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LUTI operational models review based on the proposition of an *a priori* ALUTI conceptual model

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ABSTRACT

This paper focuses on understanding to what extent the components of LUTI models and their mutual interactions are conceptually represented by eight operational LUTI models. This is important for the understanding of LUTI models' mechanisms, firstly because it may reduce communication barriers between planning communities, secondly because it may help us understand the models' applicability, and thirdly it may highlight the models' shortcomings and point for future research. We present a discussion about what subsystems should be considered for LUTI modelling, from which we derived an "a priori" conceptual ALUTI model (incorporating Activities, besides Land Use and Transport). By comparing the rationale behind each model with this conceptual model, we establish the basis for our review, focussing on whether these models incorporate the ALUTI components, its inner workings and the relationships between these components. Results indicate three main limitations of the reviewed models. First, models not always adequately include all the components of the a priori ALUTI model. Second, the ALUTI subsystems' internal functions are not explicitly modelled in several of the models reviewed, making it difficult to evaluate how planning decisions affect the subsystem. Third, only few models recognise all mutual interactions, especially in respect to the Activity subsystem.

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LUTI; operational models; activity; land use; transport; ALUTI

1. Introduction

Sixty years have passed since specialised literature started discussing the interaction between land-use locations and travel behaviour. More recent papers (Iacono, Levinson, & El-Geneidy, 2008; Timmermans, 2003; Van Wee, 2015; Wegener, 2004) present a number of advancements in theory and practice, but most importantly, they stress the scientific and technical gaps related to the comprehension and modelling of such a complex phenomenon. Two of these gaps call our attention (Acheampong & Silva, 2015; Van Wee, 2015): first, the need to bridge the gap between activity-based modelling and how these models interact with LUTI models. Second, the need for a wider and more robust accessibility measuring, a fundamental concept that bridges the effects between

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land use and thus activity locations, travel and socioeconomic activities. These gaps bring us to a conceptual discussion about LUTI modelling, its subsystems' components and interactions.

Many authors have reviewed LUTI models along different angles. In chronological order, Southworth (1995) compared 17 applied models published between 1985 and 1995, with the intention of demonstrating the theoretical evolution of LUTI modelling. Waddell (2002) discusses the advantages of UrbanSim, comparing it with other four modelling frameworks. Timmermans (2003) divided 22 models in three categories defined by the theories their modelling is based on. Wegener (2004) compares 20 models under distinct aspects, such as comprehension, general structure, and theoretical basis. Hunt, Kriger, and Miller (2005) compare the state of practice (represented by six LUTI modelling frameworks) with what they consider to be "ideal modelling" in various aspects. Iacono et al. (2008) evaluate the evolution of theoretical approaches and the representation of complexity by reviewing 18 LUTI models. Acheampong and Silva (2015) present a LUTI review focusing on the difficulties presented by the modelling approaches, and their solutions. Recently, Thomas, Jones, Caruso, and Gerber (2017), in a generic review of LUTI models applications, see limitations to the models' effectiveness due to their simplistic geographical approach. However, none of these reviews focused on how the interactions among the three components of the LUTI system (land use, transport, as well as activities) are conceptually modelled. This paper aims at the provision of such a review, which we think is relevant for three reasons:

Understanding the models' mechanisms: Frequently, models represent land use as one single system, but it covers at least two distinct aspects: the intensity of different activities (as in social and economic urban functions); and location choices of households, firms, and other actors. This means we need to clarify the mechanisms of LUTI subsystems at a disaggregate level, so we may understand the core of LUTI models and how activities, land use, and transport interact. *Minimizing the communication barriers*: the transport planning community has recognised communication difficulties as a challenge (Brömmelstroet & Bertolini, 2008; Willson, 2001). We can use LUTI models to clarify to different planning communities (mainly among transport and land-use planners) the mutual impacts of their planning efforts. *To make applications more reliable*: Understanding the causal structure in LUTI conceptual models will help planners and researchers to understand the applicability of LUTI models for specific planning or research case studies. If the key relationships among the components of the LUTI system, which are important for a real world case, are not, or not adequately, included in a LUTI model, this model might be less useful as an analytical tool.

For that, we first discuss and present an "a priori" conceptual ALUTI model, derived from literature, on how transport, land-use, as well as activity urban subsystems interact at aggregate levels. The intention is to check to what extent all the components of that a priori model are considered in some existing operational LUTI models. Then, we use this a priori model systematically for our review. More specifically our analyses strive to answer the following research questions:

- Which components of the a priori conceptual model do the LUTI models include?
- To what extent the reviewed models take into account the components' inner functions?

- Which interactions among the a priori model's components do these models simulate?

This paper is structured as follows: Section 2 discusses each subsystem and introduces the a priori model, used as basis for the analyses; Section 3 presents the core argumentation and results, and is organised along the lines of the research questions presented above; Section 4 discusses each research question's results; and Section 5 discusses further research.

2. Presenting the "a priori" ALUTI model

Current research on LUTI planning and modelling widely assumes that activities are important elements that influence locational decisions and travel behaviour. We believe that the representation of the Activity subsystem (AS), as well as its relationships with the Land-Use and the Transport subsystems (TSs), is crucial for the understanding of how people make locational and travel decisions, and thus how cities function. Several scientific papers that discuss these topics are concerned with activities for many different reasons. As far back as the 1970s, activity-based analysis has been developed with the intention to predict travel behaviour (Kitamura, 1988). After decades of research regarding activities within LUTI planning and modelling (Ben-Akiva, Bowman, & Gopinath, 1996; Kitamura, 1997; Miller, 2003; Wegener & Fürst, 1999), the concept of activities is still vague and untouched in many aspects. While Van den Berg, Arentze, and Timmermans (2012) see activities in terms of social interactions or face-to-face contacts, Macário (2012) describes them in terms of social opportunities and collective benefits. In a different manner, Coppola and Nuzzolo (2011) assume activities as social and economic conducts, while in an alternate approach Arentze and Timmermans (2009), as many other authors, recognise activities as based on personal or household needs, defining activity agendas distributed over time and space. Besides their distinct ways of describing it, all authors see activities as elements of the human environment scattered over space, and from which travel needs are derived. Some recent review papers on integrated modelling (Acheampong & Silva, 2015; Iacono et al., 2008) also recognise the crucial role of activities as important aspects to be accounted for while modelling how cities function.

2.1. Describing the activity subsystem

From all these different points of view about activities, it is possible to interpret three common aspects. First, the participation in activities is the main reason (driving-force) behind some human decisions, including locational and travel decisions (Meurs & Van Wee, 2003). Second, to engage in activities (e.g. working, shopping, and all other social and cultural relations) poses as a set of decisions that intrinsically differs from travelling and/or locating oneself. For example, choosing whether to work or not, where to take a job post, and when/how to travel to work are different decisions, made at different time spans and frequencies. Activity-related decisions (whether in the form of personal agendas or economic conducts) derive from human needs and desires (Kitamura, 1997; Van Wee, 2002). These decisions depend on two aspects that affect personal constraints, "one is predominantly time-oriented (…), the other is the more space-oriented set of imposed constraints (…) to which the individual may or may not have access according to his needs and wants" (Hägerstrand, 1970, p. 19). To engage in the activities themselves is the realisation of these needs and wants (henceforth addressed only as "needs"), which are neither bound to defined locations, nor limited to means of transport (Arentze & Timmermans, 2009). Lastly, the third prevailing concept is that the only activities that should be of interest to LUTI planners are those that have some level of influence on location and travel decisions, that is, those that happen in space consuming land (e.g. to reside or to locate businesses), as well as actually result in physical movements consuming a transport network.

For users, the realisation of these activities depends on fulfilling their needs; that is, unfulfilled needs do not render activities. One may interpret this as a system of demand and supply of human activities, not necessarily in balance. For instance, there are people in need of consumer goods and there are consumer goods supplied by a productive system. While someone may need an item, the activity (to consume) only exists in reality if such a product is available for consumption, and if the person has the means to acquire it. The same applies to any other needs such as specialised services, jobs, houses, etc. Such scheme, that we label as the AS, is one component of the urban system. As any economically driven system, the AS presents an internal mechanism described here as a demand/supply relationship which is also self-restricting. The system presents internal restrictions for demands to be met (e.g. scarcity of certain consumer goods, due to limited production or elevated demand, makes it difficult for every person to acquire it).

In a similar way, external factors also play a role in imposing restrictions to decisions within the AS. Even though these influences may come from many external sources, in terms of LUTI planning and modelling, we assume the AS is impacted by both Land-Use and TSs. For instance, the availability of a certain product may be restricted by location (low household densities or highly monopolised market) or transportation (long distances, high fares, parking or toll fees, etc.) characteristics, which could change or shape the activity to be performed, or even prevent such need from being fulfilled, thus not rendering an activity.

2.2. Describing the land-Use subsystem

Different from the AS, literature presents a more reliable interpretation of the Land-Use Subsystem (LUS), since it is a fundamental part of LUTI planning. Authors use the term land use in reference to the city form (Newman & Kenworthy, 1996; Rodrigue, Comtois, & Slack, 2013), the built environment (Handy, Cao, & Mokhtarian, 2005; Mitchell Hess, Vernez Moudon, & Logsdon, 2001), or its spatial development (Wegener, 2004). Others describe land use as the distribution of populations and jobs (Anderstig & Mattsson, 1991; Miller, Kriger, & Hunt, 1999), or the location of human activities (Acheampong & Silva, 2015; Iacono et al., 2008).

As the name suggests, land use should denote a range of uses, such as residential, commercial, and so on, which are distributed in space, more specifically over the land (Rodrigue et al., 2013). In this sense, the LUS is eminently spatial, and so are the decisions concerning this subsystem. The built environment and its form, as well as the spatial development of the city, derive from agents deciding to locate themselves (e.g. where to reside or locating a business), but only if these decisions are fulfilled in reality. This realisation depends on the congruence between agents' locational preferences and the stock of land (or floorspace) denoting a demand and supply relationship, which in turn depends on the LUS internal restrictions (e.g. prohibitive land prices, insufficient spatial capacity, restrictive regulations, etc.), but it is also subject to external influences.

2.3. Describing the TS

With little or no controversy, literature defined the TS five decades ago (Manheim, 1967) and the definition still holds steady. Its basic elements are three: (1) transported people and goods; (2) the means or services of transportation; and (3) the network through which movements happen. Thus the TS is formed by the patterns of people and goods that flow through a network (Ortuzar & Willumsen, 2011), or "can be defined as a set of elements and the interactions between them that produce both demand for travel and the provision of transportation services" (Cascetta, 2009). Current efforts of planning and modelling the TS mainly involve the description and prediction of human behaviour regarding travel decisions. These decisions encompass a number of transport related choices, such as travel frequency, time of departure, destination, mode, and route. While these decisions arise from agents' demands (i.e. someone that needs to go somewhere), they only materialise as travel once there is, from the supply side of the system, a provided service to meet such a need. This supply and demand relationship is not always balanced, meaning there is usually a shortage or surplus of service/infrastructure (supply) in relation to the demand for travel. Restrictions imposed by such supply/demand imbalances affect the performance of the system as a whole. Analogous to the other two subsystems, not only internal but also external influences (both restricting and/or encouraging) affect decisions within the TS.

2.4. LUTI interactions

From the above described subsystems (AS, LUS, and TS), it becomes clear that two-way interactions occur when one subsystem influences the others. These influences (whether restraining or encouraging) affect the way decisions are made in each involved subsystem (Stead, Williams, & Titheridge, 2000), both on its supply and demand sides. For instance, decision-makers can select implementing additional lanes to a highway, or regulation restrictions to the number of commercial buildings in certain zones (supply); travellers may choose their transport mode/route, while families can decide whether to stay home or go out for dinner (demand).

Recognising the effects of restrictions on LUTI decisions is not a new idea. Van Wee (2002, 2003) defines both the elements that compose LUTI systems, as well as the importance of modelling travel behaviour as a way to connect them. Travel resistances, location of uses, and needs/desires for activities affect one another, and at the same time they affect travel behaviour (Figure 1).

We believe that LUTI modelling should not only account for travellers' behaviour, but also for the behaviour of other agents, such as people/firms who engage in activities, as well as those who choose locations to occupy with urban uses. Additionally, once agreed that LUTI modelling should incorporate the three cited subsystems, we believe the acronym should change to ALUTI, incorporating an "A" for activities. In summary,

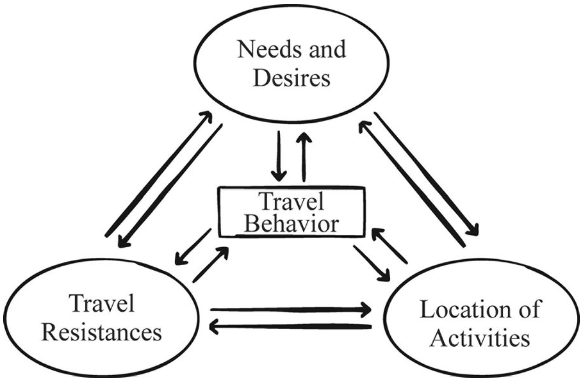

Figure 1. Subsystems that explain travel behaviour, adapted from Van Wee (2002).

decisions to be accounted for in the ALUTI system concern decisions on social and economic interactions (for AS), locational decisions (for LUS), and travel decisions (for TS). Henceforth, we assume that AS, LUS, and TS are the only subsystems under analysis in our conceptual representation of the urban system. The necessity to incorporate these three subsystems in ALUTI modelling resides in the fact that each one deals with different instances of decision-making, presenting distinct effects over the others. A non-exhausting list of examples for such effects is presented in Table 1.

Changes in transport infrastructure/services may have different effects on activity engagement and locational decisions - e.g. higher accessibility levels may generate land

Table 1. Examples of internal and external ALUTI relationships.

From \ To	Activities	Land Use	Transport
Activities	**Cause**: Shortage or surplus of jobs/ goods or services **Imbalance:** Unemployment/ wages and prices/ family planning **Effect**: Changes in income levels/ family sizes/ consumption levels	Changes in income levels/ family sizes/ consumption levels: **Affect LUS decisions**: Changes in residential or commercial location choices/ land values	Changes in income levels/ family sizes/ consumption levels: **Affect TS decisions**: Changes in trip destination, mode, and chaining choices
Land use	Changes in densities/land use mix: **Affect AS decisions**: Changes in activities engagement/ jobs creation/ production levels	**Cause**: Shortage or surplus of land/ floorspace stock **Imbalance**: Real estate prices/ housing shortage **Effect**: Densities changes/ land-use mix	Changes in densities/ land use mix: **Affect TS decisions**: Changes in trip destination, mode, and chaining choices
Transport	Changes in mobility and accessibility levels: **Affect AS decisions**: Changes in activities engagement/ jobs creation/ production levels	Changes in mobility and accessibility levels: **Affect LUS decisions**: Changes in residential or commercial location choices/ land values	**Cause**: Shortage or surplus of network capacity **Imbalance**: Congestion/ accidents/ gas emissions **Effect**: Changes in mobility and accessibility levels

Subsystems | Internal operation | External Operation price increase in certain areas of the city, while increasing or reducing specific activity levels and the distribution of people over activity locations (e.g. the distribution of households over dwellings). The ALUTI subsystems present their own internal operation, as well as external relationships with each other. The internal operation derives from the disparity between supply and demand, rendering measurable imbalances and potentially affecting supply or demand internal decisions. The external relationships derive from what we call “Impact Measures”, which are quantifiable changes in how a subsystem performs or how it influences the others.

Different urban dynamics (such as land-use changes, investments in the transport system, moves of people and companies) occur at different temporal scales (Wegener, Gnad, & Vannahme, 1986). Models need to be dynamic to adequately deal with such processes (Timmermans & Arentze, 2011). To be considered dynamic, models must encompass subsystems’ decision changes over time (Berechman & Small, 1988; Waddell, 2002) and recognise that these decisions occur in different timescales (Wegener, 2004). People generally make many travel decisions (within the TS) in a shorter time span than location decisions (winthin the LUS). Finally, decisions that do not involve spatial components (such as to participate in activities, within the AS) happen at an intermediate speed (Wegener et al., 1986). All three types of decisions can be influenced by their own subsystems’ changes in supply and demand, but also as an effect of the other two external decision processes, each at their own pace. As proposed by Wegener (2004), since the decisions continuously occur at different time scales, one cannot accept the idea of isolated influences between any pair of these decisions. One may infer that the urban subsystems are in constant process of adaptation (Hunt et al., 2005), meaning that not only the past performance of systems affect decisions, but also the expectations of future conditions.

A schematic representation of these systemic relations among the ALUTI subsystems is represented in Figure 2. We call it the a priori ALUTI conceptual model. This scheme represents all three subsystems and their internal operations, in terms of demand and supply interaction. It also represents the external relationships, described as impact measures between subsystems, showing the influences of each subsystem over the others.

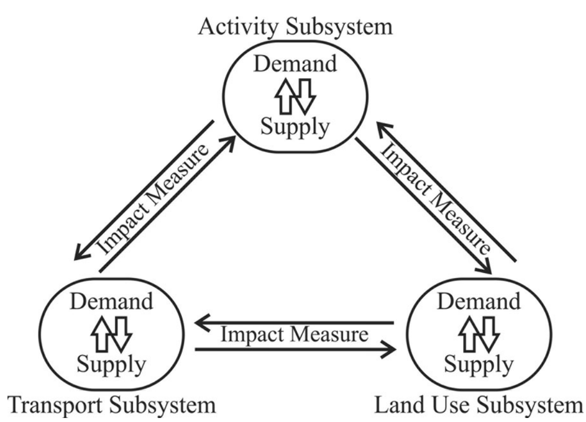

Figure 2. Proposition of an a priori ALUTI conceptual model, including the three subsystems, and their internal and external relationships.

We would like to point out that some current models and literature on activity-based LUTI modelling may fail to incorporate the integrated modelling of activity-based human behaviour, if they do not treat activity-based modelling as input for both land use and travel modelling, and vice versa. As illustrated in Table 1 and Figure 2, they should intend to predict locations and travel behaviour as derived from activities engagement, jobs creation, and production levels, as well as the other way around (Jovicic, 2001; McNally, 1997; Meurs & Van Wee, 2003). Therefore, the proposed a priori ALUTI model seeks to contribute to the understanding of activities, not simply as an input variable for transport demand modelling, but as a demand/supply mechanism with its own internal operation. Besides modelling the LUS (representing the land-use distribution) and TS (travel behaviour), the AS modelling intends to understand and represent the individual (as well as the collective) needs and desires (Arentze & Timmermans, 2009; Geurs & Van Wee, 2004) as part of a complex urban system. This kind of conceptual representation allows us to recognise not only the performed activities (those that finally happen in space), but also those that eventually did not happen due to some restrictions, as well as the ones that occur independently of generating travel demand or land occupancy.

3. Selection, analysis, and classification of LUTI models

This section presents the core of the LUTI models analysis. We organise it in three subsections, with separate analyses for each of the components seen in the a priori ALUTI model: firstly, we discuss subsystems incorporation into LUTI modelling (section 3.1); secondly, the subsystems' inner workings (section 3.2); and thirdly, the interactions between pairs of subsystems (section 3.3). Each subsection is further divided in topics contemplating the analysis from each subsystem's point-of-view (TS, LUS, and AS).

Based on previous LUTI modelling reviews (Acheampong & Silva, 2015; Iacono et al., 2008; Timmermans, 2003), we considered the existence of, at least, three main categories of integrated models: a) Spatial Interaction models; b) Econometric models; and c) Microsimulation models. The first category (spatial interaction) includes adaptations of Newton's gravitational model originating the Metropolis model (Lowry, 1964), considered to be the first integrated model (Batty, 1994; Wegener, 2004). For these models, the interaction between any two zones is proportional to the number of activities in each zone and inversely proportional to the friction impeding movement between them (Acheampong & Silva, 2015). Econometric models, including those grounded in random utility theory and econometric methods (Iacono et al., 2008), understand choices as a function of the attributes of available alternatives (multi-attribute combination), but are also subject to restrictions such as taking into consideration the non-observable attributes of alternatives, the differences between decision-makers' preferences, or uncertainties from the lack of information (Domencich & McFadden, 1977). Finally, disaggregate microsimulation models, seen as the current stage and immediate future of modelling (Arentze & Timmermans, 2003; Iacono et al., 2008; Wegener, 2004), intend to simulate behaviour at a very small scale, at the level of people (or households) and firms, all of which interacting and evolving over time (Miller, 2003). Although we recognise the limitations on any classification effort of LUTI models, we would like to point out that the three categories considered herein only serve as a base of comparison for the evolutionary stage of the reviewed models; therefore, there is no harm if different researchers classify some models in more than one group. For instance, URBANSIM, which Timmermans (2003) sees as an econometric model, Iacono et al. (2008) see as a microsimulator. Moreover, IRPUD, classified here as an econometric model, has also a microsimulation-based housing market submodel.

In our review effort, searching in SCOPUS and Google Scholar using "LUTI" and "Land Use Transport Interaction" as key terms, plus applying forward and backward snowballing techniques (Van Wee & Banister, 2016), we selected operational models that represent each of the three categories presented above. We only selected models if the documentation (articles, reports, etc.) allowed us to analyze the models according to our a priori ALUTI model. The chosen models were: LILT (Mackett, 1983), ITLUP (Putman, 1991) for the spatial interaction category; IRPUD (Wegener, 2011), TRANUS (de la Barra, 1989), MUSSA (associated with ESTRAUS model) (Martínez, 1996), and DELTA (Simmonds, 1999) for the econometric category; URBANSIM (Waddell, 2002) and ILUMASS (Strauch et al., 2005) for the microsimulation category. All information about the reviewed models was obtained via written documentation, as well as from email correspondence with the models' developpers. The authors of LILT, ITLUP, IRPUD, MUSSA, DELTA and ILUMASS replyed to our request for text confirmation and/or suggestions about how we interpreted their models, while the authors of TRANUS and URBANSIM did not react. A brief introduction to the selected models can be found in Table 2. Further explanatory introdution and comparison of advantages and disadvantages of each selected model, as well as other operational models, can be found in several publications (Hunt et al., 2005; Iacono et al., 2008; Kii, Nakanishi, Nakamura, & Doi, 2016; Pfaffenbichler, 2003; Silva & Wu, 2012; Timmermans, 2003; Wegener, 1995).

3.1. Involved subsystems

Before discussing the three subsystems individually, we note that two aspects of the reviewed LUTI models conflict with the a priori ALUTI model as presented above. First, the acronym LUTI indicates the interaction of only two subsystems, whereas we argue

Table 2. Brief introduction to the selected models (adapted from Iacono et al., 2008).

Model	Reference	Features
LILT	Mackett (1983)	Use of accessibility function; car ownership submodel; land use model capable of handling demolition, changing occupancy and vacancy rates
ITLUP	Putman (1991)	Software package for integrated modeling; robust network model with multiple modes; incorporates congestion effects in land use allocation
IRPUD	Wegener (2011)	Contains seven separate submodels; microsimulation of land use; use of differing spatial scales for submodels; separates discretionary and non-discretionary travel
TRANUS	de la Barra (1989)	Development supply model simulates choices of developers; sophisticated travel model with combined mode-route choice; travel demand derived from economic sectors relational matrices
MUSSA	Martínez (1996)	Incorporation of bid-rent framework for land, floorspace markets; detailed representation of transit network in travel model; high level of household type disaggregation
DELTA	Simmonds (1999)	Simulation of demographic changes; treatment of quality in the market for space
URBANSIM	Waddell (2002)	Land use model incorporating microsimulations of demographic processes land use development; parcel-level land use representation; high level of household type disaggregation
ILUMASS	Strauch et al. (2005)	Descendent of IRPUD. Incorporates microscopic dynamic simulation model of traffic flows and goods movement model; designed with environmental evaluation submodel

that the AS should also be included (Figure 2); second (and related), some authors (Cascetta, 2009; de la Barra, 1989; Meyer & Miller, 2001) assume that the LUS and AS are interchangeable terms, working as synonyms and representing one single subsystem. In this section, we also evaluate whether the LUS and AS are modelled separately.

3.1.1. Transport subsystem

We found transport modelling in the reviewed LUTI models to vary along two main lines. First, travel decisions can be modelled endogenously or exogenously (fed by external data or models). Second, models represent the TS as composed of either a single transport mode or multiple transport modes. In addition to these lines, the inclusion of freight travel decisions to the modelling can be seen as another important aspect.

Regarding the usage of such conceptual representations in operational models, it is noteworthy that DELTA, MUSSA, and URBANSIM seem to be the least developed with respect to transport decisions, as they rely on exogenous transport modelling. For instance, URBANSIM feeds external models with land-use data and receives input from these models, concerning transport decisions. All remaining models (LILT, ITLUP, IRPUD, TRANUS, and ILUMASS) assume decisions to be the result of travel decisons while influenced by transport LOS (level of service). Among the last five operational models, LILT, ITLUP and IRPUD focus solely on people transportation, while TRANUS and ILUMASS incorporate freight travel as well.

3.1.2. Land-use subsystem

Models see the LUS as composed of two parts. The first part is "land development" "in which the built form changes over time as land is developed and as existing buildings are modified or redeveloped over time. This is the process by which land use, per se, evolves" (Miller, 2003), which is either exogenously or endogenously modelled, implying that the models decide where new developments take place. The second part is "location choices" given the land development, in which all models incorporate in their modelling. The main observable differences among operational models rest upon the variety of urban functions considered in the modelling. Some models restrict its range to residences and work places, while others incorporate various uses. These conceptual differences, when combined, may render two possible classifications.

First, models dependent on exogenously modelled locational inputs cannot be fould. Other categories contain models that represent location decisions endogenously through different approaches, such as deterrence functions for households' location (LILT and ITLUP), or discrete-choice models applied to input-output matrices (TRANUS). The remaining models incorporate both location choices and land development through using other approaches, such as profit maximisation model (IRPUD and MUSSA), simulation of location and property market-like mechanisms (DELTA), multinomial logit model (URBANSIM), and microsimulation techniques (ILUMASS).

3.1.3. Activity subsystem

Modelling decisions on activities engagement differs along three lines. Firstly, models either incorporate activity decisions or not. Secondly, activity modelling may be limited to two types of activities (typically, "residing" and "working"), or they may include multiple activities; and thirdly, how actors choose activities to take part in. Models assume activity decisions to be either separate decisions (independent), or as a sequence of interdependent decisions.

The only model that does not include the AS is ITLUP, which only indicates employment levels of spatial zones. We recognise that all remaining models simulate AS decisions since they are able to differentiate the physical form of the city and its functions (e.g. housing and population who live in, jobs and workers employed by), as explained by Mackett (1983). These operational models use different tools to model the AS. While LILT, DELTA, and MUSSA use some form of activity-level indicators limited to two activities (to reside and to work), TRANUS see AS expressed by economic input-output matrices of multiple activities. Differently, IRPUD incorporates aging and processual submodels that recognise activity levels, as well as population aging and the subsequent changes in activity-engagement behaviour (Wegener, 2011). Some models incorporate several categories of activities (such as working, shopping, residing, and others) modelled separately, as IRPUD, or in sequence and derived from personal schedules (daily or weekly plans), which is the case of URBANSIM and ILUMASS. We summarised this whole analysis in Table 3.

3.2. Subsystems' inner workings

As explained in previous sections, the literature gives us reasons to believe that both LUS and AS could be modelled as demand/supply relations (de la Barra, 1989; Miller, 2003; Parker et al., 2012) similarly to mainstream transport modelling. Dealing with LUS and AS in terms of demand/supply relations is of researchers' and planners' interests for three reasons. First, to create models that are easier to understand, since we could describe LUS and AS in the same terms as the TS; second, to express clearly the balances/imbalances within each subsystem; and third, to measure the subsystems' performance. Next, we separately categorise both demand and supply features for each subsystem.

3.2.1. Transport subsystem

Two features constitute the modelling of transport demand. First, the nature of what is being transported (people and/or goods). Second, whether demand is modelled for

Table 3. Summary of subsystems involved in the modelling.

Modelling Decision		**Categories**		
		Spatial Interaction	Econometric	Microsimulation
TS	Exogenously modelled		④⑤	⑦
	Transport modes (people)	❶❷		
	Transport modes (people + freight)		❸❻	❽
LUS	Exogenously modelled			
	Location decisions	❶❷	❻	
	Location + development decisions		❸❹❺	❼❽
AS	Exogenously modelled	②		
	Separate multi activities	❶	❸❹❺❻	❼
	Sequenced multi activities (schedule)			❽

❶LILT ❷ITLUP ❸IRPUD ❹DELTA ❺MUSSA ❻TRANUS ❼URBANSIM ❽ILUMASS single trips (individual, single purpose travel) or tours (sequence of interdependent trips). Three of the reviewed models rely on exogenous transport modelling (DELTA, MUSSA, and URBANSIM); the others model transport endogenously. LILT, ITLUP, and IRPUD model people transport in terms of single purpose individual trips only. TRANUS does the same, but includes freight transportation. In contrast, ILUMASS models both people and freight transportation in sequential trips.

With respect to modelling of transport supply, the reviewed models vary along two lines. First, it concerns the inclusion or not of a modelled network, in terms of physical and operational characteristics; second, the modelling of the service characteristics (in terms of capacity, speed, etc.). Some models (DELTA, MUSSA, and URBANSIM) rely on exogenous transport modelling, while others model transport supply endogenously. ITLUP and LILT represent only a single network with capacity restraints. IRPUD, TRANUS, and ILUMASS permit the modelling of multimodal networks, if necessary, as well as their operational capacity. For instance, TRANUS can model different transport services (buses, trains, metro lines, and variations within these modes) as integrated networks.

3.2.2. Land-use subsystem

Models represent land-use demand in two ways. They focus on demand for land and/or demand for specific land uses given the supply, respectively resulting from "location" or "floorspace" choices. Location-based demand encompasses decisions related to land use changes; as opposed to floorspace-based demand, which focuses on the choices of specific land uses, given the supply. All reviewed models incorporate land-use demand modelling. LILT, ITLUP, MUSSA and TRANUS assume demand for floorspace (building stocks), while IRPUD, DELTA, URBANSIM, and ILUMASS assume demand for locations (land development and resulting building stocks per type).

The modelling of land-use supply quantifies the localised space availability. Models differ with respect to how to qualify such space. Some models represent "physical space" capacity (e.g. m^2); others model the supply of "organized space", defined by floorspace capacity, which may further require the definition of specific land-use functions (e.g. m^2 limited by zoning). The "organized space" can also be defined by building stocks (e.g. m^2 limited by zoning and aggregated in constructed units, such as flats, houses, etc.), which suggests stronger dependency on land-use development mechanisms and on time-consuming processes (buildings life span, demolition, etc.). From the reviewed models, LILT, ITLUP, and TRANUS depend on exogenous input of land and/or floorspace capacity and availability. Differently, DELTA assumes "floorspace capacity" as LUS supply, while IRPUD, MUSSA, URBANSIM, and ILUMASS adopt floorspace capacity plus building stock.

3.2.3. Activity subsystem

Two lines define demand modelling in the AS. First, models either limit the representation to two activities ('residing' and "working"), or they incorporate various activities. Second, if models recognise the demand for various activities, then there are two possible interpretations. Either they see them as resultant from aggregated interactions of economic sectors, or as the product of individual needs/desires (normally described as personal agenda or weekly/daily schedule). ITLUP does not incorporate activity modelling, depending on exogenous forecasts of employment, population, and activity rates (Hunt et al., 2005).

LILT, DELTA, MUSSA, and URBANSIM do model activity demands, but only in the number of employment and housing. IRPUD, TRANUS, and ILUMASS incorporate the modelling of multiple activity types. Moreover, the microsimulation model ILUMASS adopts an activity modelling approach based on schedules or individual agenda, modelled as sequences of demanded activities, their duration, frequencies, priorities, and preferred period of time (Strauch et al., 2005).

On the supply side, three reviewed models do not present any indication that the activity provision modelling occurs endogenously (LILT, ITLUP, and DELTA). We organised the remaining models in two categories. First, models that endogenously simulate the provision of housing and job posts, as is the case of MUSSA and URBANSIM. Second, models (IRPUD and ILUMASS) that represent the provision of various activities in terms of their limitations (quantification of offered jobs, goods, housing, public and private services, etc.), or through other tools such as the TRANUS' input-output production matrices. We summarised this whole analysis in Table 4.

3.3. Interfaces between subsystems

In their attempt to represent a complex system and its subsystems' interactions, LUTI models rely on measureable influences between the subsystems' composing parts. The called activity-based LUTI models describe how TS derives from people's needs and desires (as exogenous inputs), and how accessibility levels (as part of the TS) influences LUS development and location choices (Miller, 2003; Ortuzar & Willumsen, 2011; Wegener, 2004). These interfaces are simplifications of the mutual relationships between subsystems. Below we make explicit if such interactions are modelled and,

Table 4. Summary of subsystems' inner workings.

Models' internal operation			Models Categories		
			Spatial Interaction	Econometric	Microsimulation
TS	Demand	Exogenously modelled		4 5	7
		Single trip, People transport	1 2	3	
		Single trip, People/Freight transport		6	
		Tour, People/Freight transport			8
	Supply	Not endogenously modelled		4 5	7
		Unimodal Network	1 2		
		Multimodal Network		3 6	8
LUS	Demand	Floorspace (building stocks)	1 2	5 6	
		Locations (development+stocks)		3 4	7 8
	Supply	Not endogenously modelled	1 2	6	
		Floorspace Capacity		5	
		Floorspace Capacity+Buildings		3 4	7 8
AS	Demand	Exogenously modelled	2		
		Employment/housing related	1	4 5	7
		Multiple activities+Individual needs		3 6	8
	Supply	Exogenously modelled	1 2	4	
		"Jobs and housing" provision		5	7
		Level of economic activities		3 6	8

1 LILT 2 ITLUP 3 IRPUD 4 DELTA 5 MUSSA 6 TRANUS 7 URBANSIM 8 ILUMASS

if so, how models express them. We structure the argument along the lines of the outgoing arrows of each subsystem in the proposed a priori ALUTI conceptual model (Figure 2).

3.3.1. Transport subsystem

All reviewed models use accessibility indicators (e.g. travel time, generalised cost, etc.) to express the influence of TS on LUS. This corroborates what the specialised literature constantly affirms about the importance of accessibility measures to integrated modelling. On the other hand, concerning the impacts of TS on AS, if we assume that activities may be affected by time and money restrictions (Hägerstrand, 1970), we can see TS influencing AS due to (e.g.) time gains or money savings derived from transport decisions. This is true for IRPUD and ILUMASS. No direct TS indicator could be found with direct impact over activity decisions in any other reviewed operational models. One possible line of argument is that TS operates its influence over AS decisions through its effects on LUS, which does not change how we interpret this specific interface.

3.3.2. Land-use subsystem

The LUS' effects on other subsystems, as expressed by the reviewed models, are mainly based on land-use distribution patterns. The used variables relate to the relative locations of uses and to the availability of land/floorspace. In terms of LUS influencing TS, all reviewed models present some form of this interrelation. It is important to say that, even though some models (specifically MUSSA, DELTA and URBANSIM) rely on exogenous TS modelling, they still encompass and rely on how LUS affects TS decisions to guarantee that the modelling is integrated. The clearest LUS indicators that affect how TS is modelled are the relative distances and land-use mix, both derived from the relative spatial distribution of uses, which directly affect the definition of TS origins and destinations, amongst other decisions.

In terms of LUS affecting AS, almost all the reviewed models (LILT, ITLUP, DELTA, MUSSA, TRANUS, and URBANSIM) ignore any effects on activities general modelling. This is a result of either the complete lack of AS modelling by the reviewed models, or the interpretation of AS as a simple input provider for land use or transport modelling. The two remaining models (IRPUD and ILUMASS) deal with activities as limited by time and money constraints, as conceived by Hägerstrand (1970), or see LUS affecting AS in terms of the competition of activities for space (Simmonds, 1999), as many of the modelled activities are location dependent. These models consider values based on the spatial distribution of uses, meaning that opportunities for activities (limited by the restriction levels) result from the availability (quantity, concentration, affordability, etc.) of floorspace for specific location-based activities to happen.

3.3.3. Activity subsystem

The AS's influence on TS and LUS, according to the literature, is modelled via needs/desires for activities. Even though models are not consensual in explaining the variables and indicators for measuring such effects, we see that the reviewed operational models represent these needs/desires in two ways: as limited to the need, either for residing and working or for a larger number of activities, aggregated in economic sectors or discretized in personal

Table 5. Summary of interfaces between subsystems.

Modelling Decision (Between subsystems)			**Models Categories**		
			Spatial Interaction	Econometric	Micro-simulation
TS	TS→LUS	Travel Cost	❶❷	❹❻	
		Accessibility measures		❸❺	❼❽
	TS→AS	Not explicit in the model	①②	④⑤⑥	⑦
		Accessibility (travel times)		❸	❽
LUS	LUS→TS	Spatial distribution patterns	❶❷	❸❹❺❻	❼❽
	LUS→AS	Not explicit in the model	①②	④⑤⑥	⑦
		Spatial distribution patterns		❸	❽
AS	AS→TS	Not explicit in the model	①②	③④⑤⑥	⑦
		Agent-based activity interactions			❽
	AS→LUS	Need of employment/residence	❶❷	❸❹❺	❼
		Multiple needs per economic sector		❻	
		Multiple needs per individual			❽

❶LILT ❷ITLUP ❸IRPUD ❹DELTA ❺MUSSA ❻TRANUS ❼URBANSIM ❽ILUMASS

needs. From this interpretation, we can say that all eight reviewed models incorporate the effects of AS on LUS. On the other hand, concerning the effects of AS on TS, of the selected models, IRPUD and ILUMASS are the only ones that model such interaction. IRPUD adjusts discretionary activities (shopping and social services) to time and money constraints, while ILUMASS uses activity matrices (relating residential/non-residential origins and activity opportunities), from which trips are generated and distributed. However, as a limitation, these models' trip generation depend on location decisions, as opportunities for activities depend on the locations of origins and destinations, and the capacity of buildings (Wagner & Wegener, 2007). Otherwise, we could not see any direct indicator to represent such interaction in any of the remaining selected models. We summarise this whole analysis in Table 5.

4. Discussion

We believe section 3 thoroughly addressed the three research questions proposed in section 1, with our findings summarised in Figure 3, depicting how the components of the a priori ALUTI conceptual model, discussed in terms of the three subsystems' interpretation, inner workings and interactions, are incorporated into the eight analyzed operational models. Next, we comment on each research question's findings focusing on: (1) how a clear understanding of the distinct approaches to the conceptual representation and operational model structuring can help planners to more effectively bring knowledge about activities, land-use and transport interactions into the planning process; (2) how modellers can better communicate with planners to make modelling play a much stronger role, not only in the ex-ante assessment analytical effort, but especially in the problem comprehension phase of the planning process, helping establishing the bases for a more effective negotiation of the inherent stakeholders' conflicting interests.

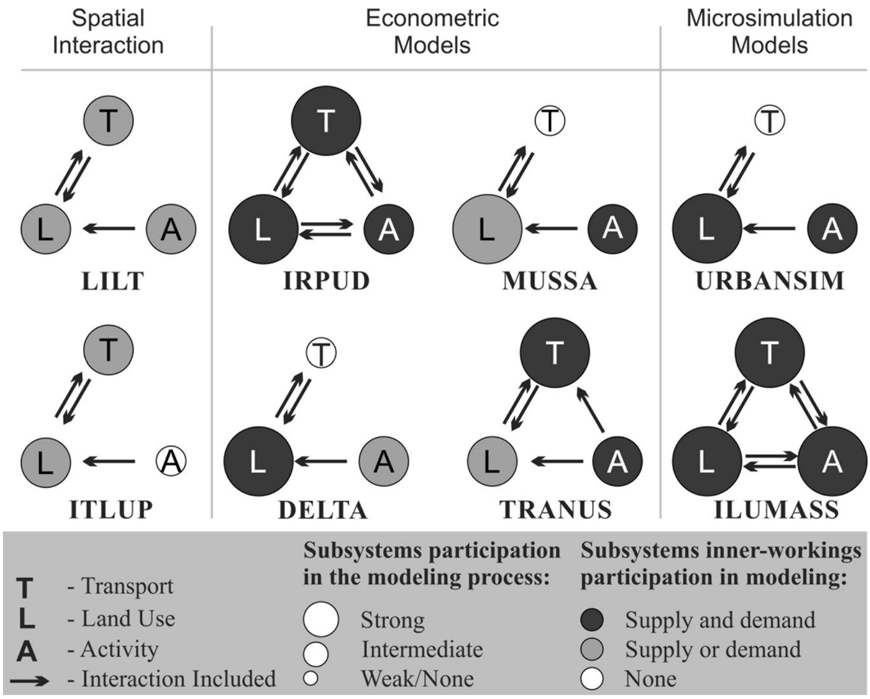

Figure 3. Synthesis of how operational models incorporate ALUTI subsystems' inner workings and interactions.

4.1. Incorporating the three subsystems

Findings, derived from the results in Figure 3, are that LUS seems to be well incorporated in LUTI modelling, as it is always strongly represented, as a more reliable subsystem, while AS and TS are frequently not fully taken into consideration. Moreover, not incorporating a subsystem into modelling means that either modellers ignore its existence, or they rely on exogenous source of information. From a LUTI perspective (assuming the existence of only TS and LUS), two situation arise. Alongside the well-incorporated LUS, to have TS incorporated in a well or rough manner means the possibility to develop strong or loose-coupled models, respectively. This is because the first step towards strong-coupled modelling is the recognition of the subsystems that constitute the system under modelling. From an ALUTI perspective (assuming the three subsystems), the same idea of loose or strong-coupled modelling applies in respect to the AS.

Having a strong-coupled modelling development implies that more disciplines should be effectively incorporated to the conceptual framework of planning, resulting in a much-desired multidisciplinary approach. For modellers, incorporating more subsystems potentially gives them more information so they can convince planners of how useful models are. Greater complexity demands a more structured and objective way of thinking, which models may provide. Furthermore, this more comprehensive modelling effort should permit (but does not guarantee) a better-integrated model that accounts for more aspects of reality; rather than a framework that ignores one or other subsystem.

4.2. Modelling the subsystems' inner workings

Inexistent or weak modelling of subsystems' inner workings makes it harder for planners/modellers to measure a subsystem's performance. This measurement depends on models being able to recognise the subsystems and its inner parts (i.e. demand/supply imbalance). It is important to realise that models do not always properly describe how demand/supply interactions occur, or if they generate performance measures. While measuring TS performance can be seen as a standard procedure, the same cannot be said about the other two subsystems. From a LUTI perspective, many models neglect to measure LUS performance, even when they effectively incorporate TS performance as a central aspect for problem's characterisation and diagnosis. From an ALUTI perspective, to not model AS performance means to ignore how decisions within the whole system affect AS as no evaluation tools are available.

A reliable representation of subsystems' inner workings would help planners to understand problems, to be able to characterise them (adopting specific indicators), as well as to decide on how to intervene in the system (performance comparison), even if they would not see performance as measured in terms of demand/supply imbalance. From a modeller's perspective, to be able to assess performance for all involved subsystems would allow to generate indicators to characterise and diagnose problems in a more objective way. It would also make it easier to convince planners that operational models help in decision-making processes since comparing performance of complex phenomena requires the adoption of more systemic and objective approaches.

4.3. Recognizing interactions between subsystems

As shown in Figure 3, models have difficulties in recognising direct interactions between AS and TS, as most models present no indicators. We believe this difficulty results from some models' poor interpretation of the AS. The exceptions are the TRANUS, which represents AS affecting TS, and IRPUD and ILUMASS, which recognises trip generation from agent-based activity interaction matrices. From a LUTI perspective, the common practice is to incorporate both directions of mutual influences between TS and LUS. Differently, from an ALUTI perspective, models often do not include the mutual relationship, but only include a one-direction relationship, from AS to LUS (with the exeption of IRPUD and ILUMASS models). A single-arrowed relation means no feedback cycles. Subsystems in the back-end of an arrow depend on external inputs to present any changes. Finally, relations between TS and AS seem to either bare little importance or are difficult to model (possibly because of its non-spatial dimension), as only two of the reviewed models indicate a feedback cycle between these subsystems.

Planners could benefit from recognising more interactions between subsystems as it allows for a better understanding of systems' dynamicity. This means higher level of integration and more feedback loops. By assuming more interactions, planners expand the range of possible interventions they can evaluate, while modellers should be able to get closer to the complexity of reality (where changes in one subsystem might have difficult-to-predict effects on other subsystems). Measuring impacts between subsystems (as a quantification of those interactions) may help modellers in the assessment of mutual effects between subsystems, allowing them to objectively recognise non-obvious relations. Despite their differences and limitations, all reviewed models assume dynamic or quasi-dynamic influences among the participating subsystems (Simmonds, Waddell, & Wegener, 2011). Even those that depend of external inputs (such as MUSSA, DELTA, and URBANSIM) explicitly include and model time dependent decisions and the different temporal scales at which such decisions are made in each subsystem. Two observations are worth highlighting. All the reviewed models show that TS modelling is based on the premise of supply/demand equilibrium (for ILUMASS, we could only recognise this premise for the assignment phase). Second, models see time scale in terms of different discrete intervals for each subsystem, meaning no continuous modelling.

We realise that a more communicative, comprehensive, and dynamic model might as well be more data-hungry, and researchers need to overcome related barriers. Recent and future developments in the are of ICT (Information and Communication Technologies) and big-data, together with related analytical tools and techniques, such as data-mining, machine learning and statistical analysis, to name a few, might reduce such barriers. Moreover, if modellers incorporate the AS in ALUTI modelling, data generated by ICT based social networks might become more important. Both modellers and planners might benefit from the use of such data. Modellers might benefit from the datasets allowing them to better calibrate and validate models. Note that big data also raise concerns, but it is beyond the aim of this paper to summarise the related debates. Planners might benefit from the better quality of LUTI models, and consequently the input for decisions to be made.

5. Research recommendations

For all the reasons given in section 4 at least five recommendations for future research should be considered. First, models should explicitly include the AS, if we aim for more complex, integrated and dynamic models. Secondly, concerning the LUS, models should both represent supply (in terms of spread of land-use categories over space), as well as demand (location choices within a given land-use pattern), so that we may be able to better model the phenomenon at hand, and, therefore, be able to estimate performance measures. Third, interactions between subsystems should be made explicit so that the model may represent some level of reality's dynamicity. Fourth, documentation of models should be improved, at least at the conceptual level, to clearly express the model's structure, so we know which output of a submodel is input for another. Fifth, the ALUTI modelling community should ponder about the lack of recent activity in the field of operational models. Because of insuficient documentation or lack of peer-reviewed publications, no recently developed operational models made it to this review, as other models, such as MARS (Pfaffenbichler, 2003), ILUTE (Salvini & Miller, 2005), and PECAS (Hunt & Abraham, 2005) to name a few, were considered, but still, they debuted more than 10 years ago.

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