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Application of Supernetworks in Modelling Activity-Travel Behaviour

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Abstract: Network representation and optimization has for long been applied to address vast engineering and scientific problems. Examples are originated from the Seven Bridges of Königsberg, to a variety of classic P and NP-hard problems such minimum spanning tree, shortest path, and traveling salesman problem etc. To capture the interdependency between different sub-systems, different levels of network extensions were proposed during the last decades to model complex systems like transportation and economy. These extensions, the so-called supernetworks, can incorporate choice dimensions which do not belong to a single distinct network in a unified fashion. Recently, further extensions, multi-state supernetworks, have been proposed as a promising way to represent complex activity-travel behaviours in the field of activity-based modelling. This paper reviews the developments of this line, beginning with the classic transport network and ending with the highest level of supernetwork thus far that is empowered to model route and mode choice, activity and parking location choice, ICT use and joint travel and activity.

Key words: *supernetwork; network extension; choice dimension; activity-travel behaviour*

This paper summarizes experiences with the elaboration and application of the concept of supernetworks, gained in the Urban Planning Group, Eindhoven University of Technology. The domain of application involves the representation of activity-travel decisions in physical and virtual environments. This presentation is relevant for accessibility analysis in multi-modal transportation systems, the simulation of activity agendas in time and space, support for individual activity-travel planning and similar problems. These issues are part of the larger domain of activity-based travel analysis, which has received considerable attention in the past several decades, especially in transportation and urban planning. Traditionally, transportation demand modeling was based on individual trips.

Travel surveys provided data on such trips, and transportation demand and traffic flows were predicted by developing and applying a series of largely independent modeling steps to predict the total number of generated trips in a set of transportation zones, the choice of destination for each of these trips, the choice of (typically single-modal) transport mode for each trip and the assignment to the road network of the resulting origin-destination tables, representing the number of trips between the set of origins and the set of destinations, to simulate traffic flows.

The activity-based approach views travel as a demand derived from the need to pursue activities distributed in time and space. Rather than directly predicting travel patterns, the approach therefore

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attempts to predict/simulate which activities are conducted where, when, with whom, for how long and the (chain of) transport modes involved, subject to several constraints. Travel is thus seen as a time episode in between two activity episodes. Consequently, activity-based models include much more interdependencies between the facets making up an activity-travel program. Most attention has been paid to the generation of activities and travel, much less to the implementation of activity-travel plans. In that sense, work on supernetworks is still relatively limited in this body of research.

In this paper, we will first discuss the basic principles of supernetworks. This is followed by a discussion of Arentze and Timmermans^[1] who suggested integrating in a systematic way the representation of the physical networks for different transport modes and the representation of the activities. In a series of papers^[2-4], this basic approach was further elaborated and tested to have an integrated representation of multimodal transport networks, locations of facilities/services for activity programs of individuals and ICT use. These ideas will be summarized in the subsequent part of the paper. Finally, we will complete the paper with a discussion of planned future work.

1 Supernetworks

Transportation research has a long history of predicting route choice. Often, this prediction is meant to reflect valid representations of actual behaviour, sometimes the approach is concerned with normative behaviour. A classical example is the application of a shortest path algorithm on a network, representing a single transport mode and the links, representing a single-dimensional attribute such as travel time or travel distance. The algorithm will then identify for the defined single transport mode network the shortest or fastest path. Whether travellers will actually demonstrate this behaviour is a matter of the validity of this approach in terms of decision processes.

To the best of our knowledge, Sheffi^[5] was the

first to propose a supernetwork which he defined as a network of transport networks to represent different modes and routes. In the representation, links were added to interconnect different physical networks to represent transfers at the same physical locations where individuals can switch between transport modes. This conceptualization implied an important generalization of the classical short route algorithm in that both the route choice and the transport mode choice problem can be solved simultaneously. It should be noted however the Sheffi's supernetwork representation was not operationalized. In fact, this extension was later suggested and applied by examples of applications of supernetworks to model multimodal trips are Southworth and Peterson^[6], Benjamins et al.^[7], Carlier et al.^[8] and Lo et al.^[9]; trips could involve any combinations of transport modes.

In the meantime, an interesting and important extension was suggested by Nagurney, Dong & Mokhtarian^[10] who proposed an integrated multi-class, multicriteria network equilibrium framework for telecommuting versus commuting. Building on earlier^[11-13], their extension of the network concept did not only include links associated with physical transportation, but also links associated with telecommunications and, hence, virtual transportation. It allowed them to predict the number of decision-makers of each class that would telecommute versus commute. In their application, the evaluation function was multi-dimensional and included travel time, travel cost, and opportunity cost. In a sequel, they extended their approach to decision-making over time^[14].

2 Multi-state, Multi-modal Networks

Arentze and Timmermans^[1] suggested an extension of the basic supernetwork concept, in which activity programs of individuals and multi-modal transport networks are integrated. Their proposal supports the shift from trip-based supernetworks to activity-based supernetworks. The supernetwork model is based on the fact that the costs on any kind

of link are mode and activity state-dependent and personalized. Hence, supernetworks are constructed for each individual and are made up of physical networks of different states. In their representation, nodes represent real locations in space; links connecting different nodes of the same activity state are *travel links*; those interconnecting the same nodes of the same activity states are *transition links* referring to parking/picking-up a private vehicle or boarding/alighting public transport; and those interconnecting the same nodes of different activity states are *transaction links* representing the implementation of activities. The cost of a least-cost path through a multi-state supernetwork represents the effort associated with implementing an activity program. Such a measure takes into account multi-modal and multi-activity patterns as well as the synchronization of transport networks and the land use system. A potential drawback of the approach is that the supernetwork may become very large and possibly intractable because it needs to incorporate as many copies of a physical network as there are possible states associated with the different stages of an activity program.

3 Improved Representation

To address this issue, Liao et al.^[2] proposed an improved representation, which is easier to construct and considerably reduces the size needed to include all combinations of choice facets. In this approach, the integrated transport network is split into a public transport network (PTN) and private vehicle networks (PVNs). A PVN contains the home location, parking locations, a few key locations and links that connect all these locations. Similarly, the PTN includes the home location, activity locations, parking locations, auxiliary transit locations and mode-specified links that connect all the locations. Both PVN and PTN can be considered as bi-directed and sparse graphs as they are extracted from road/service networks. Since the PTN is a multi-modal network, if any node induces a mode change, extra bi-directed links are added to denote

boarding/alighting transition links, as illustrated in Fig 1, where link 2→6 denotes boarding and link 6→7 denotes alighting and then boarding. This extension seems to make the PTN large again. Extended in such a way, every link in PVN and PTN is mode-specific. When copies of PVNs and PTNs are assigned to different activity states, PVNs and PTNs become mode and activity state dependent.

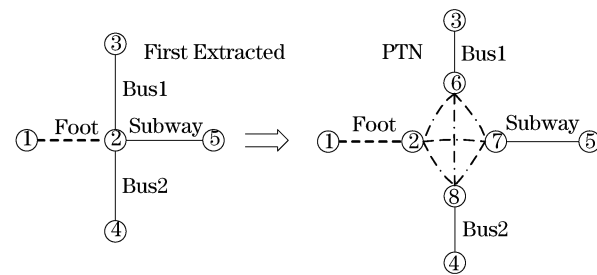


Fig.1 Extra Links for Mode Change

Next, all PVNs and PTNs in different states are connected through transition links, representing parking/picking-up private vehicles or conducting an activity. The former transition link implies an exchange between PVN and PTN, whereas using the latter links involves entering networks of different activity states. If travel is not made by a private vehicle, no parking/picking-up transition link is involved. Links from PVN to PTN are parking links, and vice versa picking-up links (Fig. 2).

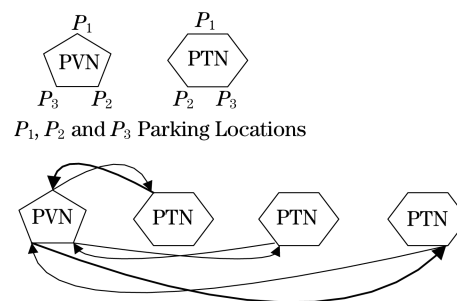


Fig.2 Parking/Picking-up Links

Activity transition links occur when any activity state alters from 0 to 1. A straightforward way to represent activity transitions in the whole activity state space is create links between successive activities (Fig. 3).

Whereas Arentze and Timmermans relied on a single representation, Liao et al.^[2] suggested to constructed separate networks for each going-out

modes. This alteration substantial reduced computing costs. The union of all going-out mode based supernetworks is the final supernetwork. Fig. 4 shows the supernetwork representations for an activity program, which includes two activities and two going-out modes (foot and car). H and H' denote home at the start and end of the activity state respectively; A_1 and A_2 denote the locations for activity 1 and 2, while P_1 and P_2 represent the parking locations for the car.

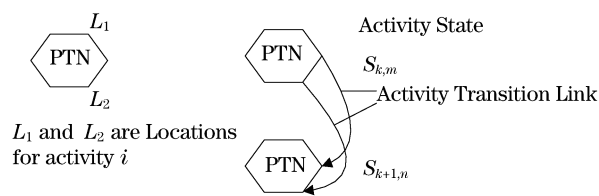


Fig. 3 Activity Transition Links

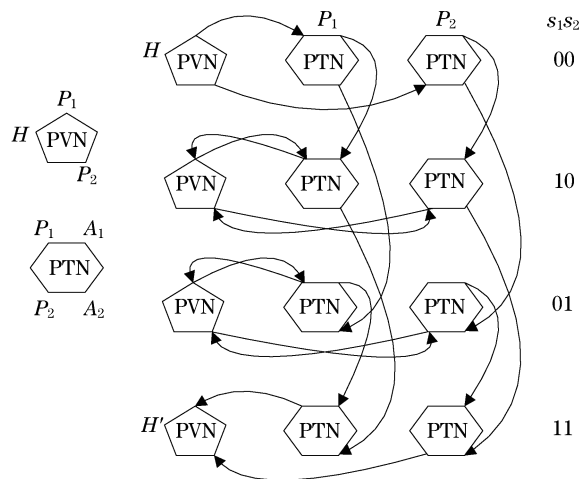


Fig. 4 Supernetwork Representations

4 Construction of Personalized Networks

Although splitting PTN and PVNs is beneficial to the personalized supernetwork representation, the approach still leaves open the question how personalized transportation networks can be constructed to reduce the representation size^[1] and thus allows larger scale applications of the model. Further exploring this issue, Liao et al.^[3] proposed a heuristic approach to construct PTN and PVNs for a given activity program based on the empirical findings that only a rather small set of possible locations for activities will be of interest to the individual and

that once the locations of activity facilities are determined, the individual will always consider the most satisfactory routes to get there. The suggested approach involves the following steps. First, in step 1, for an individual's activity program, all personalized parameters are set. Next, in step 2, the activities with a fixed location are identified. This is followed in step 3, by a selection of the choice set for activities with flexible locations using the following equation:

$$disU_{iCAjk} = disU_{iCAjk} + travel_{iCAjk}$$

where

$disU_{iCAjk}$: disutility of individual i choosing alternative k for activity j .

$disU_{iCAjk}$: disutility of conducting j at alternative k .

$travel_{iCAjk}$: average travel disutility from or to associable activity locations.

There are two ways of narrowing down the choice set: (1) selecting a specified number N_j of alternatives with the least disutility; or (2) selecting a specified proportion P_j of the total with the least disutility. Note that the target of the selection is not to find the best location, which is done in the supernetwork model, but to eliminate candidates that are highly unlikely to be chosen. For each pair of associable locations, a public transport connection choice model can be applied for the selection:

$$disU_{PTC} = (disU_iW + disU_{iPT} + disU_{iHD} + disU_{iAT})|_c$$

where $disU_{PTC}$ denotes the disutility of taking public transport connection c . If the individual does not have the possibility to use a private vehicle, the union of selections (locations and connections) represents the output PTN. If the individual can use private transport, in step 5, for each possible departing mode, first the potential parking locations are selected and then the specific parking locations are selected using Equation:

$$disU_{iPKvp} = disU_{iPKvp} + travel_{iPKvp}$$

where

$disU_{iPKvp}$: disutility of i choosing parking for v at p .

$disU_{iPKvp}$: disutility of parking v at p .

$travel_{iPKvp}$: travel disutility to its corresponding

potential parking location.

Again the union of the selections is used as the output PTN. Next, in step 6, for each possible departing mode, and for any two locations selected in the PVN, if there needs to be a private vehicle connection, the most satisfactory one is selected. Finally, in step 7, the selections are unified and the mode-specific PVN is obtained.

A key parameter in the approach is how many alternative activity locations are selected in the choice model, on which the size of the supernetwork is contingent. The larger this parameter the more likely the optimal activity locations are included in the pre-selected set by the choice model and the least-cost tour in the supernetwork is the real optimal one. Despite the lack of theoretic proof, simulation shows that the optimal set can be selected by setting very low values for this parameter compared to the real size.

5 Inclusion of ICT

Similar to the motivation in Nagurney, Dong & Mokhtarian^[15], in the field of activity-based approaches possible interactions between ICT and activity-travel behaviors should ideally be incorporated in

the modeling approach. Researchers have recognized that an increase in the use of ICT may lead to changes in the location, timing and duration of people's activities and the widespread use of ICT will likely be associated with new activity-travel patterns in time-space. Liao et al.^[4] proposed a supernetwork representation that integrates land use, transport and ICT. The short-term effects of ICT use, i.e., substitution, fragmentation, and multi-tasking are included in the representation.

The premise of substitution is that the location-based activity has an access to ICT-based counterpart. To capture this possibility of substitution, virtual transaction links can be added to connect the locations of different activity states just as the physical transaction links. For example, in Fig.5(a), the solid transaction link refers to going to the specific physical activity location L_1 for activity A_1 and the dashed indicate that substitution occurs at the corresponding locations. An advantage over the supernetwork conceptualization of ICT substitution^[14], in which a virtual link connects the substitution location and physical activity location, is that this format allows the study of substitution embedded in an activity program potentially involving multiple activities and stops.

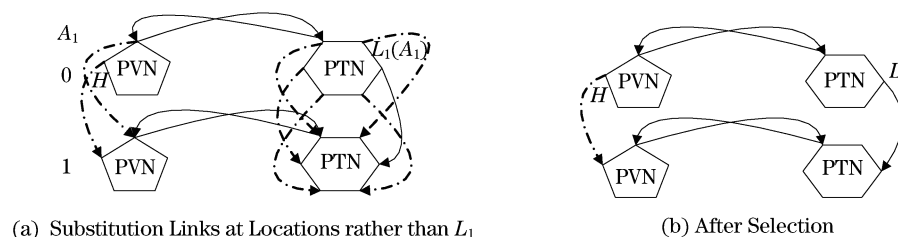


Fig.5 Example of Substitution.

Only a small set of virtual links is needed to be considered as candidates of part of the least effort path of conducting the whole activity program. Fig. 5(b) is an example where virtual links are reduced and only home is considered as a location for substitution. The situation may become more complicated if mobile devices are considered.

Fragmentation involves the decomposition of activities into multiple segments of subtasks that can be conducted at different times and/or loca-

tions. The fragmentation of activities can occur on three levels: manner, space, and time. To represent these, if an activity is likely to be decomposed into several subtasks, each subtask is regarded as a sub-activity in parallel with other activities. If all the states of these sub-activities turn to 1, this activity is conducted. Substitution may also take effect in some of the sub-activities so that the manner changes. If at least one sub-activity is substituted somewhere, it is fragmented spatially. For ex-

ample, as shown in Fig. 6(a)), A_1 can be partly done at home and partly at L_1 ; accordingly, A_1 is divided into two sub-activities: A_{11} and A_{12} . If A_1 is interrupted by another activity A_2 and resumed at

the same location, A_1 is fragmented temporally as two segments, i.e., A_{11} and A_{12} . Fig. 6(b) is an example of this situation, in which A_2 can be substituted at L_1 or conducted at L_{21} or L_{22} .

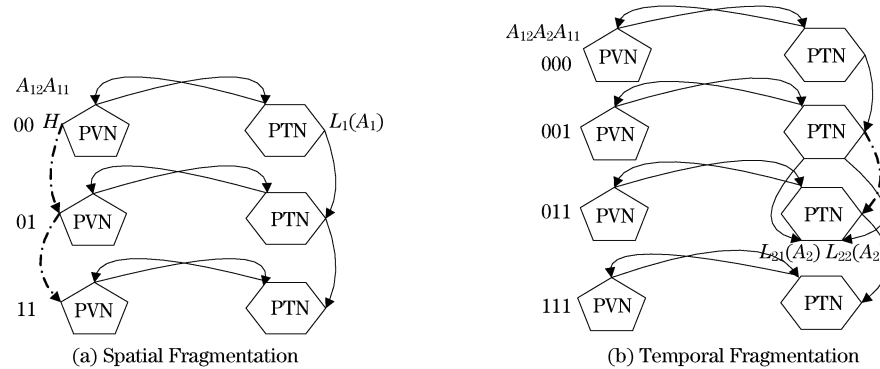


Fig. 6 Example of Fragmentation

Finally, multi-tasking enables individuals to reconfigure their activity participation in an effective way thereby releasing more time for additional activities. Two widely accepted types of multi-tasking are multi-tasking while travelling (e.g., emailing on a train) or at a fixed location (e.g., on-line shopping during work)^[16-17]. Activities conducted whilst travelling do not have an influence in terms of change of activity states but merely impact the (dis)utility of travelling (link costs of travel links) or of the primary activities (link costs of

transaction links). However, in some cases multi-tasking opportunities may affect the network and even introduce new types of links; if the activity state changes while travelling, combined transport and transaction links are needed to connect different locations across different activity states; and if more than one (sub)activities' states changes at fixed locations, the transaction links are added to connect the locations of different activity states to denote multi-tasking (see Fig. 7 for an example).

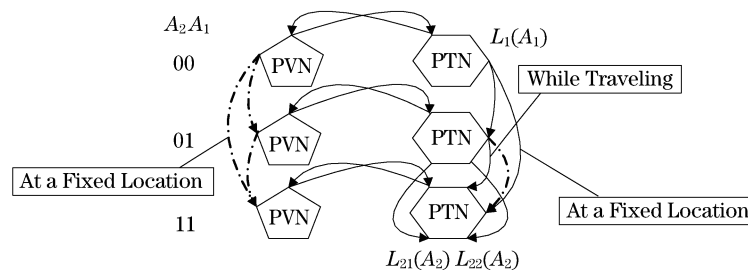


Fig. 7 Example of Multi-tasking

Thus, the effects of substitution, fragmentation and multi-tasking can be captured in extended multi-state supernetworks by adding extra activity states and transaction links. The steps for the supernetwork representation of an individual's daily activity program that integrates transportation, land use and ICT can be described as follows:

Step 1 Input an individual's daily activity program and construct the personalized transportation networks, i.e., PTN and PVNs;

Step 2 Decompose each activity into subtasks according to the individual's preference and constraints if the ICT counterpart exists and ICT access allows;

Step 3 Assign PTN and PVNs to all the (sub) activity-vehicle states;

Step 4 Connect PTN and PVNs with transition links and physical and virtual transaction links of substitution and multi-tasking, and apply a reduction on virtual links if applicable.

6 Joint travel and activity

Individuals undertake both independent and joint travel/activities as part of their daily activity-travel patterns. The joint activity pursuits are often stimulated by social factors such as desire for companionship and resource constraints such as limited car availability. As joint travel/activities have a strong linkage and implication on activity-travel patterns of individuals, to embed them into multi-state supernetwork is also of great interest. Liao et al.^[18] proposed a representation to incorporate them, in which the meeting and departure of the individuals are regarded as activities. In such a way, the all the patterns can still be modeled in the same unified fashion. Fig. 8, for example, shows individual i and j meet at location A or B , then jointly travel (if any) to activity location B , and depart each other at C after joint activity.

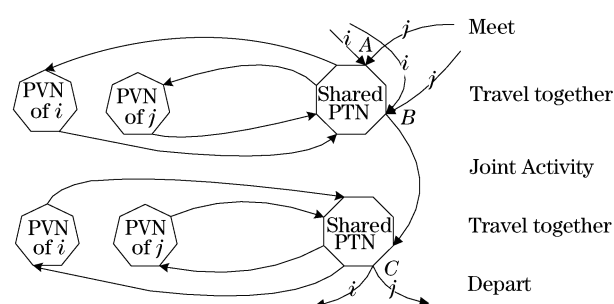


Fig. 8 Example of Joint Travel and Activity

7 Conclusions

In this paper, we have provided a summary of the work conducted at the Urban Planning Group, Eindhoven University of Technology on the elaboration and application of the concept of supernetwork for the representation of personalized networks and including ICT use that may be used to simulate the implementation of individual activity-travel programs. Being a network of networks a reduction of the size of the representation is essential for feasible large-scale applications. Our formal proofs and results of numerical simulations suggest that the combined use of intelligent representations and heu-

ristics allow the application of the supernetwork approach to large scale applications.

Although important progress has been made from the perspective of activity-based analysis, still some additional issues are on the research agenda, which include more precise estimations on individuals' preference and perception, consideration of the supply side, and introduction of more advance optimization techniques.

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超网络在活动-出行行为建模中的应用

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摘要: 网络表示和网络优化长期以来被用于解决很多工程和科学上的问题。这种应用最早可以追溯到哥尼斯堡七桥问题, 然后延伸到各种各样的经典的 P 类问题和 NP-难题, 比如最小生成树、最短路及旅行商问题等。为了表述各种子系统之间的关联, 在过去几十年里, 不同层次的网络扩展被提出来, 并对交通和经济这样的复杂系统进行了建模。这些网络扩展被称为超网络, 它们可以用统一的方式来描述不同网络上不同选择维度。近年来, 多状态的超网络被认为是一种很有潜力的方法来研究基于活动建模领域里的活动和出行行为。本文综述了这方面的研究进展, 从最开始的经典交通网络到至今最高层次的一种超网络。这种最高层次的超网络能支持对出行路径和模式选择、活动和停车位置选择、ICT 的使用, 以及共同出行和活动的建模。

关键词: 超网络; 网络拓展; 选择维度; 活动-出行行为

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