Mobility-as-a-Service in Space–time prism

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ABSTRACT

Space−time prism (STP) has been a core concept in time geography since it was first proposed by Hägerstrand (1970) as an envelope encompassing all possible space−time paths between two anchor nodes to perform a flexible activity. The projected STP on the planar space, called potential path area (PPA), includes all accessible locations. Given this appealing feature, STP has many applications for measuring space–time accessibility and delineating choice sets.

Since the early work of Miller (1991) that extended the STP modeling over transport networks to consider varying link travel speeds, the field has flourished with STP modeling extensions to capture space–time constraints realistically, such as incorporating uncertainty in travel time and anchor nodes (Kuijpers *et al.* 2010, Chen *et al.* 2013), visit probability within STP (Song *et al.* 2016), and extension in choice facets such as transport modes (Qin and Liao 2021), number of activities (Liao 2021), and interaction between individuals (Neutens *et al.* 2007). Besides the above extensions, all STP models have common applications in measuring accessibility and/or inequality (Horner and Wood 2014, Qin and Liao 2022).

Despite STP modeling extensions and applications, however, the effects of monetary budget on space−time accessibility are usually ignored. To the best of our knowledge, Mahmoudi *et al.* (2019) was the only study that explicitly incorporated multiple resource-based constraints into the construction of STPs. Specifically, they extended STP to a hyper-prism that encompasses time and other resource constraints in an expanded space−time network. However, their STP model concerns the intersection of multiple separate resource-based STPs. This method is applicable only if there is consistency in the expenses of multiple resources across links. For example, the emissions are calculated proportional to the time expenses on the corresponding links. The stipulated problem may, unfavorably, be simplified by merging multiple constraints into one single constraint. Additionally, although their model can account for different transport modes as a distinct resource constraint, it is unable to accommodate flexible trip chaining due to the lack of a unified multimodal representation, particularly concerning the use of private vehicles that require pickups before returning to destinations.

This study aims to propose an STP model extension incorporating monetary budget, referred to as STP_M, and develop an efficient search method to construct STP_M in a multimodal transport network. Regarding multimodality, we incorporate Mobility-as-a-Service (MaaS) which provides bundled mobility services of multimodality through subscriptions in a digital channel (Jittrapirom *et al.* 2017). To that effect, we first apply the multimodal supernetwork representation (Qin and Liao 2021) to integrate MaaS, referred to as SNK_M, for capturing the simultaneous mode and route choice. To incorporate MaaS into the supernetwork, we create a multi-layer network of MaaS, in which each layer is accessible by a unique mobility service and connected to other layers by transfer links between them. In SNK_M, a generic monetary cost structure is proposed based on the MaaS schemes at the link and path levels.

An efficient two-stage bi-criterion bidirectional search (TBBS) algorithm is developed for constructing STP_M in SNK_M. The proposed TBBS builds upon the efficient methods introduced by Hernández Ulloa et al. (2020) for the bi-criterion shortest path search and Liao (2021) for the two-stage search. We apply three speedup techniques to accelerate the search process, namely, upper bound PPA, goal-directed search, and approximation labels. Consequently, STP_M and PPA can be found by the TBBS in the SNK_M. Experimental tests are conducted in the Eindhoven-Helmond corridor, the Netherlands. The results show that STP_M reflects more realistic potential mobility constrained by time and monetary budgets, thereby representing a high potential for analyzing accessibility and equality. The proposed STP model and solution method can be extended to incorporate other budget constraints and is feasible for large-case accessibility evaluations.

Keywords: space−time prism; monetary budget; Mobility-as-a-Service; bi-criterion search; multimodal supernetwork

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