of spatio-temporal databases and hypothesis testing or simulation in their applications. There has been no work reported in the literature on the classification of causation in spatio-temporal domains. Allen [AEB95] classified the type of cause where a general distinction was made between intentional agents (humans) and evens caused by other events. The classification proposed here lends itself to scientific analysis, hypothesis formation and data mining. It represents a dichotomy based on spatio-temporal properties of the combined cause and effect. The classification will allow forcing of consistency checking as databases are populated since it forces the temporal and spatial constraints of causal relations.

5 Conclusions

In this paper, two related issues have been addressed. First, five categories of spatio-temporal conceptual models were identified based on the views they address, namely, What, Where, When, How and Why. The lack of rigorous causal models in the Why view was noted and attributed to the lack of a systematic study of spatio-temporal causal relations. The second part of the paper was devoted to the systematic analysis of spatio-temporal causal relations. The study distinguished between the temporal and spatial aspects. Temporally, two main categories of causal relations were defined according to whether the start of the cause was before or equal to the start of the effect. Causal relations with equal starts were further classified according to the temporal relations between their ends. On the other hand causal relations with delayed start of effect were classified according to the type of delay into diffusion delay and threshold delay.

The main spatial constraint in any spatio-temporal relation is that the causing object must connect to its affected object either directly by adjacency or indirectly through a connected path of adjacent features. A difference was made between non-directed and directed connectivity and a structure, denoted adjacency matrix was used to represent such relations explicitly.

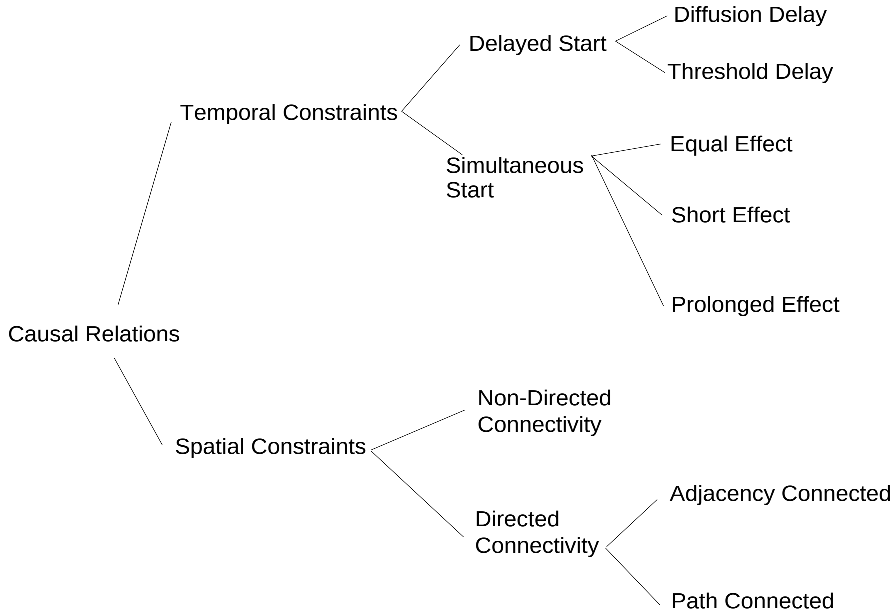

Fig. 6. Possible classification of Causal Relations.

The work in this paper is done in the context of an ongoing project on conceptual modeling in spatio-temporal GIS. Future work will address the definition of spatio-temporal data types and causal relations in this domain.

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