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Substitutability as a spatial concept to evaluate travel alternatives

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ABSTRACT

In this paper we propose the concept of 'substitutability', which we define as the extent to which the preferred travel alternative can be substituted by other initially less preferred alternatives. This is particularly of interest when the preferred alternative is no longer available, e.g. due to labour strikes, weather conditions, power failures, etc. Travel alternatives in this context can comprise of activities, modes, time of day, and routes. We argue that substitutability is a promising new concept, which is relevant for travel behaviour research. In particular, substitutability is relevant from an accessibility perspective, as well as from the perspective of 'freedom of choice'. In this paper we conceptualise the concept of substitutability, present a mathematical expression for it and discuss its relationships with other related concepts in the travel behaviour research field, such as the freedom of choice, accessibility, and robustness/reliability. We illustrate the concept of substitutability using a case study, where we look at the extent to which airports can be substituted by other airports, and by high-speed railway stations, conditional on a given destination, namely the cities of Paris, London and Frankfurt. Finally, we present a research agenda.

1. Introduction

Accessibility is a core concept often used to evaluate the 'quality' of the land use and transport system. In this paper we propose the related concept of substitutability. We argue that substitutability is a relevant concept from the perspective of flexibility of activity participation and travel, and the perspective of 'freedom of choice'. Substitutability expresses the extent to which (parts of) trips can be substituted by alternatives.

Despite the colloquial use of the word substitutability, the concept has – to the best of our knowledge – not formally been defined in the travel behaviour literature, nor has it been systematically studied. In fact, a search in Scopus (13-11-2018), combining this term and 'travel behavio(u)r' revealed only three hits, and the combination with 'transport' only 59. Examples of the latter combination include You et al. (2013) who discuss the substitutability of travel demand and García-Olivares (2015) who discusses the substitutability of electricity and renewable materials for fossil fuels. Consequently, at present there is not a clear definition of what constitutes as substitutability, it is unclear how the substitutability relates to other concepts in the travel behaviour research field (such as e.g. accessibility), and the relevance of the concept for travel behaviour research is still vague.

This paper aims to fill this gap. We conceptualise the concept of substitutability, and how the concept can be insightful and relevant for the transport community. In particular, we show that substitutability can be insightful in the context of the design and evaluation of the transport and land use system.

The remainder of this paper is organised as follows. Section 2 proposes a definition and disentangles it distinguishing travel choice options. Section 3 explains the relevance of the concept, and links it to other related concepts. Section 4 conceptualizes the concept and Section 5 proposes a mathematical expression. Section 6 illustrates how substitutability can provide insights that are relevant for travel behaviour research, in the context of airport choices. Section 7 finally presents a research agenda.

2. Substitutability: definition and alternatives

2.1. Definition

We define substitutability in the context of travel behaviour as '*the extent to which the preferred travel alternative can be substituted by other initially less preferred alternatives*'. This is particularly of interest when the preferred alternative is no longer available (due to whatever circumstances, such as labour strikes, weather conditions, power failures, etc.). Travel alternatives in this context can comprise of activities,

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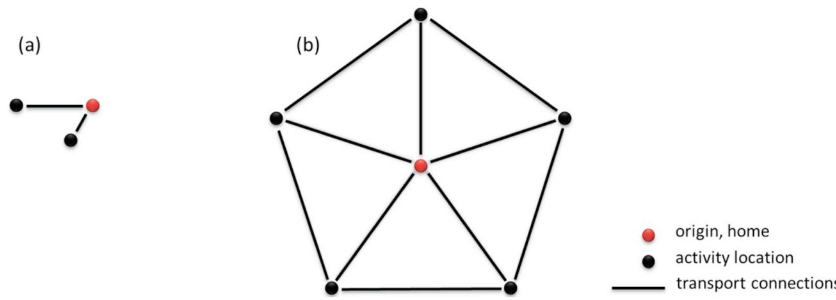


Fig. 1. Stylised example of (a) a high level of accessibility, and a low level of substitutability, and (b) a low level of accessibility and a high level of substitutability.

modes, time of day, and routes. We assume activities as given, although the characteristics of the transport system can influence activities.

2.2. Alternatives

Travel alternatives in this context can comprise choice options (dimensions):

- Activities: frequency and location. Only location-based activities need travel, so the choice is limited to activities to which people travel. Note that substitution between location based activities and virtual activities does exist, examples being e-shopping, e-learning, e-working and skyping;
- Modes, both single modes and chains of modes;
- Routes;
- Time, on various time scales, such as time of day, day of the week at which to do the weekly shopping, or the year in which to visit a certain touristic place of family abroad.

The first choice option imply substitutability at the level of origin-destination pairs, whereas the other options apply to a given origin-destination pair. Within these choice options several possibilities for disaggregation are possible. This at least applies to mode choice: even if the choice for, for example, travelling by train as the main mode is made, people can choose between a fast train and longer access or egress times, or a slower train with more stops, and a shorter access or egress time. And if a person has decided to travel by car (or bike) and has multiple cars (bikes) available, the person can chose between these cars (bikes). Substitutability in case of public transport is strongly influenced by the area of living. In case of a remote village where the only bus line can fail, substitutability is low. Urban areas, however, experience higher substitutability, as more varied choices can be made.

Choices across different dimensions – as presented above – can be dependent on one another. For example, mode choice and route choice are often found to depend on one another, because the networks for modes often differ (partly as in the case of cycling and driving, of fully, as in the case of travelling by rail and driving). Another example: mode choice is often found to depend on time of day choice, for instance in case a person travelling by car decides to travel outside the rush hours. A final example: a person might use a conventional bike to commute on Monday to Thursday, but a sports bike on casual Friday because she can wear other clothes on Friday.

3. Relevance of substitutability and related concepts

Why would the concept of substitutability be relevant for travel behaviour research? It is obvious that a high level of substitutability is generally to be evaluated positively. The higher the level of substitutability, the more alternatives to travel and participate in activities people have available, and they will typically prefer this over having fewer alternatives available. In addition, a high level of substitutability increases the flexibility of travel, and reduces the vulnerability for disruptions. It can also reduce the probably of late arrivals, and reduce the margins people consider to avoid late arrivals.

The concept of substitutability is related to several other concepts, a first one being the Freedom of choice, which is widely used in the area of philosophy. A search in the Stanford Encyclopaedia of Philosophy (assessed 1-9-2017) revealed 33 hits. Here we present the relatively easy to understand definition of Wikipedia: ‘an individual's opportunity and autonomy to perform an action selected from at least two available alternatives, unconstrained by external parties’ (assessed 1-9-2017). A high level of the freedom of choice is evaluated positively (Van Wee, 2011; Martens, 2016).

Next, it is strongly related to the concept of accessibility, as explained above. Following Geurs and van Wee (2004: 128) and limiting ourselves to passenger transport we define accessibility as ‘as the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)’. A high level of substitutability is positively correlated to accessibility because such a high level increases the extent to which people can reach activity destinations. But the concepts are not synonymous. We give an example to explain the core of the difference (see also Fig. 1). Let us assume a person living in an area without supermarkets nearby, but many alternatives at a distance of surrounding cities and towns, say 20 km, each connected by direct road and public transport connections because the person lives in the point of gravity of these cities and towns. Accessibility levels are low but the level of substitutability is very high. Let us now assume a person with a supermarket at 200 and one at 300 m distance. Then the level of substitutability is way lower than in the first case, but the level of accessibility is much higher.

In addition, it is related to the concepts of flexibility, robustness and vulnerability: a high level of substitutability is positively correlated to a high level of flexibility and robustness, and a low level of vulnerability. Note that substitutability is not the same as flexibility because flexibility is a broader concept and also includes characteristics of the traveller, whereas substitutability is a characteristic of the transport and land use system only, though experienced by a traveller. Its position relative to the robustness and vulnerability is that a high level of substitutability positively influences robustness and negatively influences vulnerability. There are multiple definitions of robustness and related concepts, and the concept can be interpreted as a specific case of accessibility and can be expressed mathematically – see Liao and Van Wee (2017: 1214) who define as ‘the ability to withstand or quickly recover from disturbances such as infrastructural and vehicular malfunctions and planned maintenance closures without significant reduction in the performance of the system (in terms of travel times etc.)’. A fundamental difference is that we normalize substitutability relative to the alternative with the lowest Generalized Transport Costs (GTC) (time, monetary costs, and effort) (see Eq. 1).

Combining the concepts of accessibility with flexibility, robustness, and vulnerability: the concept of substitutability may be helpful to further develop person-based accessibility measures from time geography, because it provides avenues to include flexibility of activity-travel patterns.

To summarize, the concept of substitutability is related to several other concepts, but it is not a synonym for any of those concepts. The concepts to which it is related most probably are accessibility or robustness interpreted as an accessibility indicator. We think that definitions and certainly operationalisations of accessibility are possible that explicitly include the level of substitutability (see also the research agenda below).

The concept can be of interest for researchers studying transport and land use systems, but also for planners designing such systems, and policy makers interested in the outcomes of alternative designs and decision making. Transport planners or companies could include the concept in travel planning apps, or Mobility as a Service (MaaS) providers could include it in their advises to travellers.

4. Conceptualizations

This section discusses several other aspects relevant for conceptualization.

4.1. A gradual concept

Substitutability is a gradual, rather than a binary concept. In other words, there is a gradual scale of substitutability. A person having two exactly equal bikes has a high level of substitutability in her choice for any of the two bikes. A person who needs to go to a hospital urgently and the only alternative to be there on time is to immediately take the only car available has zero substitutability. In practice a person often has different levels of substitutability. E.g. one route can for a small part be substituted by another. In that case the level of substitutability is low (same mode, time of day; minor change in route). Or a person can substitute a flight for a high-speed rail trip which she values about equally (mode choice change, and probably also time change), resulting in a higher level of substitutability. Note that a higher level of substitutability is not per definition always better than a lower level. Suppose a person does not have two exactly equal bikes, but two different type of bikes. That person may have one preferred type of bike for a specific trip, and an equal bike results in perfect substitutability. Another type of bike has a lower level of substitutability, but can be valued higher because of the increase in the alternatives available, and a positive valuation of the freedom of choice.

4.2. The additional value of additional alternatives

It is intuitively clear that the availability of more alternatives leads to higher levels of substitutability. A major question relevant in the context of substitutability is: What is the additional value of having more than one alternatives available? We hypothesize the answer depends on several factors.

Characteristics of the activity or activity program: in case of alternative activities, we expect the appreciation for more alternatives to depend on characteristics of the activity. For example, let us consider a person scheduling a dinner in a restaurant, but it turns out that unexpectedly the preferred restaurant is closed. This person would value positively the option between multiple alternatives. If a person wants to buy a pack of rice and the shop would be closed, a shop next door offering the same brand of rice for the same price would make further alternatives useless. Important characteristics of the activity relevant for the additional value of additional alternatives include at least (a) the appreciation for heterogeneity for the specific activity (which also depend on characteristics of people – see above); in some cases people will not at all appreciate heterogeneity, such as in the case of a person preferring to visit the same supermarket, whereas in other cases she might prefer heterogeneity, such as in case of restaurants, (b) past activities (especially relevant in case of appreciation for heterogeneity, such as in the example of the restaurant above), and (b) flexibility in activity scheduling. This flexibility can be explained via an example. Let us assume a person wants to visit a relative at night, but due to a train strike and no other travel alternatives being available this is not possible. Maybe she has several persons she wants to visit in, for example, 1 month, and she can easily reschedule which person to visit on which date. In that case the flexibility is high. But if the person she wants to visit will leave the country for a year next day, the flexibility is very low – if not: absent. So, what can be important in some cases are the implications of not being able to make the planned trip.

Heterogeneity among people: not all people will attach the same value to additional alternatives in comparable circumstances and taste heterogeneity could be included in substitutability indicators. However, since this is the first paper to introduce this concept, in this paper we do not further dwell on this source of heterogeneity.

4.3. Overlap

In case of travel alternatives, it is important to realize that alternatives to some degree can overlap. Take the example of route choice: alternatives can partly overlap. The more the overlap, the more likely a problem on a route will also apply to alternatives, but on the other hand, the difference in (dis)utility will probably be very small. We refer to Liao and Van Wee (2017) how to correct for overlap. In case of substitutability we consider a partly overlapping travel alternative as a full alternative, as long as the reasons for the preferred alternative not being available relates to the non-overlapping part.

4.4. Individual versus social choices

Choices can be made on an individual basis, or can depend on other people. At the activity level substitution between persons is possible, examples being the question which person in a household does the shopping or brings children to school, but because we assume activities to be given, we do not further discuss such interdependencies. Assuming activities to be given, a person often can decide on her own about travel alternatives, but not always. Examples of interactions between people are that within a household there could be one car available, and therefore car availability depends on the behaviour of other members. A person therefore might change modes if the car is not available, or might reschedule the time of an activity and wait until another household member returns home by car (e.g. Maat and Timmermans, 2009). Or people may decide to travel together, having implications on mode choice, time, and route.

4.5. Awareness

A fundamental notion is that the level of substitutability can be assessed by a researcher 'objectively' based on data (taking into account unobserved heterogeneity), but also on the perceptions of the traveller. The level of substitutability is not only a matter of having alternatives available, but also of being aware of the alternatives available. For example, a train commuter without a driving license, being aware about a train strike for the next day, but not being aware of a bus connection, might mistakenly think there is no alternative to substitute the train trip.

4.6. Pre-trip, on trip, during an activity pattern

The level of substitutability depends on the time at which is it measured relative to the trip. An obvious way to assess levels of substitutability is to assume the level before making a trip, at a time when all theoretically available alternatives are still open.

But not all alternatives are open at all times. The longer before a trip a person is aware of travel and activity alternatives, the higher the level of substitutability. E.g. a person facing her car brakes down the moment she wants to leave home for a job interview, cannot decide to substitute the car trip by a train trip, if she would then be too late. But if this happens 3 h in advance, she still can do this and take the train leaving home earlier.

Also during a trip substitution can take place, although during a trip the level generally is lower than before the trip. For example, a person can switch routes because of an unexpected delay on the intended route. Maybe a person intended to buy a pair of shoes in a specific shop, but that shop turns out to be closed. Or a person can decide not to take the intended bus because it is heavily crowded, and wait for the next bus. Or she can change flights after booking the initial flight. If there are nearby shoe shops, she can substitute the activity location. The popularity of inner city areas for shopping might be partly related to the high level of substitutability of shops (activity locations).

4.7. The return trip: limitations

The choice for the trip from home to a destination often has implications for further travel on the same day (the return trip or other travel). For example, a person not travelling by car to work generally does not have a car available for the trip back home. Other limitations are cycling to a station – later on the same day the person probably needs to travel to the same station to pick up the bike.

4.8. Level of analysis

An important dimension is the aggregation level of the level of substitution. We distinguish:

1. Components of trips for one person
2. A full trip or activity for one person
3. A cluster of activities/trips for one person
4. An aggregation of the three levels above, but now for a group of persons.
5. The perspective of the origin or destination of the trip

We now briefly discuss these aggregation levels. First people can substitute components of trips. E.g. a person travelling by train and arriving at the destination can substitute her intended bus trip to the final destination by walking or renting a bicycle. Secondly that person can substitute the full trip or activity, i.e. change the mode for the full trip or the destination. Thirdly a person can change multiple activities and related trips, i.e. an activity program. Fourth these three levels can also be analysed over a group of multiple people, examples for the successive levels being (1) options for multiple people to cycle from a neighbourhood to the station as opposed to taking the bus, (2) options to either drive or travel by public transport from a neighbourhood to the centre of town, and (3) options for all people in a neighbourhood to carry out a specific activity program by foot. Finally substitutability can be approached from the perspective of the origin (from which one or multiple persons chose the destination(s) and travel alternatives) or the perspective of the destination (how easily can a group of persons substitute travel to a given destination, e.g. an office location of a recreational facility). Below we will not systematically discuss both perspectives, but take the first perspective as the point of departure.

5. A formal model of substitutability

Next, we present a formal model of substitutability. However, it needs to be noticed up front that it does into incorporate all aspects that are conceptually relevant for substitutability, as discussed above. Rather, to develop a formal model of substitutability we draw from, and take as a point of departure the closely related concept of accessibility. As explained above according to Geurs and van Wee (2004: 128) accessibility is defined as 'the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)'. The paper provides four categories of accessibility measures, utility based measures being one of these. We choose this category of measures, because of its strong methodological foundation in utility theory. Within this approach there are several mathematical formalizations of accessibility. We built upon the most well-known measure of accessibility, namely the so-called LogSum (LS) (Eq. (1)), in which V_{jn} denotes the observed utility of alternative j for decision maker n and C is an unknown constant representing the fact that absolute utility cannot be measured. From a policy perspective C is irrelevant. In essence, − under certain utilitarian assumption regarding behaviour – the LS_n gives the expected maximum utility a decision-maker derives from making a choice among the J available alternatives in his choice set (e.g. Ben-Akiva and Lerman, 1985; De Jong et al., 2007). The LS is monotonous, in the sense that the LS increases (decreases) when more (less) alternatives are available (e.g. new routes are opened), or when alternatives become more (less) attractive (e.g. cheaper).

$$LS_n = \ln\left(\sum_j e^{v_{jn}}\right) + C \tag{1}$$

We pose that substitutability is high if the loss in accessibility due to the omission of the otherwise chosen alternative is low. A loss in accessibility can occur because this alternative is not available due to strikes, maintenance works, or disruptions in the transport network. That is, substitutability is the inverse of the difference between the accessibility when all alternatives are available and the accessibility *without* the otherwise chosen alternative (denoted$LS_n{}^{Y=i}$), see Eq. (2) where $LS^{Y=i}$denotes the LS without otherwise chosen alternative *i*. Note that the concept of substitutability only exist in the situation where there are two or more alternatives (otherwise the log of zero is taken). Finally, the inverse is taken to ensure that a small (large) change in the LS (due to the omission of the otherwise chosen alternative), corresponds to a high (low) level of substitutability, and vice versa.

$$S_n = \frac{1}{LS - LS^{Y=i}} \tag{2}$$

In Eq. (2), substitutability is presented in an ex-post situation, in the sense that the analyst 'knows' with certainty the chosen alternative *i*. In most practical situations this is not the case. Rather, in an ex-ante situation the analyst holds probabilistic views on the likelihood that a decision-maker n chooses a certain alternative i. Therefore, Eq. (3) generalises Eq. (2) towards the ex-ante situation, in which the chosen alternative is only known up to a probability. The level of accessibility without the otherwise chosen alternative is therefore weighted by the probability (ex-ante) P_i that alternative i is chosen. By doing so, we account for the fact that an alternative that has little chance of being chosen only has a relatively small impact on the substitutability level.

$$S_n = \frac{1}{LS - \sum_{i=1..J} P_i \cdot LS^{Y=i}} \tag{3}$$

Substitutability, as defined in Eq. (3), has a range of zero to infinity. For reasons of interpretability, we normalize the substitutability between zero and one, see Eq. (4), where $\widehat{S}_n$ denotes normalised substitutability. A normalised substitutability level of (almost) one implies a traveller is able to (almost) fully substitute his or her trip. Technically, this means that the expected maximum utility is unchanged even in case his/her most preferred alternative is omitted. This situation could occur when there are many 'perfect' substitutes. A normalised substitutability level of (almost) zero implies a traveller is (almost) not 'able' to substitute his or her trip. That is, there is a dramatic drop is expected maximum utility due to the omission of the most preferred alternative.

$$\widehat{S}_n = 1 - \frac{1}{1 + S_n} \tag{4}$$

As a final remark, it is important that the measure for substitutability is a disaggregate measure, in the sense that it is defined at the level of the decision-maker n. However, it is worthwhile to mention that the measure itself can easily be aggregated to reflect the substitutability at a more aggregate level. After all, policy analysts typically are not so much interested in the effect of a policy measure on one particular traveller, but rather like to assess the aggregated effects. Eq. (3) can be aggregated to reflect the substitutability of a certain group of travellers that commute between a given Origin Destination (OD) pair.

5.1. Illustrations of the proposed measure of substitutability

To illustrate our measure of substitutability, Table 1 shows 4 stylised example situations. In each situation, we suppose that a traveller would like to go shopping. Furthermore, in all situations we assume that the traveller has a marginal utility of travel time of −0.2 utils per minute and a marginal utility of travel cost of −0.5 utils per euro (Eq. (5)). For all other factors (e.g. mode of transport), the traveller is indifferent. Error terms are assumed to be i.i.d. Extreme Value type 1, such that the choice probabilities are given by the well-known logit formula (Eq. (6)).

$$V_i = \beta_{time} TT_i + \beta_{\cos t} TC_i \tag{5}$$

$$P_i = \frac{\exp(V_i)}{\sum_J \exp(V_j)} \tag{6}$$

In Situation 1, there are two shopping centres. One shopping centre is located nearby and has 3 min of travel time and no travel costs, the other centre is located at a bit further up and has 15 min travel time and €3 of travel cost. The degree of substitutability can be derived by computing the probabilities and logsums. The degree of substitutability in this situation is $\hat{S}_n = 0.21$. This is in line with intuition, in the sense that if either of the shopping centres is no longer available the traveller can still conduct his shopping activity.

In Situation 2 a new shopping centre is opened close by. This new shopping centre is a good substitute for shopping centre 1. It has the same travel time and travel cost. In line with expectations, we see that the degree of substitutability substantially increases to a value of $\hat{S}_n = 0.60$ due to the addition of an attractively located shopping centre.

In Situation 3, ten more shopping centres are opened. All ten shopping centres are good substitutes for shopping centres 1 and 3. In this situation the substitutability is very high: $\hat{S}_n = 0.90$. This is in line with expectations since whichever shopping centre closes down or is no longer available, a good substitute is at hand.

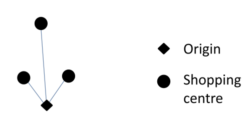
Finally, Situation 4 illustrates the situation in which there are 10

Table 1
Four stylized situations and to illustrate substitutability.

Situation 1: baseline

	Travel Time [min]	Travel Cost
Centre 1	3	€0
Centre 2	15	€3

Situation 2: new shopping centre close by



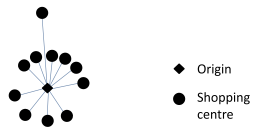
	Travel Time [min]	Travel Cost
Centre 1	3	€0
Centre 2	15	€3
Centre 3	3	€0

	Situation 1	Situation 2
Observed utilities (equation 5)	$V_1 = -0.60$ $V_2 = -4.50$	$V_1 = -0.60$ $V_2 = -4.50$ $V_3 = -0.60$
Choice probabilities (equation 6)	$P_1 = 0.98$ $P_2 = 0.02$	$P_1 = 0.49$ $P_2 = 0.01$ $P_3 = 0.49$
LogSums (equation 1)	$LS = -0.58$ $LS^{Y=1} = -4.50$ $LS^{Y=2} = -0.60$	$LS = 0.10$ $LS^{Y=1} = -0.58$ $LS^{Y=2} = 0.09$ $LS^{Y=3} = -0.58$
Substitutability (equation 3)	$S = 0.26$	$S = 1.48$
Normalised substitutability (equation 4)	$\hat{S} = 0.21$	$\hat{S}_n = 0.60$

(*continued on next page*)

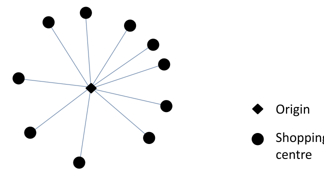
Table 1 (*continued*)

Situation 3: many new shopping centres close by



	Travel Time [min]	Travel Cost
Centre 1	3	€0
Centre 2	15	€3
Centre 3	3	€0
…	…	…
Centre 10	3	€0

Situation 4: Many shopping centres at distance



	Travel Time [min]	Travel Cost
Centre 1	15	€3
Centre 2	15	€3
Centre 3	15	€3
…	…	…
Centre 10	15	€3

	Situation 3	Situation 4
Observed utilities (equation 5)	$V_1 = -0.60$ $V_2 = -4.50$ $V_{3..10} = -0.60$	$V_{1...10} = -4.50$
Choice probabilities (equation 6)	$P_1 = 0.11$ $P_2 = 0.002$ $P_{3..10} = 0.11$	$P_{1..10} = 0.10$
LogSums (equation 1)	$LS = 1.60$ $LS^{Y=1} = 1.48$ $LS^{Y=2} = 1.60$ $LS^{Y=3..10} = 1.48$	$LS = -2.20$ $LS^{Y=i} = -2.30\,\forall i$
Substitutability (equation 3)	$S = 8.53$	$S = 9.49$
Normalised substitutability (equation 4)	$\hat{S} = 0.90$	$\hat{S} = 0.90$

shopping centres which are reasonably far away (travel time = 15 min, travel cost = €3). All shopping centres are however good substitutes for one another. In line with expectations, we see that the degree of substitutability is high: $\widehat{S}_n = 0.90$. After all, each shopping centre can be substitutes for another. However, since the shopping centres are far away getting there requires substantial efforts from the traveller (in terms of cost and time). As a result the accessibility is poor (as compared to situation 3), despite the fact that there are 10 shopping centres available. Hence, this situation clearly demonstrates a fundamental difference between the concept of accessibility and the concept of substitutability.

The mathematical approach we propose has the elegance that it is builds on established concepts from the field of accessibility. Moreover, because the measure is normalised between zero and one, it is relatively easy to interpret. However, as alluded before, it needs to be acknowledged that the proposed measure for substitutability does not account for all aspects relevant to substitutability. For instance, it does not explicitly deal with overlap, social choices, the awareness of the decision maker, and return trip implications. Finally, it is important to realize this formulation is not the only one possible. Other formulations can be conceived that are appropriate for other specific purposes. The formulation that we propose is embedded in behavioural models of choice, but despite its clear outcome between zero and one, it is relatively complex as it builds on the LogSum. This, in turn, may hamper its use in the policy arena in the same way as the LogSum is still rarely used for transport policy appraisal (e.g. De Jong et al., 2007). Perhaps, less complicated measures of substitutability may be proposed. We consider this an interesting avenue for further research.

6. Application

6.1. Introduction

We demonstrate the practical application of the concept of substitutability using the case of airport choice, given a predefined set of destinations (Paris, London, Frankfurt), by Dutch citizens. The Netherlands have five international airports, Amsterdam Schiphol Airport being the country's only intercontinental airport, while the other airports are oriented on Europe and the coastal areas of the Mediterranean. Ordered on the number of passengers, these are Eindhoven, Rotterdam, Groningen and Maastricht. However, Dutch passengers also depart from both Brussels airports, and some German airports, in particular Düsseldorf and Weeze (Gordijn, 2015). Access in terms of travel time is of vital importance for the choice of an airport (Harvey, 1986), but unlike users of railway stations generally do, airline passengers are inclined to consider not only the most accessible one, but multiple airports.

Table 2
Departure locations characteristics.

Departure location (IATA)	Type	Access by PT	Parking cost [€] per day	Travel cost (excl. access, incl. egress)			Travel duration (minutes) (excl. access, incl. egress)		
				Paris	London	Frankfurt	Paris	London	Frankfurt
Amsterdam Schiphol (AMS)	Airport	HST	39	86	75	113	243	221	196
Eindhoven (EIN)	Airport	bus	28	.	33	.	.	238	.
Rotterdam (RTM)	Airport	bus	20	.	62	.	.	185	.
Groningen (GRQ)	Airport	bus	35	.	48	.	.	251	.
Maastricht (MST)	Airport	bus	19	.	.	.	.	.	.
Brussels Zaventem (BRU)	Airport	IC	34	290	55	57	225	246	191
Brussels Charleroi (CRL)	Airport	bus	42	.	.	.	.	.	.
Düsseldorf (DUS)	Airport	S-bahn	39	94	53	73	270	256	186
Weeze (NRN)	Airport	–	36	.	29	.	.	243	.
Amsterdam CS	Station	HST, IC	60	97	60	40	244	160	265
Rotterdam CS	Station	HST, IC	60	97	60	.	204	160	.
Utrecht CS	Station	HST, IC	90	.	.	40	.	.	234
Arnhem CS	Station	HST, IC	45	.	.	40	.	.	203
Antwerpen CS	Station	HST, IC	24	55	51	.	168	163	.
Aken Hbf	Station	HST, IC	36	73	64	.	202	326	.
Luik-Guillemins	Station	HST, IC	20	51	51	.	177	277	.

HST is high-speed train; IC means intercity train, mainly calling at larger stations; S-bahn is light rail.

This multiple orientation suggests that potential air travellers highly benefit from higher levels of substitutability. First, accessibility to airports plays an important role, but varies between travellers with the same origin location (e.g. income, car availability) and varies according to conditions and circumstances (e.g. time restrictions, travel party). Modal choice for the trip to and from the airport is one condition, as parking comes with high costs in terms of money and extra time needed to park at for instance Schiphol Airport, while this airport is excellently connected by rail, including high-speed rail. Public transport to Rotterdam Airport however, is limited to a bus connection and to Weeze it is even absent, while parking is easier and cheaper. In addition, airports vary in reliability of access, which is important since the cost of missing a flight is generally high (Koster et al., 2011). Second, a reason to prefer another airport than the most accessible one are ticket price differences, due to competition between airlines and airports, resulting in repeatedly changing fares. Third, probably the most important reason why substitutability in case of airports matters is that airports highly differ in the destinations they offer and the frequency with which they offer these destinations. Note that in our specific case study we assume the destinations to be given.

Another issue which should be taken into account, is that airports not only compete with other airports, but also with high-speed rail connections. From a societal perspective, train use is preferred because of the much lower environmental impacts. The Netherlands is linked to the European high-speed rail network with three railway connections. The ICE directly connects Amsterdam, Utrecht and Arnhem to a number of German cities, including Frankfurt, and finally the Swiss city of Basel. The Thalys connects Amsterdam, Schiphol and Rotterdam with Antwerp, Brussels and Paris. The Eurostar partly uses the Thalys track to connect Amsterdam and Rotterdam directly with London through the Channel tunnel. This direct connection was introduced in 2018, which previously required a change in Brussels.

6.2. Data

We illustrate the insights that can be obtained using the concept of substitutability with real data for all municipalities in the Netherlands to three destinations, the city centres of Paris, London and Frankfurt. Specifically, we show how well each municipality is situated in terms of substitutability when travelling to the three destinations. For reasons of comparison, we also add the closely related logsum, as an accessibility indicator.

We calculated the total travel times and costs as the sum for the main journey, access travel, and egress travel. The *origins* of travel are municipalities, the airports and high-speed train stations are referred to as locations of *departure* respectively *arrival*, and the city centres of Paris, London and Frankfurt as *destinations*. Table 2 shows the main characteristics of the locations of departure.

Travel indicators were collected for all municipalities, geographically described by their geometric centres, representing travellers home (origin) locations. Access travel distances and travel durations between origins and departure points are retrieved from the Google Maps Distance Matrix API, a batch service that provides travel distances and times for a matrix of start and end points, based on the route recommended by Google algorithms, which is generally the fastest route. We retrieved these data during weekday rush hours for driving, taking into account traffic congestion, and for public transport, including the connection to the closest stop on foot. Travel durations by car were increased by adding 30 min extra parking time. Travel costs were derived from travel distances. Driving costs of € 0.40 per car kilometre (Source: ANWB) were assumed. Long-stay parking charges were added for the departure points, for simplicity 1 day, as multiple days also highly vary between airports (source: municipal and airport websites). Driving costs per person were obtained dividing car travel costs by two, assuming an occupation rate of two persons. Public transport costs were based on a boarding tariff (€ 0.891) plus a tariff based on the travel distance in kilometres according to a sliding scale with thresholds. Tariffs and thresholds are respectively € 0.169 for the first 40 km, € 0.165 (km 40–80), € 0.147 (km 80–100, € 0.118 (km 100–120, € 0.081 (km 120–150), € 0.068 (km 150–200, € 0.025 (km 200–250), and free of charge above 250 km (source: treinonderweg.nl).

Flight times and costs for the main journey were based on the cheapest direct flights and direct train rides, retrieved from Google Flights and NS International, based on booking a flight 2 months before the departure date. Flights times were increased by 120 min airport service time from the intercontinental departure airports, 90 min for the regional airports, and train travel durations were increased by 30 min service time.

Egress times and costs were calculated by public transport, assuming a public transport ride, or alternatively if no public transport is available, a taxi ride to the city centres of the destination cities. Obviously the high-speed train here has the advantage of flying.

6.3. Results

Stata software was used to process and map the data (Pisati, 2007). When interpreting the maps it should be taken into account that visual interpretation of the distances on the maps may differ greatly from the underlying resistances (travel time and travel costs via transport networks available) that have to be bridged. Both travel times and costs can vary widely, depending on whether the car or public transport is chosen as access travel mode, and whether air transport or the high-speed train is chosen as the main travel mode. We present a selection of the results obtained. Three travel alternatives (depicted in Figs. 3, 4 and 5 respectively) are presented for three destination cities, Paris, London and Frankfurt respectively, represented in the columns. For each alternative, the logsum and substitutability are depicted.

6.3.1. Air (driving)

The alternative in Fig. 2 describes the logsum and the substitutability indicator for air travel, with driving as the access mode. Due to strong competition from high-speed trains, only three airports offer flights to Paris. The area around Amsterdam shows the highest logsum levels, with the value decreasing concentrically. The reason that the highest values are not found somewhere in between the three airports, is partly because of the high travel costs from Brussels. However, substitutability shows a very different pattern, with almost only high levels in a belt in the east of the country, while the level elsewhere appears to be low. If a flight from one of the three airports were to be cancelled, this would make little difference to the inhabitants of this area, but even more so to the inhabitants elsewhere. All airports are therefore essential for air traffic to Paris, in the sense that only few people have a high level of substitutability.

There are many alternatives for travel to London, namely from seven airports. Around the northern city of Groningen the logsum is high, because from this regional airport, flights are operated to London. All other departure locations are located south of Amsterdam, which means that high logsum levels are also seen in the southern part of the country. The logsum peaks in particular around Eindhoven, with its own airport and many airports all around. In terms of substitutability, a large central part of the country is covered with high values. Groningen is obviously vulnerable because of its single airport. Striking however, is the low substitutability level of the Eindhoven area. The explanation is that the next best alternatives are way less attractive than the first, best alternative.

Frankfurt is accessible through the same airports as Paris, however, as Brussels offer cheap flights to Frankfurt, the logsum increases to the south. For this reason, the disappearance of Brussels would have a major impact on the accessibility of the southwest, as evidenced by the low value for substitutability there.

6.3.2. Air and high speed train (driving)

It is interesting to see what changes when high-speed railway stations are added, as shown in Fig. 4. The centre of gravity of the logsum is rather southern for Paris because there are, in addition to the airports, also the Thalys railway stations. This is also the case for London, which is directly connected by high-speed trains. In addition however, also Groningen Airport plays a role here. In general, logsums for London are high as there are so many opportunities. Frankfurt can be reached by high-speed rail from Amsterdam via the centrally located cities of Utrecht and Arnhem. This leads to high logsum levels in the middle-eastern part of the country.

Looking to substitutability, Paris shows again a belt in the country's eastern part, but now also the north-western part benefits, as cancelling the flight from Amsterdam Schiphol would still make it possible to travel by high-speed train. The southwestern region still shows a low substitutability level, as residents without a high-speed station would first have to travel to Amsterdam. The very same pattern of substitutability by air and rail to London raises the question of whether it is possible to consider cancelling certain flight connections.

The substitutability for Frankfurt is remarkable, because it is high in a curved band from Amsterdam to the southeast: it makes little difference to people in this area if the first best option would not be available. However, if Arnhem were to be discontinued as a high-speed station, accessibility would immediately drop dramatically in the rest of the country.

6.3.3. Air and high speed train (public transport)

Finally, Fig. 5 shows the effect for passengers who do not travel by car, but use public transport to travel to the airport or high-speed railway station, and are therefore more dependent on the route of the railway lines. This variant is favourable for high-speed travel, since none of the airports, apart from Schiphol, are directly connected to the railways. This variant shows higher values for the logsum and substitutability along the major intercity railways.

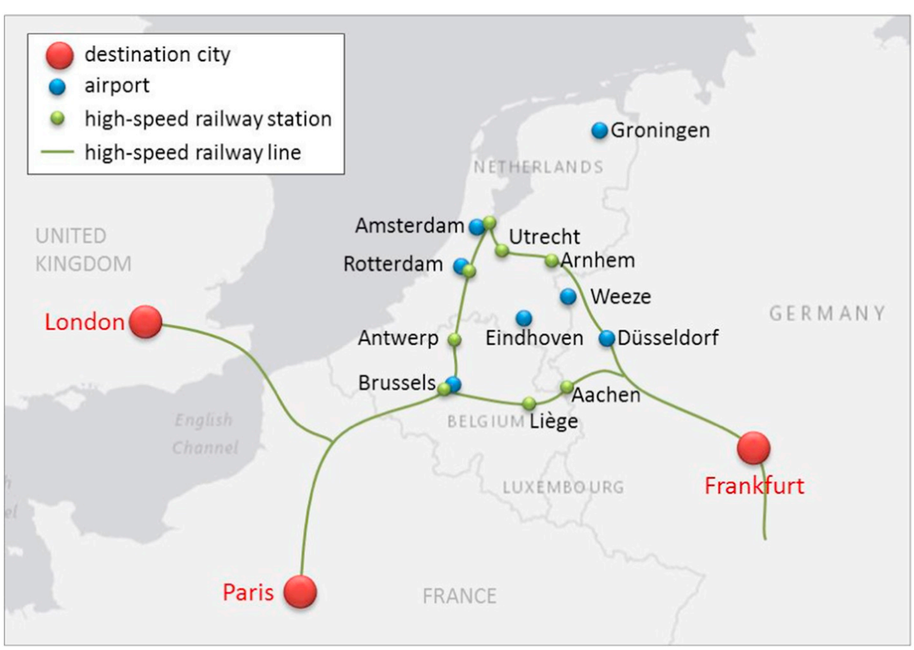


Fig. 2. Orientation map for the application case study.

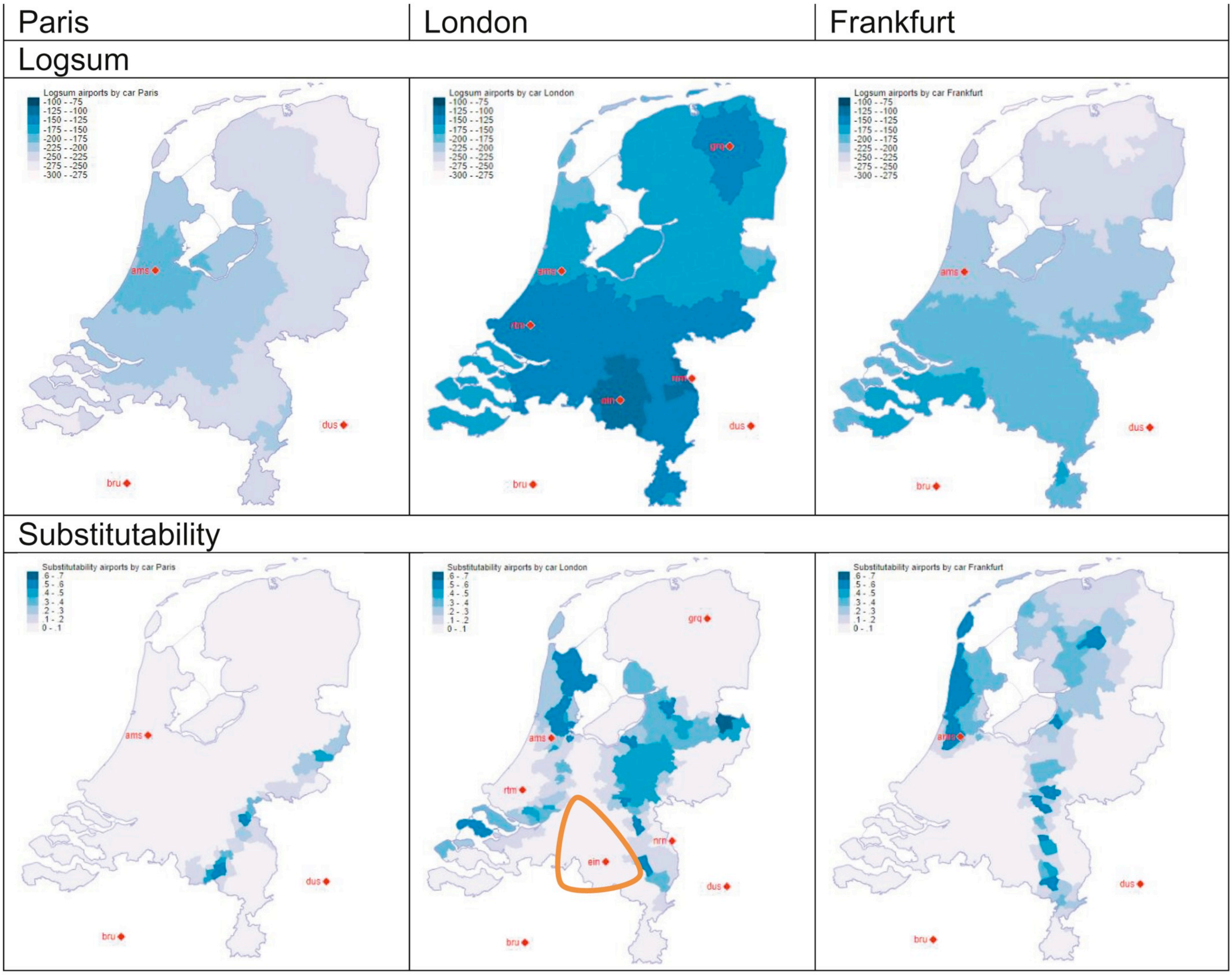


Fig. 3. Logsum and substitutability by air, with driving as access mode.

6.4. Conclusions

This case study shows first of all that the proposed operationalisation of the concept of substitutability can be used for a real world case. Secondly it reveals that the results, as depicted on the maps are not directly intuitive, as travel times cannot be directly deduced from the maps and the travel costs (which vary greatly) even less. However, they all can well be explained and provide new insights which are relevant for travel behaviour research. Thirdly, they show that the spatial patterns of substitutability levels differ significantly from the spatial patterns of the logsum accessibility measure, despite the fact that the mathematical formulations of substitutability the logsum accessibility measure are closely related to one another. We therefore conclude that the concept of substitutability, at least in our case, provides additional information compared to a logsum accessibility measure only.

7. Research agenda

We suggest next options for future research and development of methodologies in the area of substitutability.

- *A methodology to disentangle the contribution of different components of the transport and land use system*
  Different components of the transport and land use system contribute to the level of substitutability. A methodology could be developed to disentangle the contribution of each component (characteristics of (parts of) the land use, and the transport system, characteristics of people and activities/activity locations), comparable to the methodology as presented by Geurs and Ritsema van Eck (2003) to disentangle the concept of accessibility.
- *Empirical research into perceptions*
  We recommend empirical research on the perception of substitutability for different groups of people, different trip purposes and different travel alternatives. Groups of people can be distinguished based on car ownership and availability, maybe on the ownership and availability of other modes of transport (e.g. the bicycle), income groups, lifestyles, and types of residential areas.
  An important element in this research relates to the awareness set: of which alternatives are which (groups) of people aware, under which conditions, and when? And how does the awareness set relate to the set of measured alternatives, considering the characteristics of the land use and transport system? Of course exploring the awareness set is in theory relevant for all discrete choice research and models, but at least in our case and in the area of accessibility in

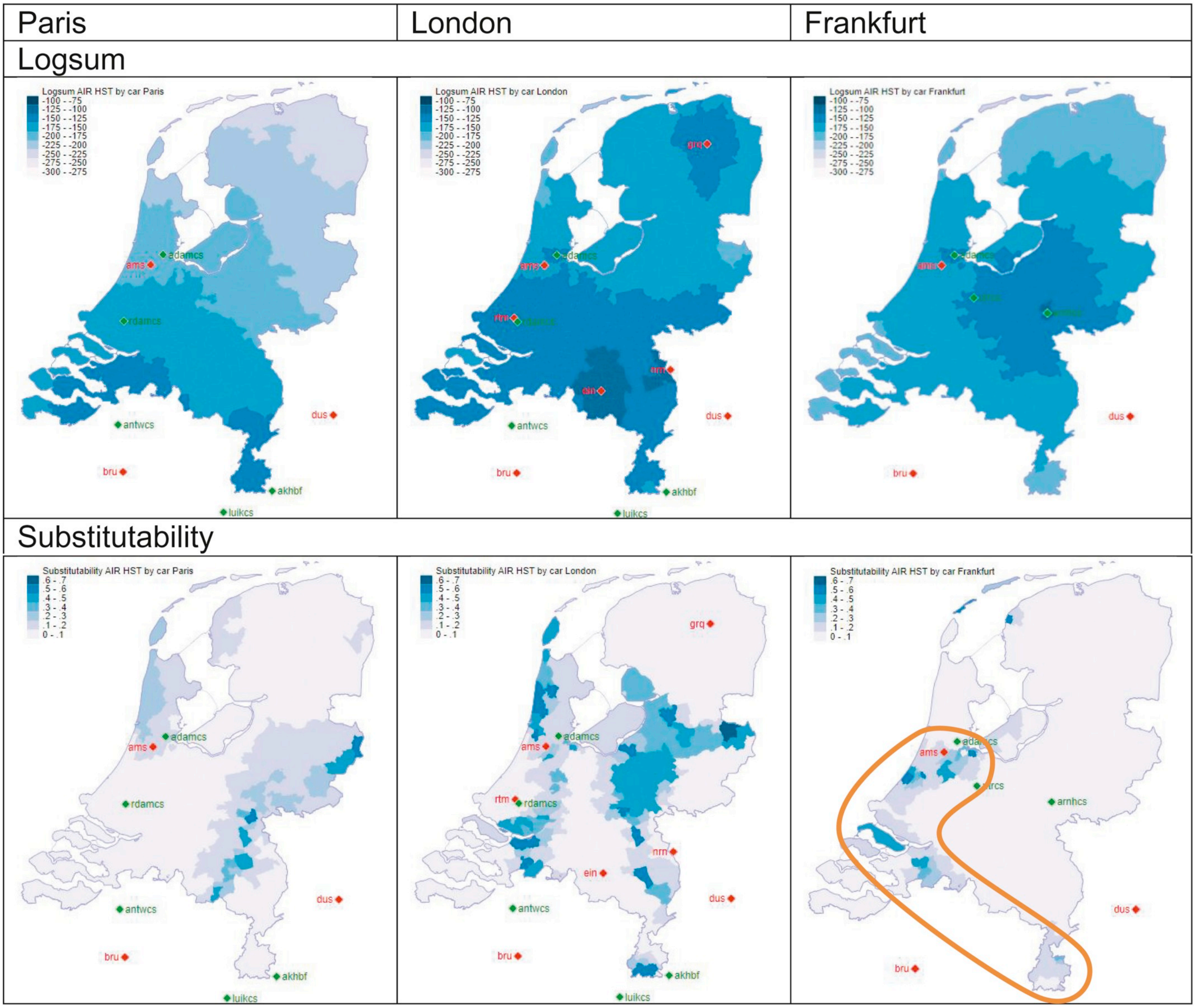


Fig. 4. Logsum and substitutability by air and high-speed rail, with driving as access mode.

general it is a relatively unexplored area. This research can also focus on perceptions of substitutability related to activities and activity programs. In case of both trips and activities/activity programs, research can provide the basis for parameter settings (see Section 5), and maybe also for other mathematical formulations of the concept of substitutability.

- *Extending or adapting the framework*

In our study we propose a mathematical representation of substitutability, but as with accessibility, depending on the purpose of study, the mathematical framework may need to be extended, or adapted to suit the problem. For example, for welfare analysis it would be valuable to be able to estimate the monetary value a change in substitutability before and after a policy. We believe this is a promising avenue for further research, which could be inspired by the works of De Jong et al. (2007), McConnel (1995) and Dekker and Chorus (2018). An entirely different approach could be to develop a substitutability framework based on travellers' perceptions on substitutability. For instance, travellers can be asked to rate their loss in travel options in case the first best option would no longer be available. A next and very simple approach could be the travel time (or generalized transport costs) of the first best option divided by the second best option (or divided by the average of the X next options). We consider exploring different options, and discussing the pros and cons of these options as one of the first challenges to be faced.

- *The role of constraints*

Next we think including the role of constraints as included in time geography (Hägerstrand, 1970; Neutens et al., 2008; Farber et al., 2013) is a challenging topic for further research. How important are constraints for the selection of the consideration set? The constraint of not having a car available (as addressed above) is only one type of constraint. Other examples include the authority constraints (e.g. opening hours of shops, kindergarten) and coupling constraints (such as joint dinners, work related meetings). Some constraints probably are not 100% strict, such as the exact time of a dinner in a restaurant.

- *The role of ICT*

ICT can influence travel choices in several respects, including route choice (satellite navigation, Dynamic Route Information Panels), mode choice (providing travel information), or a preference for a longer train trip without having to switch trains so that the traveller can continue working on a laptop.

- *Interactions between dimensions*

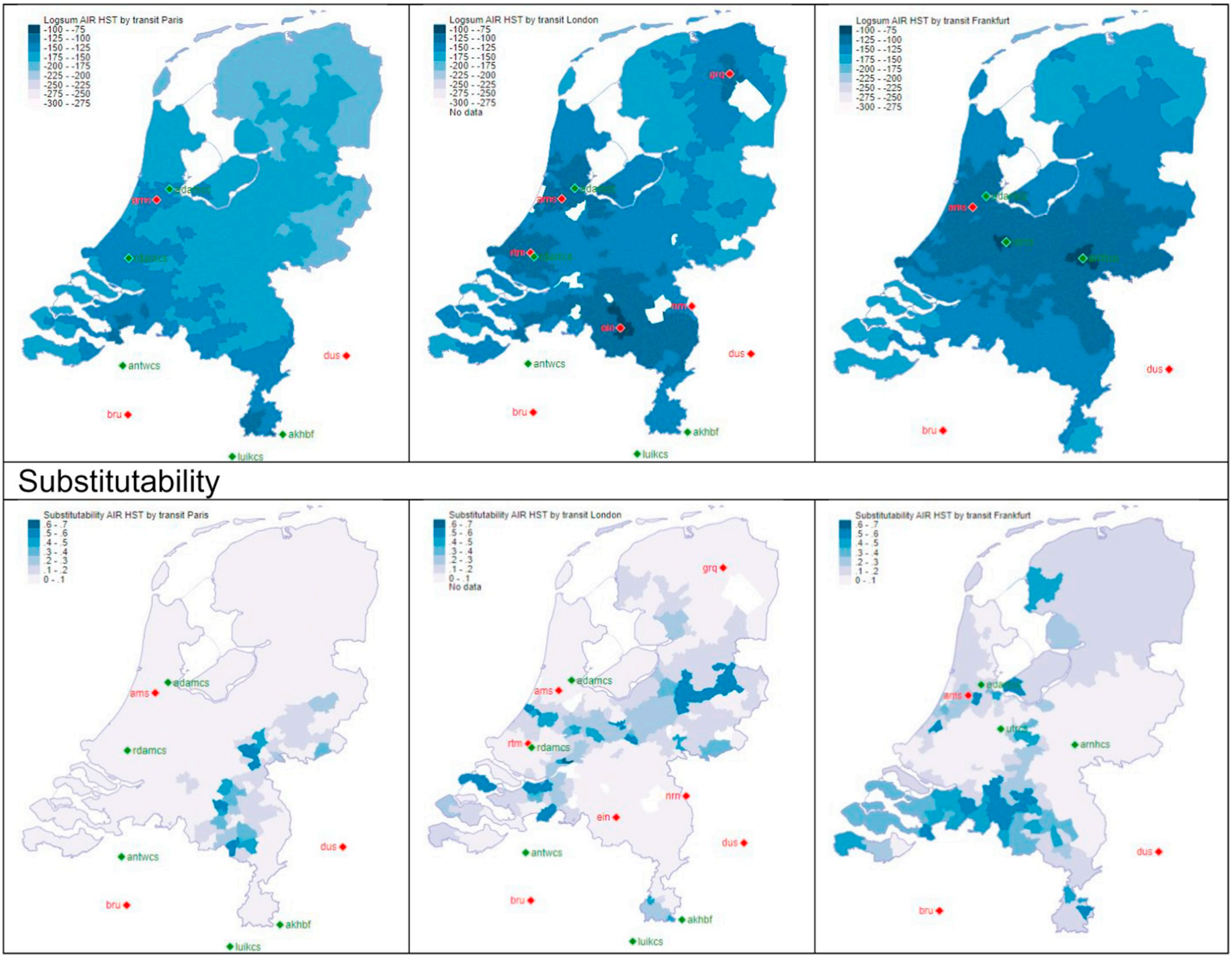


Fig. 5. Logsum and substitutability by air and high-speed rail, with public transport as access mode.

Because the level of substitutability depends on different factors, these factors can potentially interact. E.g. a low level of substitutability due to the spatial distribution of opportunities can probably be partly compensated by changes in the transport system of ICT based accessibility.

- *The wants and needs of clients of research*
  The major question is: how to evaluate the importance of different levels of substitutability in the eye of the decision maker and other clients of research? A first step can be answering the question how useful the utility and welfare based evaluation is, as suggested in the calculation of the levels of substitutability above. This can be done by discussing with decision makers which information they think is useful, and how it should be presented to them.
- *Pros and cons of evaluation frameworks*
  In addition to the previous suggestion, we recommend case studies exploring the pros and cons of different choices to be made methodologically, with respect to the choice of data, presenting the results, and using the concept in broader evaluation frameworks, such as Cost-Benefit Analyses (CBA) and Multi-Criteria Analyses (MCA).
- *Policy implications.*
  Finally we recommend exploring the possible policy implications of explicitly including substitutability in policies, land-use planning, the transport system, ICT related policies, and policies related to opening hours being dominant policy areas.
- *The perspective of activity locations*
  Above we considered substitutability from the level of the origin of trips, the residential location of a decision maker being the most important origin. But as explained above, accessibility, and therefore also substitutability can also be considered from the perspective of the location to which people travel. E.g. a dentist needs a certain number of clients. Depending on the location higher or lower levels of substitutability of clients can occur.
- *Goods transport*
  So far we only discussed substitutability from a passenger activities and transport perspective. We argue the concept can also be applied to goods transport. E.g. a company producing wooden tables need to buy wood, and multiple alternatives companies selling wood can exist. The quality, prices and variety of the wood can vary, as well as the generalized transport cost of transporting the wood to the table producing company.

So far we only discussed substitutability in the context of travel behaviour and activities, but it is probably also a useful concept in other areas, such as the substitution of products and services, software, contacts …

To conclude: we see this paper as a first attempt to propose, define and conceptualise the concept of substitutability. In the future the concept can be further developed in several ways.

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