The Development of a Unified Modeling Framework for the Household Activity-Travel Scheduling Process

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The goal of this paper is to propose a new approach to activity-travel schedule modeling that provides a unifying framework for past research in different areas. This approach is based on empirical evidence gathered using a Computerized Household Activity SchEduling (CHASE) survey. The survey provided a means to examine the underlying scheduling behavior of household over a one week period as it occurs in reality. Results show that a clear distinction can be made between routine scheduling decisions that are pre-planned before the week commences, and the more short-term, impulsive, opportunistic decisions made as the schedule is executed during the week. This distinction allows one to conceptualize the modeling task as a multi-stage process, wherein routine planning is approached with existing optimization models (assuming that routine activities are the result of a long-term thought and experimentation process) followed by a more sub-optimal rule-based simulation model to replicate the decisions process during the week within the constructs of the optimal routine plan. Such a model is proposed in this paper as a long term development, and would rely on the type of data provided by new data collection techniques such as CHASE. Operationalization of the model as an event-oriented simulation is proposed. Various components of the model are explored in detail, and discussed within context of existing models.

1 Introduction

Activity-based approaches to travel analysis have made extensive contributions to the understanding of travel behavior and the likely impacts of social and policy changes. The 1970s saw the initial development of the theoretical framework for viewing travel as part of an activity-based framework, whereas the 1980s saw major advances in methodology, particularly model development, as well as initial application of models to policy analysis. The early nineties have seen important contributions to the development of modeling techniques which have become more operational but require further validation and unification before they are fully applied in practice.

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The major impetus for this research is a need for improved models to assess the impact of travel demand management policies that have emerged as the focus of transportation policy. These needs have led to the development of models of specific aspects of activities, and more recently to the modeling of entire activity-travel patterns or "schedules".

Models of Activity-Travel Schedules

Activity-based models have sought to replicate one or more of the four basic dimensions of activities: i) activity choice; ii) duration (over what time periods); iii) location; and iv) sequencing (i.e. when they take place, in what order, and with what frequency). Many of the first models sought only to replicate certain dimensions, such as time allocation to activities. Later models incorporate all dimensions within their model in an attempt to replicate the way individuals and households arrive at a total activity pattern in time and space. These are often grouped under the heading of activity "schedule" models, since a schedule of activities embodies all four of these dimensions.

Many different categorizations of activity scheduling models have been made and discussed in the literature (for more thorough reviews see [1, 2, 3]). Two important dimensions of these models are 1) whether the modeling approaches are static in nature (i.e. estimate activity patterns *simultaneously* in one step) or *sequential* (i.e. step-by-step structure), and 2) whether they adopt an *econometric* (e.g. utility maximization and optimization) or *rule-based* psychological approach (i.e. sub-optimal, satisficing style rules) to model development. Distinctions are also made between theoretical versus operational models, the latter being exclusively based on observed data.

Previous modeling efforts have relied mainly on the traditional utility maximization framework to replicate specific aspects of the scheduling process in limited combination or to capture the static choice of an entire daily activity schedule. Three basic approaches have been adopted. The first is to model the sequential choice of activities and locations to add to a sequence/pattern of activities and travel (e.g. [4, 5], and [6]). Conventional logit type models are used to predict the choice(s) conditional on the characteristics of activities/locations that proceed and follow the given choice. A second approach focuses on the simultaneous choice among a set of activity-travel sequences/patterns, rather than on their sequential construction (e.g. CARLA [7], STARCHILD [8, 9], and [10]). A third approach that represents a mix of the sequential choice of pre-defined patterns is the tour based nested logit model developed by Bowman et al. [2, 11, 12].

However, the behavioral validity of the utility maximization framework as a description of how people actually make decisions has continuously been questioned [13]. Criticisms focus on assumptions regarding full information and the capacity of individuals to determine optimal solutions. Specifically, the main criticism of simultaneous schedule choice models is the assumption that people choose amongst a large set of patterns to maximize their utility, which is viewed as unrealistic since people are rarely aware of all possible patterns available to them.

In the case of *tour* based models, the behavioral assumption is that the activity scheduling decision structure consists of a series of choices that can be described by discrete choice models. However, simply adding more nests to the utility maximization model to account for the complexity of scheduling is insufficient on behavioral as well computational grounds. For instance, Bowman and Ben-Akiva's [2] attempt to incorporating the time dimension led to the addition of another nested level to their model. Not only does this involve a behavioral assumption about how timing decisions are made, but computational limits meant that only four time periods could be included for choice, which is clearly inadequate for policy analysis. Extension to more precise time periods would cause serious problems in a nested logit system.

Several models appear to be well conceived from a theoretical standpoint, as was the case with STARCHILD and Bowman and Ben-Akiva's models, but their operationalization suffered from a limited focus on the use of utility maximization discrete choice techniques. Insights from cognitive psychology about how people perform complex scheduling tasks suggests that people apply a large range of heuristics and strategies when faced with such tasks [14, 15]. Gärling et al. [16, p. 356] argues that an even more serious issue relates to the tendency of traditional models to be confined to specifying what factors affect the final choice of *pattern* whereas the *process* resulting in the choice "is largely left unspecified."

In response to these criticisms, recent modeling efforts have attempted to more explicitly replicate the *sequencing* of decisions made during the scheduling process, under alternative "rule-based" behavioral structures. These include SCHEDULER [16, 17], SMASH [18], and models by Lundberg [19], Gärling et al. [20], and Vause [21]. The most advanced operationally of these models is the SMASH model. The model starts with similar inputs to the CARLA and STARCHILD models (a list of activities to schedule along with their attributes), however, an individuals schedule is successively constructed by maximizing utility at each step (add, delete, reschedule) taken to construct the schedule, rather than for the schedule as a whole. Although this model is highly innovative, several key criticisms can be noted. Firstly, the authors note that "the mechanisms of the model allow for the adjustment of the schedule during the travel phase", however, this adjustment is limited only to substitution of activities between the agenda and schedule, ignoring other adjustment possibilities such as changes in activity duration and location. The authors also note that changing travel times and unexpected activity durations effect the utility in a sense that the chance of completing the schedule may vary, but they do not go on to describe how the adjustment of the schedule during execution is incorporated in the model. In this way, the SMASH model is still somewhat limited to the same "pre-travel phase" of scheduling as the STARCHILD model.

Overall, these behavioral limitations may seriously hamper the use of SMASH to assess the impacts of policy that inherently invoke a rescheduling response involving more than just substitution of activities (e.g. tele-communication), or that involve changes in behavior during execution of the schedule (e.g. ITS - Intelligent Transportation Systems). These criticisms may be due in part to the limitations of their interactive computer experiment MAGIC [22], which was limited to investigating activity scheduling behavior in a lab setting essentially ignoring the portion of scheduling decisions made during execution of an individual's schedule. The Ettema findings were also used in general to support the more recent sequential ruled-based models of Gärling et al. [20] and Vause [21], which may explain why they too are somewhat limited in the extent to which they address how scheduling decisions are subsequently modified during execution, and why they struggle with assumptions concerning the sequencing of decisions.

Future Directions

From the literature, it is clear that contributions to the complex field of activity scheduling are widely dispersed. Scheduling models based on existing econometric techniques are severely limited by their behavioral assumptions which limit their applicability to policy assessment. Alternative theories about activity scheduling that have been introduced are quite difficult to operationalize in their full form (e.g. SCHEDULER, STARCHILD). Operational scheduling models that have been developed (e.g. SMASH) have been criticized by practitioners for their complex data requirements and as discussed, are still limited in their ability to capture more complex rescheduling of activities. This scattered nature of the research is reflected in Ettema and Timmermans [1, p. 33] conclusion that

> "From a scientific point of view, it can be argued that to date a considerable body of knowledge exists regarding aspects of activity and travel patterns. At the same time, however, it should be noted that research in this area has been fragmented and that a *unifying framework* which links researches in different areas is still missing. This is probably due to the complexity of the phenomenon and the applied nature of most activity-based research."

What is not made clear in the literature is that observed activity schedules are the result of an unobserved decision "process" involving the planning and execution of activities over time within a household context. Travel behavior researchers are increasingly recognizing the need for in-depth research into the household activity scheduling "process" in order to advance model development. For example, Pas [23, p. 461] noted that "understanding travel and related behavior requires the development of models of the process by which travel and related behavior change" while Polak and Jones [24, p. 2] state clearly that "the degree to which travelers will be able or willing to adjust the timing of their journeys in response to Road Pricing charges will ultimately depend upon the nature of these scheduling processes. The development of improved understanding of these processes and the translation of these understandings into operational modeling techniques is a major research priority." Axhausen and Gärling [3] emphasize in general, that the rescheduling of activities is at the core of many of the changes in travel behavior brought on by recent policy initiatives related to information technology and transportation demand management. Thus, it is becoming ever more important that the development of travel forecasting models capable of assessing these types of emerging policies need to explicitly account for how people would temporally and spatially adjust their travel behavior, which is dependent on an underlying process of activity scheduling.

Linking Activities and Integrated Urban Model

Growing environmental concerns, and the awareness that long term reductions in emissions requires transport as well as land-use policies, has renewed interest in integrated models of Land-use, Transportation, and the Environment (LTE). Wegener [25, 26] stresses that future LTE models need to respond to a new generation of activity-based travel models that require more detailed information on household characteristics and activity locations. For the most part however, LTE modeling has continued in a business-as-usual fashion, focusing on single-purpose trips and the integration of traditional travel demand models. One state-of-the-art microsimulation model of (L)TE that does incorporate an activity focus is the TRANSIMS model [27, 28]. The "Household and Commercial Activity Disaggregation Activity Demand" sub-module is designed to be probabilistic in nature, in that for a given set of households a distribution of activities and their attributes are produced. Attributes include activity importance, the activity duration, activity location (for mandatory activities) and a time interval during which the activity can be performed. The mechanisms used to actually *schedule* the list of activities is not described in either paper, but was identified as a major "question mark" for future development at a recent conference [29].

A conceptual framework of how an activity scheduler would contribute to an LTE model is presented in Figure 1 (italics in the text represent components in the figure). For a similar approach see for example Axhausen and Goodwin [30]. The upper portion of the model focuses on long term *Land-use* and demographic processes, including *Household Demographics*, *Residential Location*, *Employment Location*, *Vehicle Ownership*, and *Firm Location*, and the *Road/transit Network*. Each of these sub-modules are currently being developed within the micro-simulation platform of the ILUTE model currently being developed in Canada [31]. It is proposed that several of these sub-modules will input information to the *Household Activity Agenda* and/or *Household Activity Scheduler,* at specified intervals or as events unfold in the micro-simulation to support creation of new travel demands.

The *Household Activity Agenda Simulator* consists of a list of household activities, along with the salient attributes that influence their scheduling, such as their desired frequencies and durations, possible start-end times and location choice sets. Some of these attributes would likely be probabilistically related to individual/household characteristics based on activity diary data (or perhaps, modified travel diary data), in a similar approach to that adopted in the TRANSIMS model. The *locations* of home, work, school/daycare and other mandatory activities could be taken as given from previous sub-module steps. The location choice set of other activities would require a model of an individuals cognitive map, perhaps simulated based on residential and employment location histories. The adaptation of the activity agenda in the long term, such as in the case of learning new activity locations or activity types, would be a necessary component of this sub-model. Simulated changes in the agenda as a result of policy (e.g. shorter working days, longer working hours for females, increased tele-commuting) would be reflected in changing attributes of certain activities that effect scheduling patterns and resultant travel patterns. Spatial, temporal, coupling, institutional, household resource, and transportation related constraints need also be imbedded in the structure of the household activity agenda. For instance, a household constraint that parents be at home at a certain hour to care for their children would be represented as a pre-planned activity with highly fixed time and location.

The *Household Activity Scheduler* would take the agenda of household activities and model the steps/process by which the activities are sequenced in time and space. Such a model is the focus of the remainder of this paper. The output from the *Household Activity Scheduler* would include the *Travel Demands* of each household member by time of day. This would feed into a *Traffic Flow Model* in order to generate network flows and updated travel times due to congestion. The updated travel times can be used to feedback to the Household Activity Scheduler in the random events that could result in further scheduling modifications. The activity scheduler could also be used to feed information to a residential choice model, in the form of the variables that indicate the potential utility of activity patterns associated with a set of residential choices for a given household. Practically, the activity patterns that could be feasibly evaluated by a household in a new location would be restricted to high priority or "routinized" activities. This would expand upon traditional residential choice models which use only "work trip" accessibility as a variable in the model (e.g. [32]) and could provide especially useful for certain population segments that are relatively insensitive to the work trip accessibility (e.g. telecommuters). Keeping track of residential mobility in a microsimulation may also play a complementary role in the construction of activity schedules, allowing one to consider history dependent variables that effect activity schedules (e.g. length of residence). Exactly how the linkages are made, and at what time scale are additional issues that must be resolved.

2 The Weekly Household Activity Scheduling "Process" Model

Data Collection

Despite the need, very few data collection efforts have targeted the underlying activity scheduling process. Exceptions include Hayes-Roth and Hayes-Roth [15] who used a "think aloud protocol" to investigate the kinds of behavior exhibited when people are posed with a series of errands to perform, and Ettema et al. [22] who used an interactive computer experiment to identify the types of steps people used to construct a one-day schedule. The CHASE (Computerized Household Activity SchEduling survey) survey developed by Doherty and Miller [33] goes beyond these methods by providing a means to observe the scheduling process as it occurs in reality in a household setting over a multi-day period. In this way it is able to capture both routine and complex scheduling processes as well as observe those scheduling decisions made during the actual execution of the schedule.

The CHASE program is designed to track the sequence of steps taken by individuals in a household to add and subsequently modify/delete activities from a household "agenda" to form weekly activity schedules. An upfront interview is used to establish a household's activity agenda which consists of a full list of activities potentially performed by household members, along with their attributes. This information is entered by an interviewer into computerized "forms" linked to a database file that the CHASE program can access in order to display the information back to the user in choice situations. Users are basically instructed to login daily to the program for a week long period (starting Sunday), and continuously add, modify, and delete activities to an ongoing display of their weekly schedule (Monday-following Sunday), not unlike a typically dayplanner. Aside from these basic scheduling options, the program automatically prompts the user for all additional information. The result is a highly detailed trace of the scheduling decisions adults in a household. Doherty and Miller [33] show that the program has a relatively low respondent burden and minimizes fatigue effects commonly associate with multi-day surveys. This approach goes a long way towards solving the data collection problem highlighted by Bowman and Ben-Akiva [2] that simulation models of activity scheduling require "very complex surveys for model estimation" wherein "respondents must step through the entire schedule building process." CHASE data can also provide considerable support for other sequential decisions process models, such as those proposed by Gärling et al. [20] and Vause [21], that have lacked direct empirical support.

CHASE data from a sample of 40 households (55 adults) in Hamilton Ontario is used in this paper to support the proposed model. The households represented a roughly equal mix of married couples, married couples with children, and single person households. The majority of households were located within two kilometers of the McMaster University campus, which is situated at the very tip of the western end of Lake Ontario (Hamilton region population: ~600,000).

Model Structure

The following conceptual model is presented as a means to describe how past research can be brought together into a unified modeling framework, and to lay the groundwork for future operationalization of the model. Note that italicized terms in the text refer to the model components as depicted in Fig. 2 and Fig. 3. In general, the model attempts to dynamically replicate the scheduling process as it occurs over time through the use of various modeling constructs and decisions rules. It begins by taking an individual's *Household Agenda* of activities, and establishes a set of *Routine Activities* and a *skeleton schedule* for the individual for the week, via an optimization model. This is followed by a *Weekly Scheduling Process Model* that replicates the scheduling decisions (additions, modifications, deletions) made by individual during the execution of their schedule during the course of the week. An activity priority function combined with various decision rules are key ingredients in the simulation model. Each of these aspects of the model are described in more detail in the following sections.

The Household Activity Agenda

On a fundamental level, activity scheduling reflects personal and household related basic human needs constrained in time, capability, and in space by the urban environment. These needs can be viewed as manifested in a household's activity *agenda* which represents the initial input to the model as shown in Fig. 2. The agenda consists of a list of uniquely defined activities that a household could potentially perform. Each activity on the agenda is viewed as having a unique set of (perceived) attributes that affect their scheduling, including duration (min, max, mean), frequency, earliest and latest end times, mandatory/optionally involved persons, costs, perceived locations, etc. These rather flexible parameters are used to determine the exact start/end times, location, etc. of the activity once scheduled, as shown in Fig. 3 (*Refine A Choice*). What is key to the success of the scheduling model is not the activity types as defined by traditional means (e.g. work, school, shopping, mandatory, discretionary etc.), but rather that their salient attributes are unique, giving the model the ability to address any number of individuals/household types. Although the derivation of household activity agendas are of considerable interest on their own, they are taken as exogenous to the process of scheduling in the short term (see also Figure 1 and related discussion).

Routine Weekly Activity "Skeleton"

Empirical evidence derived from the CHASE survey shows that households begin the week with a planned set of *routine weekly activities*. On average, 45% of weekday and 20% of weekend activities were pre-planned on the First Sunday of scheduling (remembering that users began scheduling on a Sunday for the activities that take place Monday to the following Sunday). This represents a total average of 34 activities per adult pre-planned on the first Sunday. Of the decisions, a full 70% were part of multi-day entries (the activity was added on 2 or more days simultaneously), with 80% of these consisting of entries across 4+ days. Comparatively, on Monday, only 21% additions were part of multi-day entries, followed by 2%, 6% and no more than 1% on remaining days of the week. Such repetitive entries are indicative of highly routine activities. Other characteristics, such as longer durations (double those of other planned activities) and a higher degree of spatial-temporal fixity, differentiate these routine activities.

Further empirical analysis using an appropriate discriminant analysis technique will be performed to further differentiate these types of activities from other activities on their agenda based on their key attributes, including duration, frequency, and indicator variables of temporal and spatial fixitivity. The resulting D*iscriminant Function* would be used to establish the R*outine Activity Subset*, as displayed in Fig. 3. It is reasonable to assume that these routinized activities pre-planned before the week starts are the result of a long-term thinking and experimentation process, and thus represent an "optimized" pattern or "skeletal" basis around which other scheduling decisions are made during the week. Given this, it is reasonable to assume that an *optimization model* would be appropriate to derive the *Pre-week skeleton schedules*. This model would use the discriminated activities as input, which represent a much more limited choice set of activities that are more amendable to the assumptions that underlie these models. These techniques include those that start by generating all possible feasible combinations of skeleton structures and choosing the most optimal of the set (e.g. CARLA, STARCHILD). The notion of adopting existing models for this purposes is discussed further in the concluding section.

Weekly Scheduling Process

Results from the CHASE survey show that after the first Sunday, a more active, opportunistic, and impulsive mix of decisions follows. On average, adults make about 8 additions, 2 modifications, and 1 deletion per day during the execution of their schedule over the course of the week, which include an average of 12.4 activities and 4.9 trips per adult per day. These scheduling decisions are made on a variety of time horizons. Outside of the routine activity additions made on the first Sunday (38% overall), a substantial proportion of additions are scheduled *impulsively* just before execution (28% overall), on the *same day* (20% overall), or are *pre-planned* one or more days in advance during the week (15% overall). When *pre-planning* during the week, adults were found to reach out beyond one day 38% of the time to make an addition, in an opportunistic fashion. The distribution of time horizons for modifications and deletions differed, as more impulsive modifications occurred (62%), while more deletions are made the same day (38%), reflecting more forethought for deletions compared to modifications.

This evidence strongly suggests that activity scheduling is a dual process of routine optimal planning, followed by a more dynamic process of continued pre-planning, revision, impulsive, and opportunistic decisions made over the course of the week within the bounds of an optimized skeleton structure. Given the goal is to develop a behaviorally sound model, a modeling structure is needed that can simulate this latter process. The *Weekly Scheduling Process Model* shown in Fig. 2 (and elaborated upon in Fig. 3) attempts to fill this gap.

Given that routine scheduling decisions are conveniently made in advance, it follows that they would form an input to this simulation model, as does the agenda of household activities. At this point however, some of the activities on the agenda will already have been placed on their scheduled, and while they always remain on the agenda, their "priority" for subsequent addition and/or modification will change over time in response to changes in the schedule (see the following section for details). The notion of a changing or "momentaneous" priority of activities is viewed as the driving force behind the variety of decisions made during scheduling (for similar ideas see [34] or [35]). The scheduling process simulation depicted in more detail in Fig. 3 will incorporate a mix of empirically derived "priority" functions and decision "rules" that serve to sequentially simulate the series of additions, modifications and deletions taken to construct the activity schedules of individuals in a household over time.

The simulation begins with a set (or stack) of simulated individuals who share an activity agenda with other household members. Individuals are visited and re-visited in sequence at the beginning and end of each scheduled activity or empty time window on their schedule. These visits are ordered in time along with all other individuals such that everyone's schedule is constructed simultaneously. Once an individual is visited, they are faced with a *choice to add* activities anywhere in their schedule, including in the immediate time slot (an impulsive decision) or at a later time slot (on the same day, or one or more days in advance). The priority of activities on the household agenda at that particular moment in time determines what, if any, activity will be added (the priority function is described in the next section). Once an activity is deemed high priority enough to schedule, *feasible windows* of opportunity are defined and one is chosen. Random events may also be generated at the same time that activities are being added to the schedule. Random events include both random changes in activity duration or travel times, or the generation of unexpected or emergency activities (accidents, surprise visits). These latter activities would automatically be assigned the highest priority for scheduling.

Only after this point are refined choices in the activity made, including decisions about travel if needed (mode, route choice, etc.), exact start/end times, exact location, and involved persons. Some of these choices may already be fixed (e.g. location is fixed to at home). Other choices will be simplified, if not limited in their choice set, given the fact that the individual may already be placed in a given spatial-temporal situation that constraints their choice. For instance, if the person is already at certain location outside the home, with a car and with their spouse, and is making an impulsive decision, the mode and involved person choices are somewhat fixed, whereas the location choice set can be simplified given the proximity of perceived locations in the area. When faced with more flexibility in scheduling, factors such as how many other high priority activities are on the agenda, and the desired attributes of the current activity (e.g. desired duration) will effect the refined choices.

Once the final refinements are made, the activity is placed on the schedule of the individual, and a decision is made whether to continue scheduling at the time. This will depend on the number of high priority activities on the individual schedule at the moment. If yes, the process repeats itself, otherwise the individual is placed back in the stack of all individuals, which is ordered in terms of when each individual is visited next.

Conflicts that arise due to random events, the need for more time to accommodate a high priority activity, or cases where activities may be extended to fill time, are handled by the *Modify and Conflict Resolver*. Results from the CHASE survey indicate that the most common modification is to the start or end time of an activity, representing 73% of all modifications. Changes in involved persons (8%), activity type (7%), location (6%), travel time (4%), and mode (2%) were recorded less frequently.

This suggests that people are most often responding to time pressures when they modify activities. People also tend to modify more than one attribute of activities to accommodate scheduling changes, as more that one half the 1241 recorded modifications involved a change to two or more attributes. The *Modify and Conflict Resolve* is intended to take the previously scheduled activities and determines those which have the highest priority for modification. A set of possible modifications is determined, and a choice is made as to which ones to implement and their extent. If the (set of) modification(s) does not meet the requirements of solving a conflict, then the *deletion of an activity* is considered. The procedure for deletion is similar to modification, except that the activity attempting to be scheduled is compared directly to the revised priority of the activity chosen for potential deletion. If none of the deletions is justifiable, then the model reverts back to the beginning, and the originating activity is left unscheduled. If an activity is deleted, control reverts back to the assessment of window feasibility.

Although the scheduling simulation proceeds in a sequential fashion, without directly involving the optimization of the schedule as a whole (apart from the optimization already achieved via routine scheduling), a degree of sub-optimization is achieved by revisiting previous activities for modification. This leads to more optimized locations, durations, mode choices, etc. that minimize travel time or durations via the *Modify and Conflict Resolver*. However, this occurs only in the event that other activities of high priority need to be scheduled within limited time windows. Behaviorally, this reflects the notion that people consider optimizing their behavior only when and where needed and/or possible.

Priority Function and Decision Rules

Although activity "priority" has been proposed as the determining factor in the choice of activities to schedule in previous models (e.g. SCHEDULER [16-36]), it has remained a difficult attribute to operationalize. Asking people to assess the priority of a list of activities is difficult not only because of a definition problem, but because the priority of an activity <u>depends on the situation at hand</u>. Any one static assessment of the priority of activities will be inadequate to deal with all possible situations that arise during the scheduling process.

To meet this challenge, the priority of activities on the household agenda should be modeled as a function of the attributes on the activity on the agenda (duration, frequency, etc.), as well as the attributes of the activity relative to the scheduling state of all household members at the time of decision making. For instance, history and future dependent variables that account for the likelihood that activities that have been already scheduled, or that have taken place recently relative to their desired frequency, would have lower priorities. The temporal and spatial fixity/flexibility of activities suggested to influence the sequencing of activities [37, 38] and hence their priority, could also be investigated by a combination of activity and scheduling attributes. For instance, the number of perceived locations in the vicinity of an individual's current location could be used as a measure of the spatial fixity, whereas the ratio of minimum activity duration to the difference between the earliest possible start and latest end time could serve as indicators of a temporal fixity. The flexibility of an activity in terms of duration in relation to the maximum size of any feasible time windows (max W) on a schedule should presumably influence its priority for scheduling. An appropriate variable for the priority function would then be:

$$\frac{\min d_i}{\max W}.$$

The smaller this is, the higher the priority should be. For activities that represent tasks to be assigned to household members (e.g. shopping), the same variable for other household members could be included to reflect the lower priority for an individual when other household members schedules are relatively more flexible. The high priority of joint activities that reflect household constraints (e.g. chauffeuring) could be reflected in a dummy variable that is set to 1 for activities that have already been scheduled by the other household member. The proximity of perceived locations for the activity in combination with available modes and travel times, should also effect priority. Many other variable are possible to reflect the changing level of priority of activities, and to capture the seemingly complex array of decisions and resulting patterns that result. Separate models need be constructed for the priority of activities for addition, modification or deletion to the schedule. Future estimation of these priority functions will be possible using CHASE data.

Throughout the simulation, decision rules are used to replicate the variety of choices made. In some cases, these rules may be rather simple reflecting practical considerations or straightforward logic, whereas in others, they will reflect more complex decisions structures. For example, the decision rule to determine which *activity to add* from the agenda could be as simple as choosing the one with the highest priority. A more complex decisions rule example would apply to the choice of whether to *Continue Scheduling.* The decision rule could be of the form:

IF [Priority of highest activity] > (α) THEN [*continue*]

where the α threshold value is determined empirically from observed data, based on how much free time is left on an individuals schedule before they stop pre-planning. An alternative would be to base the decision on the sum of priorities of activities on the agenda, replacing the left side of the above equation with the sum of all priorities on the agenda. This would reflect the aggregate amount of pressure the particular person is under to continue scheduling activities. This rule would need be combined with other practical rules that require that scheduling proceed in light of any open time windows, regardless of activity priorities. Other rules would be needed for choosing *Feasible Time windows* (closest in time?, longest?) deciding when modifications/deletions are needed (when priority of an activity is sufficient high relative to scheduled activities to justify modification/deletion to accommodate its scheduling), deciding which modification(s) to make, and the variety of activity choice refinements that need be made. Clearly, much more work is needed on the cognitive behavioral side to improve these rules, however, simplified rules could be used to operationalize the model in the short term.

Operationalizing the Simulation

The scheduling process suggested in the discussion above and summarized in Fig. 3 has to be operationalized as an event-oriented simulation, which is able to model the interactions between persons in time and space [39]. Event-oriented simulations divide all operations of the model and of the entities, here persons, into individual *events,* which encapsulate a particular set of actions and which are executed at a particular moment (simulated time). Each event selects the relevant next event, which needs to be scheduled for the entity concerned and calculates the time when this event is going to be executed.

At this point it is not possible to give a full list of all relevant events, as this list will depend on the amount of functionality envisaged for the initial implementation. Still, the following core will be required (next event to be scheduled):

Agenda construction: constructs the initial agenda for a household. (Skeleton optimization)

Skeleton optimization: selects the routine activities from the agenda and constructs the optimal skeleton schedule. (Preplanning)

Preplanning: For the remaining days of the week the schedule is advanced, i.e. activities added, modified and deleted. (Day of)

Day of: For the remainder of the day the schedule is advanced. (Preplanning or Impulsive)

Impulsive: the next activity is selected by finalizing the *local* schedule by filling the time window immediately in front of the person, implying choice of all aspects of the movement to the chosen location (mode, route/lines, transfer points, preferred parking location/stop, preferred type of parking, acceptable search time). (Day of or Activity start)

Activity start: If the activity is undertaken at the same location, then the following calculations are undertaken:

- The activity duration is finalized by randomly drawing the duration, as a function of the anticipated duration: $\Delta t(\text{duration})$.
- Given the activity duration the occurrence of a random external event requiring scheduling is determined at $\Delta t(\text{random}) < \Delta t(\text{duration})$ including the type of event.
- Schedule next *Impulsive* at $t+\min(\Delta t(\text{random}), \Delta t(\text{duration}))$, which is implicitly the end of the current activity, unless this is the last activity of the day, i.e. going to bed for the night.

If the next activity is elsewhere, schedule *Movement Preparation* at t+min Δt.

Movement Preparation: Based on current information and the prior choices, confirm the route and mode chosen. If the expectation is, that movement can be performed in the time allocated, schedule *Move* at t+min Δt, otherwise schedule *Impulsive* at t+min Δt.

Move: Move down the next (first) link of the current route, calculate travel time as a function of the link usage Δt(link). Revise preferred parking location/stop, if required by actual travel conditions. If outside anticipated time limit for this point, schedule *Impulsive* for t+Δt(link). Otherwise schedule:

- If parked vehicle reached, schedule *Move* at t+Δt(Getting the vehicle started), which depends on the type of vehicle, the type of parking, the size of the group and the purpose of trip.
- If initial stop reached, schedule *Move* for t+Δt(until the next arrival of vehicle of preferred line).
- *Move* at t+Δt(link), if not yet at preferred parking location, stop, destination.
- If at the preferred parking location, schedule *Parking* at t+Δt(link).
- If at preferred stop, schedule *Move* at t+Δt(link) for final walk to destination.
- If destination has been reached (by walking), then schedule *Impulsive* at t+Δt(link).

Parking: If parking of the preferred type is available within the acceptable time frame, calculate Δt(search time) and schedule *Move* at t+Δt(search time) for the final walk to destination or next mode, in case, for example, of P+R or Kiss+Ride. Otherwise, schedule *Impulsive* at t+Δt(wasted time), which depends on the type of parking preferred and the acceptable search time. (It is assumed, that the duration of the parking search can be determined from the number of vehicles travelling on this link and those searching for parking. See [40] for an example and the literature cited there).

This formulation is open to include a whole range of further events and interactions, which might be of interest to a particular context. For example:

- Simulation of telecommunication by including interrupts of activities of others, as part of *Impulsive.*
- Traveler information by adding *Impulsive* scheduling events depending on whether a traveler has received certain information while traversing the current link.

- Simulation of public transport vehicles and their interactions with other traffic and the resulting early/late arrivals or changed waiting times.
- Detailed simulation of traffic control devices, in particular signals, by modeling detector locations and the associated adaptive signal control.

The exact implementation of the event-driven simulation is a question of the available computing resources, but current programming tools, including agent-based languages, are greatly facilitating the task.

3 Discussion

Model Comparison

The conceptual model presented in this paper can be compared to previous sequential activity scheduling process models such as SMASH [18], and models by Gärling et al. [20] and Vause's [21]. It is similar to these models in a sense that an activity agenda is assumed to exist, that a sequential approach is adopted to mimic the decisions involved in activity scheduling, that a "meta" decision process exists to control the flow of decisions (similar to Vause) and that alternatives to utility maximization are proposed. It goes beyond previous models, however, in terms of how priorities are assessed, how other household members schedules are incorporated in the model, how decisions are organized over time are subsequently modified during execution via the simulation model, and how the two dominant operational techniques (i.e. utility maximization versus rule-based approaches) are "unified" in the model.

Specifically, there are several aspects of the current model that make it unique from past approaches. First, it is shown how the priority of activities can be derived as a dynamic function by adopting the use of scheduling state characteristics of individuals and their household members schedules at the time of scheduling. This of particular importance for capturing the constraints imposed by other household members. Second, the current model incorporates a natural means for the rescheduling of activities that occur during execution of schedules, in the form of continuous addition, modification and deletion to the schedule. This aspect of scheduling behavior is not addressed directly in Gärling et al. and Vause's model, and is quite limited in the case of Ettema's model. This aspect of the current model largely reflects the new insights made possible by the CHASE data. Third, the current model directly addresses the sequencing of activity choices over time, something that past authors have struggled with, assuming either that decisions are made purely sequentially in time, or that some meta-decision process existed as a control mechanism. Perhaps most importantly, the current model is based on observed data that provides the necessary behavioral support of the model, and allows one to consider new types of variables for future operationalization. Both Gärling et al. and Vause stressed the importance of obtaining more data on the underlying scheduling process for future operationalization and empirical estimations of their model.

Overall, the behavioral power of the scheduling process model and simulation rests in it realistic replication of how activities are scheduled over time, how a sub-optimal solution is achieved, the allowance for a variety of decision rules, and the sensitively of the priority model over time. The priority function allows certain activities to jump up in priority depending on the circumstances. This allows infrequent, discretionary, or otherwise unusual activities to emerge depending on the situation, contributing to complex activity-travel patterns. The priority model also inherently determines the sequencing of activities in terms of the order in which decisions are made and their order in execution, without having to explicitly determine this in the model. Overall, the variables used in the priority models that reflect the state of the schedule relative to activities on the agenda are what makes this model unique, and give it the power to explain the apparent behavioral complexities of observed activity-travel patterns. The ability to collect these variables via the CHASE survey has opened up significant opportunity for future development of this model.

Providing a Unifying Framework

Looking at the derived need for travel from the perspective of an activity scheduling process allowes new insights into how past research can be brought together into a unified modeling framework. The scheduling process was shown to separate into a dual process of pre-week routine scheduling, followed by a more dynamic process of impulsive and opportunistic planning as the schedule is executed during the week. This distinction is rather convenient from a modeling perspective, as it provided a logical and behaviorally sound way to unify past econometric approaches for the modeling of routine activities, with the "rule-based" simulation approached adopted in this paper for modeling the more dynamic weekly decision process. This goes a long way towards addressing the concerns of Ettema and Timmermans [1] that a *unifying framework* which links the research in different areas is still missing.

In particular, the STARCHILD [8, 9] model appears clearly amenable to providing a model for the creation of a "skeleton" schedule of routine activities. Although in theory, the STARCHILD model makes a distinction between "planned" and "unplanned" activities, in operationalization, the model produced an activity pattern "that can be expected to be executed during the action period" [8, p. 314], and that is "sensitive to the possibility of unforeseen events arising" [9, p. 327] - very similar to the "skeleton" schedule proposed in the current model that forms the basis for unplanned scheduling during execution . The only significant modification would be to restrict the generation of feasible activity patterns to "routinized" activities, and leave "flexibility" in the form of open time periods for the remaining "unplanned" activities scheduled during the week. Tour-based models, such as that of Bowman and Ben-Akiva [2, 11, 12] could also provide the needed "routinized" framework to start the scheduling process. Although not shown, it is suspected that routinized activities are related to the "primary" tour of the day. Thus, a tour-based model could be used up to the point where the primary tour is developed via utility maximization. This would partially minimize the computational problems exhibited in these models, and provide a more solid behavioral basis for them as they are restricted to scheduling activities that do indeed lend themselves to optimization.

Future Model Development

The model proposed in this paper seeks to provide a framework for the long term development of an operational household activity scheduling model capable of outputting details on the travel demands in urban area and examining the impacts of emerging policy issues. The most immediate future research needs related to operationalization of specific components of the model using CHASE data. This includes the development of a discriminant function for routine activities and definition and estimation of the momentaneous priority function. Equally important is the identification of the types of decision rules underlying the variety of scheduling steps incorporated in the model and an assessment of how they might differ across individuals and situations. This would involve more in-depth probing using techniques such as "thinking aloud" pioneered in psychology. Additional needs include the development of a microsimulation model of activity agendas that includes the relevant attributes necessary for the discriminate and priority functions, and collaborative efforts focussing on the unification of existing optimization models for modeling the weekly routinized "skeleton" schedule. Overriding these developments is a need to develop a computer algorithm capable of simulating the scheduling process in all its components for all people in an urban area.

The ultimate future task is the integration of the scheduling modeling within a larger integrated urban model. The most obvious linkage is through the output of household level travel demands by time of day and day of week, as depicted in Figure 1. Such an effort would drastically improve the models ability to predict the impact of a wider range of policies and urban form scenarios, as well as provide inputs and feedbacks to other modeling components.

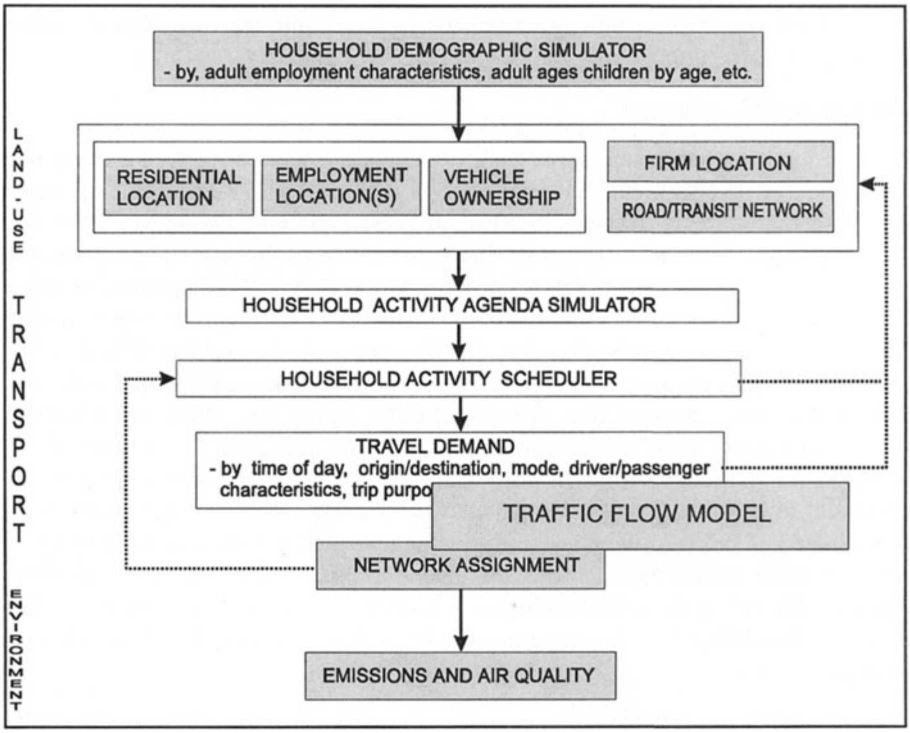

Figure 1: Household activity scheduling within an integrated land-use, transportation and environment modeling framework.

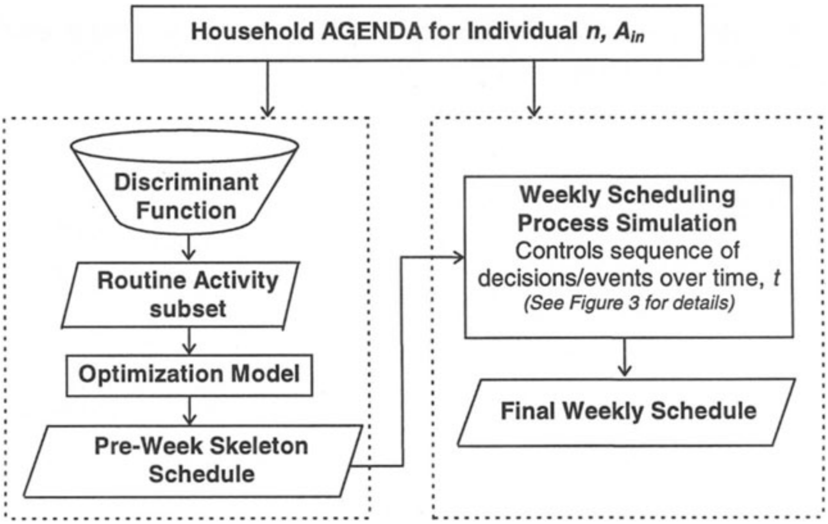

Figure 2: Weekly household activity scheduling process model, showing three major components.

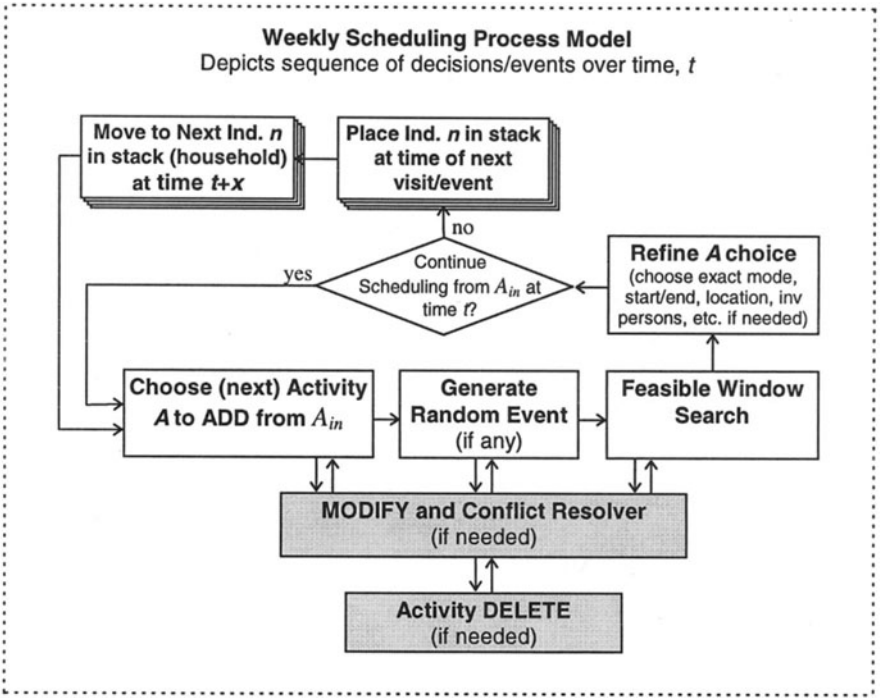

Figure 3: Weekly scheduling process model.

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