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A MODEL FOR SPATIO-TEMPORAL NETWORK PLANNING

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1. INTRODUCTION

GIS is used today for holding a wide range of data relating to spatial networks – from utility and communications infrastructure companies to transport operators the network is recorded and modelled within a GIS. This data is then used for a variety of tasks from basic inventory to operations management, and as a basis for planning the future of the network. For many of these tasks a spatio-temporal model may be advantageous, for network planning the temporal aspect is likely to be of even greater importance. However, most temporal GIS research appears focussed on recording historical data, which has many different characteristics to data relating to future plans.

In this paper we present a spatio-temporal model for network planning allowing multivariate optimisation incorporating spatial, temporal, financial and other aspects. We show how this model could be used as part of a decision-support process applied to a scenario of planning a network of cycle paths and discuss some issues involved in the analysis of the model.

2. TEMPORAL MODELS

In general, GIS systems do not incorporate a temporal model; they represent one state of the real world, usually the present. Most temporal GIS research (as outlined in e.g. [1]) attempts to extend the representation to include a series of states (either of the database or of individual objects within the database), allowing the changes in the real world to be recorded. This reproduces a linear model of time in which each object has at most one history (Fig. 1 a). Whilst this is generally suitable for recording what has previously happened in the study area, where there is no ambiguity as to what has occurred, it is of limited value in modelling what may happen in the future where one of a number of scenarios may occur.

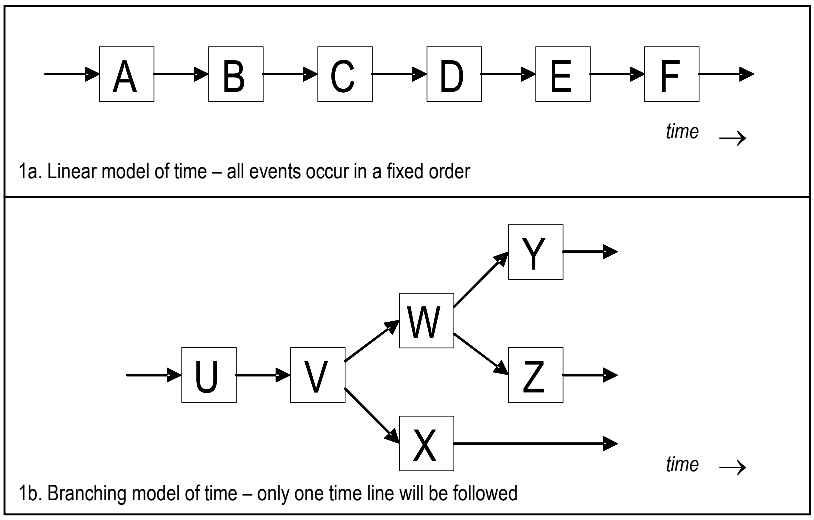


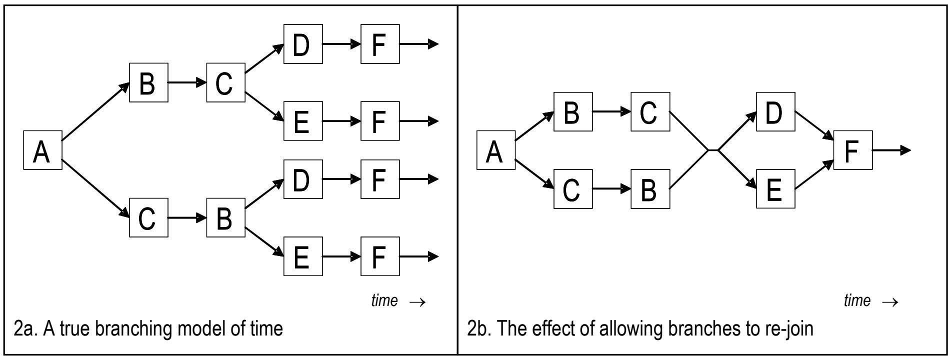
Fig. 1 Linear and branching temporal models

In order to represent the ambiguous situation, some form of branching time model (Fig. 1 b) is required. In such a model, each object may have multiple histories, branching from some point; usually these are multiple possibilities for the future branching from the present time. Only one of these histories is generally considered valid, i.e. only one time-line will actually be followed. The philosophical and logical basis for such a model has long been established, stretching back to Aristotle [2], although there remain conflicting views on exact semantics (see e.g. [3]) which are beyond the scope of this work. Facilities exist within some software allowing evaluation of alternative scenarios, although without any explicit temporal model being included (e.g. GE Network Solutions' Design Manager [4]).

Whilst a branching model of time can represent immediate alternative scenarios well, it rapidly becomes more complex the greater the time span covered, with many branches forming. Particularly if the scenarios being considered involve the same conceptual events (e.g. construction of a new bridge) occurring at different times and/or in different orders, a true branching-time representation would become overly complex with multiple records of the same features and near-identical branches (Fig. 2 a). The following section shows the development of the temporal topology model which attempts to overcome such problems, allowing an efficient representation of these situations, together with metadata to enable optimal scenarios to be chosen.

3. THE TEMPORAL TOPOLOGY MODEL

The "Temporal Topology" model was developed from extending a simple branching model of time to allow branches to re-join – i.e. considering that given two events, B and C, which may occur in either order BC or order CB, the end result is the same (0Fig. 2 b). Whilst temporally this is obviously not the case, spatially it may well be – e.g. if events B and C are construction of two different sections of network then the end spatial result is that both are present, regardless of the order in which they were constructed. Additionally if there is a choice of time-lines followed by a common section, these could also be considered re-joining branches (Fig. 2 b), similar to the concept of "ultimately converging time" discussed in [5]. This leads to the hypothesis that all that is required to model multiple scenarios is the relationships between different sections of those scenarios – the "temporal topology" between events – whether these relationships be temporal (i.e. orderings) or logical (i.e. occurring only on separate time-lines).



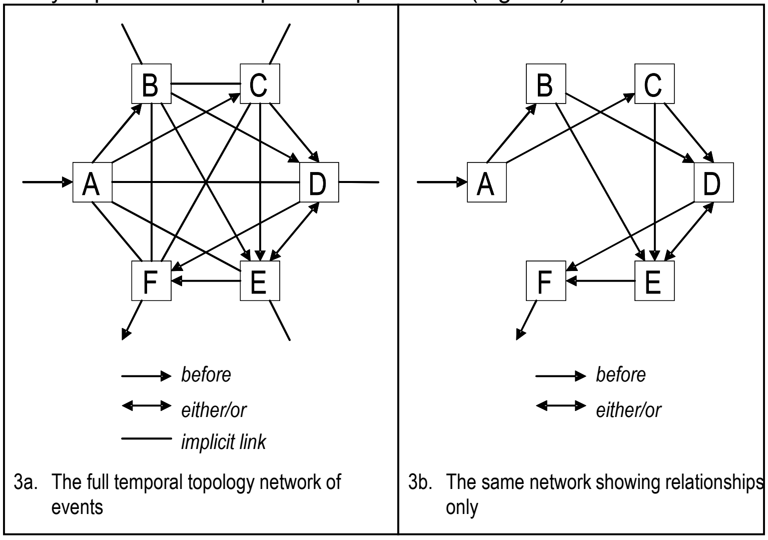
2a. A true branching model of time

2b. The effect of allowing branches to re-join

Fig. 2 True branching time, and the effect of allowing branches to re-join

From this, the underlying theory of the temporal topology model is that planned designs can be separated into self-contained blocks of work (*events*) which have a fixed spatial location, some associated cost data and an initially undefined temporal location. Linkages between events are defined as *relationships* which may be temporal (e.g. one event must occur before another), logical (e.g. two events being mutually exclusive), cost-based (e.g. if two events both occur, an additional cost is incurred) or a combination of these. *Costs* may be of any type – financial, temporal or abstract variables such as desirability. Events may or may not be mandatory, allowing multiple alternative designs for individual sections to be considered concurrently, or 'extensions' to the core work to be considered. Additionally, *constraints* may be introduced to limit the possible solutions to those where a cost falls below a maximum value, or an event occurs at a specified time.

Arbitrarily arranging the events in a 2D-space and adding the relationships and all the potential links between events, whether valid or not, produces a network (Fig. 3 a) that could be analysed using traditional network analysis tools, with a valid path through the network being a valid branch of time, i.e. order of events. However, a clearer graphic can be produced if only explicit relationships are represented (Fig. 3 b).



3a. The full temporal topology network of events

3b. The same network showing relationships only

Fig. 3 The time-line from Fig. 2 represented as temporal topology diagrams

4. EXAMPLE APPLICATION OF TEMPORAL TOPOLOGY

The following example shows how the temporal topology model could be applied to a realistic scenario of planning improvements for cyclists along the route of a busy road. For simplicity only a small section is covered, showing a selection of different solutions, and how they could be broken down into events and relationships. Additionally, only the centrelines of the proposed routes are shown; a full model would include the associated crossings, signs, road markings, etc. which would be required, and which would all be associated with the temporal topology events.

This scenario (Fig. 4) is based around a busy main road (hatched), which is located in a walled cutting, and a station. The intent is to have a continuous cycle route running along or parallel to the main road, with an additional requirement to provide direct access to the station shown from both east and west. Some possible routes near the station are shown, consisting of a variety of dedicated cycle paths, converting footpaths to dual-use, signing routes along quiet roads and marking out cycle lanes along existing roads. These different options have differing implementation costs, in terms of financial, temporal and ease of installation. Additionally, some solutions may be more desirable than others (e.g. dedicated cycle routes are preferable to on-road lanes in terms of environment and safety for the cyclist), and the route should be overall as short and as straight as possible.

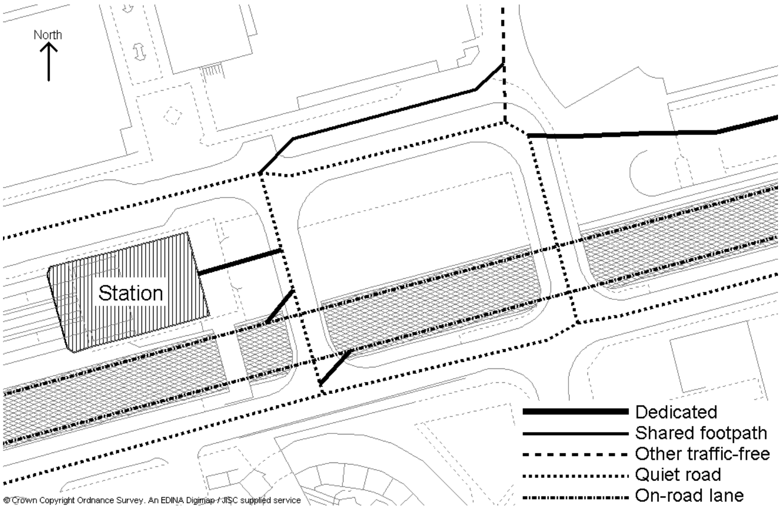


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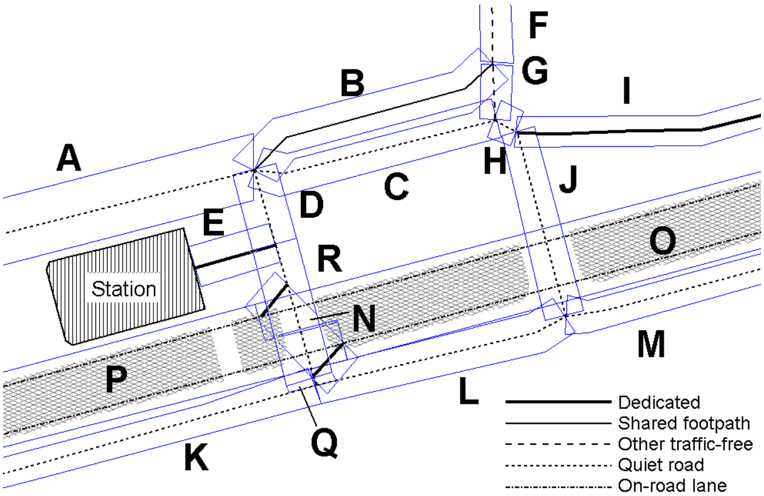
Fig. 4 The example scenario of possible cycle routes

The options could be considered as being split in to three distinct routes – a predominantly quiet road route to the south of the busy road, a mixture of route types to the north of the busy road and with-traffic cycle lanes on the busy road itself. There is an additional option to the northeast of the study area of a traffic-free route heading north then east. Two bridges to the east of the station allow the busy road to be crossed safely, and also allow crossover between the route options, e.g. the westerly section north of the road could be matched with the easterly section south of the road to produce an optimal route. However, only the construction of one complete east-west route will be considered possible, i.e. building more than one parallel east-west section is not allowed.

To the northeast of the station there exist two local alternatives, of converting the pavement to a shared foot/cycle-way or using the quiet road. It is thought that to save costs initially, the quiet road could be used for this section, with the pavement being converted later if necessary – although doing one then the other would be more expensive overall. It would not however be allowable to first change the pavement to dual use, and later remove this and use the quiet road.



Event	Description
A	Quiet road route W to N of busy road
B	Shared footpath link to north of busy road and east of station
C	Quiet road link to north of busy road and east of station
D	Link to station from northerly options
E	Link to station entrance
F	N mixed route E
G	Link from E bridge to NE quiet road route
H	Link to E routes
I	Dedicated route to E, N of busy road
J	Easterly quiet road bridge
K	Quiet road route W to S of busy road
L	Quiet road route to S of busy road
M	Quiet road route E to S of busy
N	Cycle ramps from busy road
O	With-traffic lanes on busy road to E
P	With-traffic lanes on busy road to W
Q	Short link section from W bridge to S of busy road routes
R	Link from station over W bridge

Fig. 5 The example scenario as temporal topology events

Fig. 5 shows this scenario broken down into the structure of temporal topology events, with a summary of what these events entail. The only constraint is that the station must be connected to both the east and west (therefore either A, P or K are required to link to the west, and F, I, O or M to the east). The relationships between events are shown in Fig. 6 , based on only one complete route being constructed. An additional relationship, illustrating a purely temporal relationship, is that since construction of the ramps (event N) would entail works at the edge of the busy road, the cycle lanes along the busy road (events O and P) may only be built after the construction of the ramps.

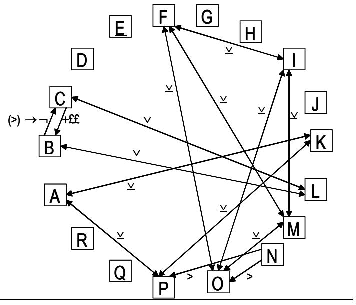
LOGICAL	SYMBOLIC	GRAPHICAL
A or K may occur, but not both	$A \veebar K$	
A or P may occur, but not both	$A \veebar P$	
K or P may occur, but not both	$K \veebar P$	
B or L may occur, but not both	$B \veebar L$	
C or L may occur, but not both	$C \veebar L$	
if B occurs before C has, C does not occur	$(B > C) \rightarrow \neg C$	
if B occurs after C, cost is increased by ££	$(C < B) \rightarrow +£$	
N must occur before O, should both occur	$N > O$	
F or I may occur, but not both	$F \veebar I$	
F or M may occur, but not both	$F \veebar M$	
F or O may occur, but not both	$F \veebar O$	
I or M may occur, but not both	$I \veebar M$	
I or O may occur, but not both	$I \veebar O$	
M or O may occur, but not both	$M \veebar O$	
N must occur before P, should both occur	$N > P$	
E must occur	$\underline{E}$	

Fig. 6 Representations of relationships in the example scenario

5. ANALYSIS OF TEMPORAL TOPOLOGY NETWORKS

The aim of temporal topology network analysis is to determine an optimal set and order of events based on the specified costs and satisfying all the given relationships and constraints. This gives the events a relative temporal location and discards all events deemed not to be in the optimal set. From the duration of the events in the sequence and a given time, an absolute temporal location for each can then be calculated if required. Currently it is assumed that there is no overlap between events, i.e. they occur sequentially, although the model could perhaps be extended to allow overlap. One other assumption that may be made in many cases is that having spatially close or spatial-topologically connected events occurring temporally close or adjacent is desirable - i.e. that building continuous sections of networks is advantageous.

How optimality is defined will affect the result of the analysis. The least-cost solution for one individual variable is unlikely to give optimum results for other costs under consideration. Aggregating all weighted costs to give a single variable is also likely to be unsatisfactory due to the artificial nature of the combination of different classes of variable (e.g. calculating weightings between financial and abstract variables). The most satisfactory option is therefore to perform a true multivariate optimisation producing a solution, or set of solutions, to which the contribution of each individual variable can be seen, allowing the decision-maker to make a more informed decision [6]. This however is a more complex, and therefore time-consuming process, and so single-variable methods are considered here first.

5.1 Single-variable Optimisation

The intent of the temporal topology model is that it is possible to analyse it as a network using traditional network analysis tools. Thus, through adding start and end events to the network and putting in all links, a variation on a shortest-path algorithm such as

Dijkstra's [7] could be used to perform the optimisation with the list of nodes crossed being the optimal order. Obviously some modifications to the standard algorithm are necessary to take account of constraints and relationships in the temporal topology model, but such a method should rapidly produce a good single or aggregate variable solution. Such solutions may be of particular use as initial candidates to test in a multivariate optimisation.

5.2 Multivariate Optimisation

The optimisation theory used here for multivariate optimisation is that of Pareto optimisation (from [8]) wherein a solution is considered to be optimal if there exists no other feasible solution that has equal or better costs across all variables considered. This usually results in a set of good solutions being produced, from which the decision-maker can choose. In order to search the solution-space for Pareto-optimal orderings of events, a genetic algorithm [9] is being used. This is an algorithm which mimics the principles of natural evolution and is suited to problems where there is a large and poorly understood solution space and no easy analytical or linear approach [10]. The fundamental idea is that combining sections of good solutions with sections of other good solutions will produce further good, or better, solutions. Thus, given sufficient iterations where only the best solutions survive to the next generation, a set of approximations to the best solution will be produced. This iterative process is however time-consuming, and so for small systems it may be more efficient to test all possible solutions (i.e. an exhaustive search).

6. IMPLEMENTATION OF A TEMPORAL TOPOLOGY APPLICATION

A decision-support application has been implemented based on the temporal topology theory. This implementation is based in the GE Smallworld GIS software, using a metadata database to record the assignment of real world objects to temporal topology events and the relationships between these events. From this database, schematics of the temporal topology network can be produced which can then be analysed for single-variable optimisation using customised versions of the standard Smallworld network follower tools. An analysis engine using the Pareto optimal principle with a genetic algorithm has been written in the Smallworld Magik object-oriented language for multivariate analysis. This can read the data from both the metadata and GIS databases to perform the analysis. Once temporal topology network analysis is finished, complete optimal solutions can be viewed in the GIS so that the planner can make a final decision.

In order to test this implementation, a case study is being undertaken together with Sustrans, a UK Sustainable Transport charity. This involves the planning of cycle routes to ensure the most efficient use of resources whilst providing suitable routes that meet cyclists' needs. The planning will be undertaken both using the temporal topology application and by Sustrans through their normal procedure so that comparisons can be made between the routes produced. Results should indicate whether the temporal topology application produces solutions that would not otherwise be considered, and through working with Sustrans the feasibility of the solutions can be determined.

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