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Maintaining Mobility in Substantial Urban Growth Futures

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Abstract

Integrated land use/transport models traditionally follow a simple integration concept: The land use model provides the origins and destinations of trips, and the travel demand model provides aggregate travel times between zones. High levels of congestion and the limitation of travel budgets, however, require travelers to scrutinize travel options and housing locations more carefully. In this paper, a microscopic integration of land use and transport models is proposed that – for the first time – is capable of capturing travel times and constraints at the level of the individual traveler. This level of integration allows choosing housing locations from which workplaces of all household members are accessible. In addition, discretionary travel can be limited to a household's travel budget after mandatory trips have been completed. The model is expected to represent travel and housing location choice constraints more realistically under high congestion/high cost scenarios.

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Keywords: Travel demand modeling, land use modeling, integrated modeling, scenario analyses, alternative modes of transportation

1. Introduction

Over the last decade, large metropolitan areas in Germany have switched back from shrinking places to growing cities, where housing costs rise and developable land to accommodate growth becomes rare. In addition, since 2015 Germany experienced substantial immigration of asylum seekers. Some metropolitan areas have been pushed to the

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limits of their capacity, both in terms of available housing and in terms of maintaining an efficient transportation system on a network that was congested even before immigration rose.

At the same time, new transportation technology is at the horizon that may overhaul the way cities are built and organized substantially. With rising telework, housing location search becomes independent of workplace locations. Taxi-on-demand services provide easy and almost immediate access to transportation services. Car-sharing offers car availability even to low-income households or those households who do not have the space to park a car. And autonomous (sometimes also called self-driving) vehicles provide individual mobility that is less onerous, as drivers may work or watch a movie while traveling in a personal vehicle.

The impacts of these new transportation technologies are largely unknown. While autonomous vehicles may provide additional mobility to elderly and young travelers, effortless travel may induce additional trips and longer trips. Autonomous vehicles may also solve the last-mile problem for transit, but such vehicles are also expected to compete with transit. Some households may choose to move to the suburbs if autonomous vehicles provide almost effortless travel into the city, while other households may decide to move back into the city as the necessity for parking is eliminated with shared autonomous vehicles. While the impact of new transportation technologies is likely to be a mix of these effects, most transportation scientists agree that these technologies will significantly alter how we travel as well as how our cities will be organized. Sometimes, autonomous vehicles are even called the third major transportation revolution, equal in impacts to the arrival of rail in the 19th century and the widespread availability of the automobile in the 20th century.

2. The land use/transport feedback system

While the land-use system is concerned with the locations where people and commercial entities perform their activities, such as sleep, eat, work, production or leisure, the transport system is concerned with how people and goods are moved between these locations. There is interaction between these two systems: new housing may be easiest to build at the outskirts of existing cities, but then the transport system has to react by connecting these areas to the rest of the system; conversely, a congested transport system can limit further land-use development. This relationship has been explained in more detail by Wegener and Fürst (1999) as the land use/transportation feedback cycle (see

Figure 1). While the transport system affects accessibilities, and thereby makes certain areas more attractive than others, the land use system defines trip origins and destinations, and thereby affects the transport system (for definitions of accessibility see Section 3.3).

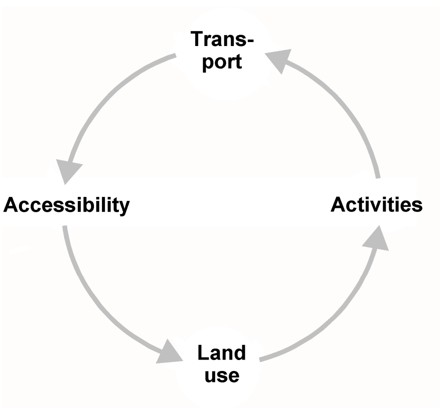

Figure 1: Land use/transport feedback cycle (Wegener and Fürst, 1999)

The influence of accessibilities on land-use decisions has also been described empirically (Hansen, 1959; Kreibich, 1978). Timmermans (2007), in contrast, shows empirical evidence that the link between the transport and the land-use system may be weaker than expected. Simulations (Nicolai, 2013: Chapter 5.4.2) show that better accessibility of locations is sometimes compensated for by higher prices, resulting in the effect that accessibility quite often is not a very significant factor when estimating location choice models based on empirical data (Lee et al., 2010). This, however, does not mean that accessibility would not play a role; it only means that accessibility gains are soaked up through price increases by the land owners.

3. A short history of integrated land use/transport modelling

This section provides a brief introduction into the state-of-the-art in integrated land use/transport modeling. Comprehensive overviews on existing integrated land-use/transport models were provided by Wegener (1994; 2004), the U.S. Environmental Protection Agency (2000), Timmermans (2007), Hunt et al. (2005) and Acheampong and Silva (2015).

3.1. State-of-the-art in integrated land use/transport modeling

The first integrated land use/transport model was built by Herbert and Stevens (1960) in cooperation with Britton Harris as an equilibrium model. Lowry (1964) built the Model of Metropolis to generate an equilibrium between land use and travel times. Wilson's Entropy Model (Wilson, 1967) generated an equilibrium by maximizing entropy of trips, goods flows or the distribution of population. Based on the Lowry model, Echenique et al. (1969) developed the MEPLAN model, applying systematically the bid-rent approach (Alonso, 1964) to land use decisions. Models similar in concept include TRANUS (de la Barra, 1989), MUSSA (Martínez, 1996) and PECAS (Hunt and Abraham, 2003). All these models are equilibrium-based, offering the benefit that land prices are an endogenous output of the model. A shortcoming of equilibrium models, however, is the assumption of complete information, leading to model results that are “more perfect” than reality.

Discrete choice models, on the other hand, try to mimic decisions made by travelers, households and developers that lead to urban development, rather than assuming a perfect equilibrium from the outset. Commonly, discrete choice models apply logit models (Domencich and McFadden, 1975) to account for the uncertainty behind decision making. Important integrated models using the discrete choice approach include IRPUD (Wegener, 1982a), DELTA (Simmonds, 1999) and the Dallas/Fort Worth Model (Shukla and Waddell, 1991).

Microsimulation, first proposed by Orcutt (1960) for demographic models, has been applied for integrated land-use/transport models in CUF (Landis and Zhang, 1998a; Landis and Zhang, 1998b), ILUTE (Miller and Salvini, 2001), UrbanSim (Waddell et al., 2003), and IRPUD (Wegener and Spiekermann, 1996), ILUMASS (Strauch et al., 2005; Moeckel et al., 2003), among others.

3.2. Model complexity

A well-known critical paper by Lee Jr. (1973) has reminded modelers to focus on models that are operational and can be used in policy analysis, rather than building extremely complex models that may never reach maturity to be applied. Wagner and Wegener (2007) proposed that too many model developers start with a big model design that includes all "bells and whistles" that can be imagined, making the system too complicated to be implemented within common project runtimes. They criticize that model developers notoriously underestimate the complexity, and therefore, tend to overdesign models that too often do not become operational. The land use and transport modeling community has responded with the paradigm of Agile development (Donnelly, 2010), a concept common in computer science that starts with simpler models and gradually adds complexity. The Agile paradigm forces the developer to have an operational model at any point in time.

Wagner and Wegener (2007) also discuss problems of software integration and computational difficulties based on their experiences with the ILUMASS (Integrated Land Use Modelling and Transportation System Simulation; Strauch et al., 2005) project. Eight years later, Nicolai and Nagel (2015) report limited success with a similar approach, this time using the MATSim (Multi Agent Transport Simulation; Balmer et al., 2009; Horni et al., 2017) software as a travel model plug-in to UrbanSim (Waddell, 2002). In this case, the complexity of the resulting model system was still rather large because MATSim and UrbanSim are written in different programming languages.

3.3. Accessibility

Accessibility is both a quantity that is often used as an explanatory variable in location choice modelling and a quantity that is interesting for analysis in its own right. Accessibility can be seen as the result of the following four components (Geurs and van Wee, 2004):

1. A land-use component that deals with the number and spatial distribution of opportunities.
2. A transport component, which describes the effort to travel from a given origin to a given destination.
3. A temporal component, which considers the availability of activities at different times of day, for example in the morning peak hours.
4. An individual component that addresses the different needs and opportunities of different socioeconomic groups.

A fairly generic approach is to define the accessibility A of a spatial location i as

$$A_i = g\left(\sum_J s_j^\alpha \cdot f(c_{i,j})\right)$$

where the sum goes over all destinations j (such as workplaces or households), $f(c_{i,j})$ is a decreasing function of the generalized cost $c_{i,j}$ of travel from i to j, s_j^α is an indicator for the attractiveness of location j emphasized (or deemphasized) by the parameter α, and g is an arbitrary, but typically increasing function.

A variant of this formulation is the logsum term,

$$A_i = \frac{1}{\mu} \cdot ln \sum_J s_j \cdot exp(-\mu \cdot c_{i,j})$$

which can be seen as a distance-digressive averaging, but also has an economic interpretation as the expected utility of location i under some conditions (Train, 2009). Accessibilities are the most common variable used in land use models to account for the impact of the transportation system on location choice.

4. Microscopic integration of land use/transport modeling

Households looking for a new place to live try to optimize a number of location factors. The dwelling should be of high quality yet affordable, the neighborhood should be appealing, and travel times to work, shopping locations and friends should be within a reasonable range. In integrated land use/transport modeling, this has been solved traditionally by optimizing user benefits (bid-rent approach, compare Alonso (1964)) or satisfying maximum utility expectations (discrete-choice approach, compare Domencich and McFadden (1975)).

In reality, however, location choice is much more driven by constraints than commonly represented in existing models. The household income strictly limits the budget available for housing, travel times to work or school firmly limit the region for housing search (except for regular teleworkers), and should transportation costs reach the high levels predicted since years (e.g., Goodstein, 2005), total transportation costs at a housing location will become another constraint for location choice.

A shortcoming of existing approaches is that integrated land use/transport models work with aggregate travel time or travel cost matrices, providing the same travel times, costs and distances for every household. In reality, however, a worker who commutes at 5:00 AM experiences a different level of congestion and different transport mode options than a commuter going to work at 8:00 AM. Workers who regularly telework may not be too concerned about travel times between work and home at all, and choose housing locations independent of work location. The impact of travel options on accessibility becomes even more complex for households with multiple workers. Existing aggregate approaches are unable to account for individual travel experiences. This research will overcome this gap by linking land use and transport time microscopically. Policy analyses, such as testing the impact of zoning, transportation infrastructure or pricing alternatives, will turn from aggregate approximation to a behaviorally rich representation of individual decision making.

In this research, a tightly coupled integrated land use/transport model is developed. To account for the land use/transport feedback cycle, the land use model provides the location of households and employment to the transport model, and the transport model provides travel characteristics (such as travel times, distances or costs) to the land use model. By representing the land use/transport feedback cycle explicitly, the modelling system is able to provide more realistic sensitivities to model policies that affect land use or transport.

For the first time, this integration of the land use and transport models is accomplished microscopically. Instead of providing aggregate values that are averaged across many users, microscopic values are exchanged that are actually experienced by individual users.

5. Model implementation

The integrated land-use/transportation model described in this paper consists of the land-use model SILO[†] (Moeckel, forthcoming) and the transportation model MATSim[‡] (Balmer et al., 2009). Both models work microscopically, and therefore, handle households and persons individually.

5.1. SILO

In SILO, the demographic development of households (including aging, marriage, birth of children, children leaving the parental household, divorce, death, and others) is modeled on a year-to-year basis from 2000 to 2050. A household relocation module simulates housing search with a series of logit models. A developer model simulates investment decisions of developers who build new residential floorspace if demand is high. Housing renovation, deterioration, demolition and price adjustments are modeled as well by the developer model. **Fehler! Verweisquelle konnte nicht gefunden werden.** lists all events that are modeled in SILO.

The model implements a synthetic population for the study area. A synthetic population is a long list of households, where each row represents one household. Household attributes, such as income, car ownership or housing location, are provided for each household individually. A synthetic population is not a replication of the actual population, but rather a statistically equivalent representation of households in the study area. While individual households of the synthetic population do not exist in reality, the aggregation of synthetic households matches the observed number of households in many dimensions, including households by income, by car ownership, by size, etc. For SILO, four synthetic datasets are developed and linked, namely households, persons, dwellings and workplaces.

Table 1. Events modeled in the land use model SILO

Household	
• Relocation	• Buy or sell cars
Person	
• Aging	• Divorce
• Leave parental household	• Death

† for more information on SILO see www.silo.zone
‡ for more information on MATSim see www.matsim.org

	• Marriage		• Find a new job
	• Birth to a child		• Quit a job
Dwelling			
	• Construction of new dwellings		• Demolition
	• Renovation		• Adjust housing price
	• Deterioration		

At the beginning of every simulation period, events are created that are executed in random order. Somewhere, a child is born, someone else celebrates her birthday, elsewhere a new dwelling is built, some people get married, etc. By executing events in random order, artificial path dependency is avoided while events may affect each other as they do in real life. For example, the birth of a child often triggers a move to a larger apartment or a single-family home. Attention is given to maintaining fast runtimes to ease many model applications. Initial tests show that the model runtime of SILO is about 1½ hours to complete 50 years for the study area described in section 5.3 (excluding the transport model).

5.2. MATSim

MATSim is a framework for large-scale agent-based transport simulations. The basic principles are similar as in SILO except that they operate on a much shorter time scale: Travelers are modeled individually throughout a typical day. Each traveler at some point in time leaves her/his first activity location, follows a – typically multi-stage – trip to its second activity location, performs that activity, etc., until eventually the day is over. This is called the mobility simulation, or mobsim. In contrast to SILO, MATSim assumes (noisy) equilibrium conditions, which are approached by repeating the simulation of this typical day over and over again, while the synthetic travelers try out various travel options until they eventually settle at the one that returns the highest benefit. In other words, a typical MATSim run iterates between the mobsim and a mental step where the synthetic travelers evaluate and memorize past synthetic experiences, come up with new travel options, or choose between memorized travel options.

For the current project, we take for each synthetic person her/his residential location, her/his status (employed, in education, other), and her/his workplace/education location (if applicable) from SILO. This is used to generate, as a first step, home→work/education→home plans for each synthetic person where this is applicable; these plans are then used as a starting point for iterations as discussed in the previous paragraph, again using route choice as the only choice dimension in this first step. For the time being, it will be assumed that a MATSim run, including iterations, will be performed once per SILO model year; see Section 6 for how already this can be put to use for much more detailed queries than possible in the past by the land use model.

This is conceptually still the same as for the MATSim-UrbanSim coupling as reported by Nicolai and Nagel (2015), but technically considerably simpler since both SILO and MATSim are written in Java. For preliminary results, see Ziemke et al. (2016).

From there on, the travel model plugin will undergo a number of improvement steps, at least into the following directions:

- *Full activity patterns.* An activity-based demand generation model will be used to extend the home→work/education→home activity patterns to additional activity types such as shopping or leisure.
- *More choice dimensions.* Besides routes, synthetic persons will be allowed to try out different modes of transport, different departure times, and different locations for their "secondary" activities.

As stated, these elements will be included one by one, as they are needed either by the land use model or by the case study under consideration. It is our experience that home→ work/education→home activity patterns are already sufficient to generate plausible commuting traffic patterns.

5.3. Study area

The modeling suite is implemented for the Munich Metropolitan Area in Southern Germany. To capture population shifts and traffic flows both at the intercity and the intraregional level, the city of Munich and the surrounding suburbs and hinterlands are included in the study area. To delineate the study area, commute data was examined to approximate the region that is closely connected to the city of Munich with regular commute flows. Analyses showed that the five main urban centers in the area, namely Munich, Augsburg, Ingolstadt, Landshut and Rosenheim, have high commuter flows among each other. In particular, higher costs of living in Munich have triggered households who work in Munich to live in other main cities in the region and commute every day. Municipalities in southern Germany, from which at least 25% of its workforce commute to one of the five main cities were included in this study area. Some rural municipalities from which fewer than 25% of its workforce commute into one of these five main cities were included as well to create a somewhat smooth boundary of the study area.

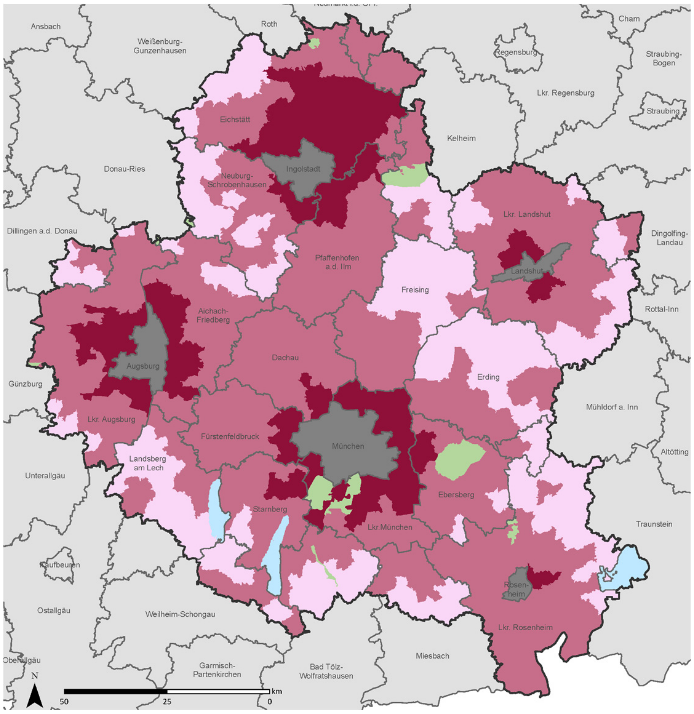

Figure 2: Study region of the Munich Metropolitan Area

5.4. Application

The integrated land use/transport modeling system shall not remain an unproven theoretical concept, but rather a model that has been stress-tested with real-world applications in Munich. Policy scenarios that are likely to be faced by public agencies as well as idealized (and maybe politically unfeasible) scenarios that show actions needed to achieve certain goals will be tested. By providing a series of scenarios, the reasonableness of model sensitivities can be assessed, and the plausibility of model results can be established or rejected.

To demonstrate the policy sensitivity of the SILO/MATSim modeling suite, it is planned to implement at least the following scenarios:

- Absorb population increase (including refugees) into the normal urban fabric within Munich, accepting higher housing prices due to increasing demand.
- Absorb population increase into one location with large-scale new construction inside the city limits, possibly by conversion of parts of the commercial area (Gewerbegebiet) near Ostbahnhof from industrial use to housing or by converting greenfield areas near the former airport Munich Riem into housing.
- Absorb population increase into traditional suburban fabric outside city limits, fostering growth of smaller surrounding cities.
- Absorb population increase into one large-scale satellite city outside city limits, possibly testing a purely auto-accessible site in Forstrieder Park between Starnberg and Munich and a transit-accessible site near Eglharting between Rosenheim and Munich.
- Impact of long-distance bike trails in the Munich Metropolitan Area. The Planungsverband Äußerer Wirtschaftsraum München intends to implement bike trails free of general-traffic street crossings to entice commuting by bike.

The integrated land-use/transportation modeling suite will be used to test alternative, and sometimes dramatically different, future developments. Scenarios will include both massive population growth as well as the introduction of new transportation technologies. Such scenario analyses will allow to assess the impact of population growth on our transportation system. It will also be analyzed how new transportation technologies may alleviate congestion.

6. Microscopic model integration

Traditionally, the integration between land use and transportation models is done in a rather simple way: The transportation model provides travel times (and sometimes travel distances and costs) that are used in the land use model to calculate accessibilities, which in turn affect land use decisions. Vice versa, the land use model provides the location of households or persons and firms or jobs, which are used in the transportation model to derive trip origins and destinations. This rather simple integration has been accomplished for more than four decades (such as Echenique et al., 1969; Wegener, 1982b; Putman, 1983; Waddell, 1992). It is, however, too simple for many current policy questions. More generally, Badoe and Miller (2000) state that “studies have worked with zonal-aggregate variables for gross spatial units ... thus clouding the effects ...", and “other studies have not considered any variables of transit supply". They “strongly recommend using an integrated urban model".

Most commonly, land-use and transportation models are coupled by using accessibilities. As both SILO and MATSim work microscopically, this model setup allows considering actual travel times experienced by individual people. For example, a worker who leaves for work at 10 AM will see a different level of congestion and modal options than a worker who needs to report to work by 8 AM. Regular teleworkers may disregard travel time to work entirely. Another worker who commutes by bus will only consider transit travel times while auto travel times are mostly irrelevant. Travel time to work is an actual constraint in housing location choice. The individually experienced travel time can be considered in household relocation in SILO. This microscopic linkage between SILO and MATSim is expected to better represent actual constraints households face in housing search.

The approach presented here goes beyond existing approaches by allowing the land use model to query the travel model for individual people (compare Figure 3). To evaluate whether travel time to work is a trigger for household relocation, actually experienced travel times, costs and mode choice logsums of all workers in that household are evaluated. If a household decides – for whatever reason – to look for an alternative housing location, the travel model will be queried for each potential residence about the travel effort to and from work by the various modes of transport for all workers in the household. Instead of providing aggregate (or averaged) travel time matrices, this integration will allow to represent individual travel times. This is straightforward to do since the travel model, by its co-evolutionary approach, is already designed to consider each synthetic traveller’s options individually. If more precise answers are needed, the so-called pseudo-simulation approach (Fourie et al, 2013) could be used, which runs synthetic persons through a simplified version of the mobsim without re-computing the congestion effects. Providing individual travel times will help representing actual transportation constraints experienced by households when relocating.

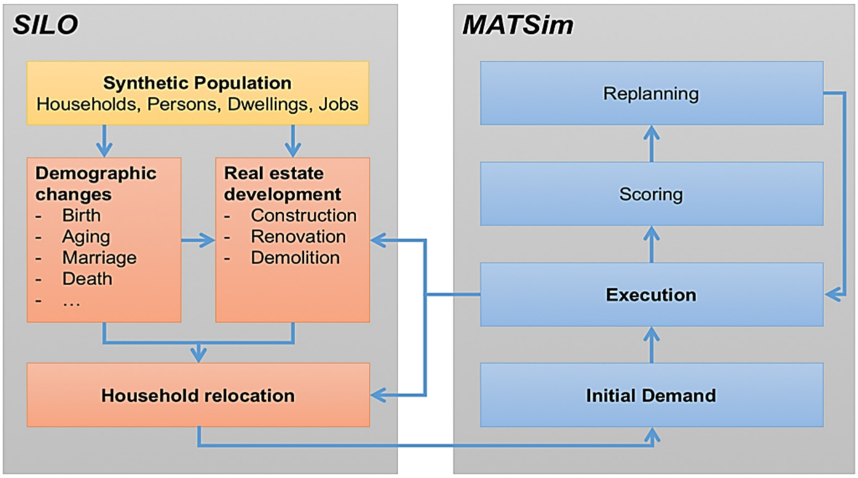

Figure 3: Integration of the land use model SILO with the transport model MATSim

Likewise, auto availability will be accounted for explicitly. If one worker takes the only car owned by a household to work, another worker in this household will be limited to non-motorized modes and transit. MATSim will provide travel time, distance and costs for available modes only, providing a more realistic choice set. This tight integration will lead to a more realistic representation of travel demand and congestion, and thereby, provide better input for modeling household relocation.

7. Conclusions

The integration of SILO and MATSim presented in this paper is the first implementation of a microscopic integration of land use and transport models. Instead of aggregated travel times and distances, actually experienced travel times, distances and costs of households in the synthetic population are used to model household relocation.

This paper focused on the information transfer from the transportation model to the land use model. However, the reverse direction is equally important and envisioned for this integration as well. A microscopic trip generation model (Moeckel et al., 2015) has already been linked to SILO, and a microscopic model to estimate travel time budgets for every household (Moreno and Moeckel, 2016) is under development. A microscopic destination choice model is envisioned to only select destination for each trip that are within the households travel time and monetary budgets. Mandatory trips, i.e., trips to work and school, are modeled first based on the home, work and school locations that have been set in SILO. The remaining travel time and monetary budget will be used to select destinations that are within the budgets modeled for every household. This approach will allow to account for constant travel budgets (Zahavi, 1974) that are remarkably constant across the aggregate of the population in a study area.

The microscopic integration described here is a required step to rigorously account for constraints in housing location choice, activity destination choice, mode choice and route choice. To the best of the authors' knowledge, this is the first implementation of such a tight and person-centric integration between land use and travel models. Under scenarios of increased congestion and increasing energy prices, such constraints will become even more important in the future.

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