Chapter 2
Literature Review

Evacuation plans are developed for buildings, ships, stadiums or districts, cities or whole sub-national region. In the following literature review, mathematical programming and simulation approaches that consider, mainly, the evacuation planning concerning the evacuation from regions like districts, towns or regions will be presented. Recently, there have been a number of articles concerned with evacuation planning and evacuation support. They could be divided into flow-based optimization approaches which seek to compute an optimal solution of certain objectives and simulation approaches that evaluate an existing evacuation plan.

We will concentrate on dynamic network flow models. Traffic assignment models will be briefly introduced and presented when introducing approaches that apply traffic assignment models to evacuation planning.

2.1 Flow-Based Optimization Models

Dynamic network flow problems and traffic assignment problems are applicable to model flow for evacuation planning. In the following, general approaches of dynamic network flows will be presented and specific approaches of dynamic network flow models and traffic assignment models which are constructed for or applied to evacuation planning will be summarized.

Dynamic network flow models can be used to describe evacuation problems. The question of how to obtain the quickest flow with multiple sources is often referred to as the evacuation problem (see e.g. Hoppe and Tardos, 1994). Dynamic network flow problems are generally applied to model network flow problems where the amount of flow on an arc may vary over time and flow needs a certain amount of time to traverse an arc. In the case of a discrete time model, the considered time horizon is divided into time periods of equal length. Every node and every arc is considered in every point in time. The term *dynamic*, in the case of dynamic network flows, refers to the characteristic of the inflow on an arc which may take different

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values in different points in time. The parameters are known in advance and no new information about the values of parameters are updated during solution. Dynamic network flows are also called flows over time.

A dynamic network is defined as a directed graph G = (N,A) with non-negative capacities and non-negative, integer transit times on arcs. Two subsets of nodes, the set of sources and the set of sinks, are defined. A dynamic feasible flow satisfies flow conservation constraints and is called feasible if the inflow capacity is regarded. The flow or inflow rate on an arc is the amount of flow in arc (i, j) that leaves node i at point in time t, arrives j at point in time t plus the corresponding travel time. Typical dynamic network flow problems are to find a feasible flow traveling from sources to sinks under certain supply/demand constraints and fulfilling flow conservation constraints while optimizing an objective.

A variety of dynamic network flow problems are considered for evacuation planning: the dynamic maximum flow problem, the earliest arrival flow problem (also known as universal maximum flow problem), the quickest flow or the transshipment problem, or a dynamic minimum cost flow problem. Variations and extensions of the dynamic flow problems correspond to the number of sources and sinks, to the dependencies of attributes of the arcs and nodes, e.g. constant, time-dependent or flow-dependent capacities or transit times on arcs, or as well as additional constraints and/or variables. Dynamic network flow problems model time in discrete time steps or continuously.

The traffic assignment problem seeks to determine flows on links of a given road network under certain optimality or equilibrium conditions, where a flow rate for origin-destination pairs, i.e. OD-pairs, of nodes for every considered point in time is given. The departure flow rate for an OD-pair at time t determines the amount of flow leaving the origin node to travel to the destination node at time t. When the given flow rate for the OD-pairs is constant over a long horizon, the traffic assignment problem is called static, otherwise dynamic (Merchant and Nemhauser, 1978). Models that describe the dynamic traffic assignment problem generally claim to model traffic phenomena like congestion or shockwaves realistically or at least approximate them. Traffic assignment problems are used in simulation approaches where beside the solution of a traffic assignment problem, steps like the determination of the OD-matrix or appropriate path generations have to be implemented. Dynamic traffic assignment problems are used to study evacuation problems as part of a simulation approach (see Sect. 2.4) and as linear optimization problems that are often based on the cell transmission model developed by Daganzo (1994) and Daganzo (1995).

Dynamic Network Flow Models with Constant Attributes

First, "classic" dynamic network flow problems with constant attributes will be considered. The maximum dynamic s-t flow problem was presented by Ford and Fulkerson (1958). The goal is to send a maximum amount of flow from a source

node s to a sink node t in a given time horizon. Ford and Fulkerson (1958) assumed the attributes of the problem, i.e. transit times and inflow capacities, to be constant. This problem can be easily interpreted in the evacuation context as evacuating as many as possible people from a danger zone (source node) into a safe zone (sink node). Ford and Fulkerson (1958) solve this problem optimally by letting start "temporally repeated flows" in every time period from the source such that the chain flows will reach the sink before the observed time horizon will end. The temporally repeated flows are based on flows computed with a certain minimum cost flow problem.

The earliest arrival flow problem, also called universal maximum flow problem, presented by Gale (1959) is an extension of the maximum dynamic s-t flow problem with an additional property: the cumulative amount of flow having reached the sink in every considered time period and all preceding time periods of the considered one have to be maximal. The earliest arrival flow translated in the evacuation context means that until every considered time period the maximal amount of evacuees enters the safe area. Considering, for example, an impending dam failure, this is a useful and reasonable property.

In case of multiple sources and/or sinks, additional parameters, e.g. supplies for sources and demands for sinks, and corresponding constraints may be added to the maximum dynamic flow problem or the earliest arrival flow problem. A maximum dynamic flow with the earliest arrival property does not necessarily exist if there are multiple sinks with predefined supplies and demands. Baumann and Skutella (2006) give an example with a single source and two sinks where no earliest arrival flow exists. For the evacuation scenario it is not a real limitation, if we assume that the exit, the sink, is not important in a case of an evacuation and the assignment of evacuees to exits is part of the decision making. This can be easily incorporated by adding a super sink to which all sinks are connected. The demand of the super sink is the sum of supplies of all sources, i.e. the total number of evacuees. Different variants of constraints that state, if the demand has to be satisfied within the time horizon or if as much as possible of the demand has to be satisfied are thinkable.

The quickest transshipment problem seeks to minimize the time the given supplies and demands in sources and sinks, respectively, are satisfied. For the evacuation scenario the quickest transshipment problem determines the evacuee-flow such that all evacuees leave the danger zone in a minimum amount of time or, in other words, the clearance time of the evacuation zone is minimized. The single source, single sink case of the quickest transshipment problem is called the quickest flow problem. The quickest path problem allows just a single path from a source to sink while minimizing the network clearance time (see Pascoal et al., 2006). The quickest transshipment problem with multiple sources and a single sink is called evacuation problem (see e.g. Hoppe and Tardos, 1994).

Burkard et al. (1993) use the relation between the quickest flow problem (single source, single sink) to the maximum dynamic network flow problem. They propose polynomial algorithms and a strongly polynomial algorithm to solve the quickest flow problem. The algorithms are based on parametric search with respect to the time horizon, like binary search. A maximum dynamic flow problem or an earliest

arrival flow problem is solved several times with changing time horizon until a feasible solution regarding to the amount of flow that should reach the sink with the smallest time horizon is found.

Hoppe and Tardos (1994) present polynomial time algorithms for several dynamic network flow problems: the general multiple source quickest flow problem, the lexicographic maximum dynamic flow problem, and the earliest arrival problem. The lexicographic maximum dynamic flow problem maximizes amounts of flow leaving the sources in a specified order, i.e. the sources are ordered from high to low priority. They introduce "generalized temporally repeated flows", where flow is allowed to travel in the opposite direction of an edge. These algorithms are also explained in detail in Hoppe (1995) and a subsequent algorithm of the quickest transshipment problem is presented in Hoppe and Tardos (2000). Baumann and Skutella (2006) develop a strongly polynomial time algorithm to solve the earliest arrival flow problem with multiple sources and a single sink exactly, where the supplies and demand are given. Continuous dynamic flows are considered. Fleischer (2001) investigates the quickest transshipment problem, where the transit times of all arcs are zero, but the inflow is still assumed to be capacitated. Fleischer and Skutella (2007) present approximation algorithms for quickest multicommodity flows. A commodity is defined as a source–sink pair.

The minimum cost dynamic network flow problem seeks to find a dynamic network flow that satisfies the given supplies and demands such that the total cost defined e.g. on arcs or nodes is minimized while fulfilling the flow conservation and inflow capacity constraints. Minimum dynamic cost flow problems are considered in Chalmet et al. (1982), Hamacher and Tufekci (1987) and Hamacher and Tjandra (2001) for building evacuation. The average evacuation time per evacuee is minimized and waiting in nodes (storage in nodes) is allowed. Klinz and Woeginger (1995) and Klinz and Woeginger (2004) consider a dynamic minimum cost flow problem without waiting in nodes for the problem with a single source and a single sink. They state that there always exists a minimum cost flow, which does not use the opportunity to temporally store flow in nodes, if storage/waiting in nodes have nonnegative costs. Fleischer and Skutella (2002) prove the more general result that the minimum dynamic convex cost flow problem with multiple sources and sinks does not require storage in nodes. The supplies and demands that are assigned to sources and sinks have to be satisfied within the time horizon. The time when a certain amount of flow enters the network through a source, i.e. the network load, is not predetermined in advance.

If the time horizon is chosen high enough such that the flow assigned to the sources can leave the network within the given time horizon, then the "triple optimization result" (Jarvis and Ratliff, 1982) is valid. It states that an optimal solution of the dynamic maximization flow problem with the earliest arrival property or an optimal solution of the minimization of the weighted sum of flows entering the arcs pointing to the super sink solves the following three problems optimal: The earliest arrival problem, the minimization of the weighted sum and the quickest flow problem. The time copies of the sink are all connected to a super sink and the weights associated with the arcs that lead to the super sink are increasing with time.

Chalmet et al. (1982) refer to the result of Jarvis and Ratliff (1982) as the "triple optimization result". Jarvis and Ratliff (1982) proof the result for the single source, single sink case, but is also valid for the multiple source, single sink case (see e.g. Baumann and Skutella, 2006), where the sources have given supplies.

The result of Jarvis and Ratliff (1982) may be extended to the multiple sources, single sink case, but if the network capacities are to be determined in the optimization model then this result is no longer valid for the urban evacuation model we will present in the following chapters. We will give an example of an instance of our urban evacuation model, where the minimal cost flow leads to a longer clearance time and the minimum clearance time flow leads to a higher cost flow (see Sect. 3.5.1). In the urban evacuation model that we will introduce in Chap. 3, the inflow and the capacities of the arcs have to be determined and additionally a total capacity of the street segments will restrict the flow. A single sink situation is given for the urban evacuation model with the incorporation of the super sink and the fact that the street network sinks do not have a predetermined demand.

Dynamic Network Flows with Time-Dependent Attributes

The attributes of the dynamic flow problems were so far constant, but they may vary over time. The values of parameters varying over time are known in advance. This can be used to model the progress of a hazard like the rising of water when a dam failure occurs. Capacities may decrease over time or can be zero after a certain point in time. Dynamic network flow problems with time-varying attributes and solution methods is explicitly considered in the following literature: Tjandra (2003) considers time-dependent attributes, i.e. travel times, inflow capacities and costs. He presents solution algorithms for the single source, single sink case of the maximum dynamic network flow problem, the earliest arrival flow problem and the quickest flow problem with time-dependent attributes and time-dependent supplies as well as an algorithms solving time-dependent bicriteria dynamic shortest path problems (see also Hamacher et al., 2006).

A minimum cost dynamic flow problem on time-varying networks is considered by Cai et al. (2001) for the single source, single sink problem. Variables are the flow on an arc during a certain time period and the amount of flow waiting in a node during a certain time period. The time-varying attributes are the costs, travel times and capacities on arcs as well as on nodes. Algorithms with pseudopolynomial time complexity are suggested to solve the problem with waiting capacity, with unlimited waiting in nodes and with the prohibition of waiting in nodes. Miller-Hooks and Stock Patterson (2004) investigate an integral time-dependent quickest flow problem with time-varying attributes, i.e. arc travel times, node and arc capacities, and the supply at the source vary with time. They present an algorithm that solves the single source, single sink variant of the problem and, additionally, they propose a transformation of the network associated with the quickest transshipment problem into a single source, single sink problem such that the algorithm can be applied

to the multiple source case, too. The demand is time-dependent, but the flow that has to meet a certain demand at a certain time may arrive in the sink before and wait there on a holdover arc of the super sink. Waiting in the super sink is not penalized with costs. Nasrabadi and Hashemi (2010) investigate a minimum cost flow problem in a discrete time model with time-varying transit times, transit costs, transit capacities, storage costs and storage capacities. An algorithm is presented to solve the considered problem.

Dynamic Network Flows with Flow-Dependent Travel Time

An extension of dynamic network flows such that affects of traffic flow are captured more accurately models the travel time dependent on flow, e.g. the travel time depends on the inflow of a certain point in time. With different models of flow-dependent travel times the following approaches try to map the traffic flow behavior more accurately while preventing computational tractability.

Kaufman et al. (1998) propose a mixed integer programming model for dynamic route guidance with traffic-dependent travel times that considers a discretization of an inflow-travel time relationship. The travel time depends on the amount of traffic inflow and is modeled with an alternative time-expanded network, where exactly one arc of finite different time-space arcs emerging from a time copy of a node has to be chosen. The traffic load onto the network is predetermined and may vary over time. A similar alternative time-expanded network is introduced by Carey (2001) to capture the flow behavior of traffic flow more realistically. They propose a linear model that is defined on an alternative time-expended network. The traffic flow is given a choice among time-space links. These links are associated with different travel times that depend on a given interval of inflow capacity. Thus the trip time of a vehicle on a link is influenced by the inflow rate when vehicles enter a link. Köhler et al. (2002) introduce two variants of an alternative time-expanded network that map a relaxation of inflow-dependent transit times similar to the approach of Carey (2001). The alternative time-expended graphs are modeled in such way that standard network flow algorithms can be applied to solve the problems defined on them. The considered problem is the quickest dynamic s-t-flow problem. With an introduction to dynamic flows, these results are also presented in Langkau (2003). Köhler and Skutella (2005) introduce a model that considers load-dependent transit times. They assume that the total amount of flow traverses an arc at each point in time with uniform speed and that the speed depends only on the current amount of flow (or load) on that arc. An approximation algorithm for the quickest dynamic flow problem with load-dependent transit times is suggested. The earliest arrival flows, where the flow is defined according to the above-mentioned approaches of the inflow-dependent (Köhler et al., 2002) and load-dependent (Köhler and Skutella, 2005) travel times, are investigated in Baumann and Köhler (2007).

Another approach to capture the properties of traffic flow present Hall and Schilling (2005). They consider a rate-dependent flow model that takes the flow rate on any point on a link into account and present a heuristic for the quickest flow problem with rate-dependent travel time.

Surveys on Dynamic Network Flow Problems

For more details and different focuses on dynamic network flow problems, we refer to the following surveys: Aronson (1989) gives a survey on discrete dynamic network flows, especially on the maximum dynamic flow and the minimum dynamic flow problem, on corresponding solution techniques and he lists an extensive number of references of examples and applications. Mentioned examples are dynamic traffic assignment models or problems that occur in communication or traffic systems. Hamacher and Tjandra (2001) give an overview over mathematical modeling of evacuation problems concentrating mainly on building evacuation. They especially present variations of discrete time dynamic network flow problems that can be used to model evacuation problems, like the minimum cost dynamic network flow, earliest arrival flow or quickest flow problems and as well as solution algorithm of the corresponding problems. Kotnyek (2003) gives an overview of dynamic network flows. He concentrates on the "basic" dynamic problems, the minimum dynamic cost flow, the maximum dynamic flow, the earliest arrival flow and quickest flow problem as well as on generic solution techniques. Skutella (2008) presents a survey of continuous time dynamic network flows with constant travel times and capacities. He concentrates on the maximum s-t flow problem and earliest arrival problem with a single sink s and a single source t and solution algorithms. In "Traffic Networks and Flows over Time", Köhler et al. (2009) summarize approaches and algorithms of static flows and dynamic flows with and without the incorporation of congestion. They review dynamic networks flows with constant and especially flow-dependent travel times.

Evacuation Models Based on Dynamic Network Flow

Explicitly for the evacuation of pedestrians developed dynamic network flow models are e.g. for building evacuation (Chalmet et al. 1982, Choi et al. 1988 or Chen and Miller-Hooks 2008). Chalmet et al. (1982) model a dynamic network flow problem that minimizes the average time an evacuee needs to exit the building. Using the "triple optimization result" proven by Jarvis and Ratliff (1982) the considered problem solves also the maximization of the total number of evacuees as well as the minimization of the total evacuation time. Hamacher and Tufekci (1987) consider among other variants, a building evacuation problem that avoids unnecessary movements during evacuation. Both evacuation models, i.e. the models presented

in Chalmet et al. (1982) and Hamacher and Tufekci (1987), allow multiple sources and define a single super sink to which the exits of the buildings are connected in the constructed network. Choi et al. (1988) model different dynamic network flow problems for buildings that take flow-dependent capacity into account. For special graphs, so called path structured networks and tree structured networks, which can be considered as typical for common buildings, greedy algorithms are presented. Chen and Miller-Hooks (2008) incorporate "shared information" (modeled with binary variables on arcs and in every point in time) in their building evacuation problem that updates the evacuation routes in every point in time. The travel times and arc inflow capacities are time-dependent and known a priori. Evacuations of people from hospitals (e.g. Taaffe et al., 2005) or naval ships (e.g. Pérez-Villalonga et al., 2008) are also investigated.

Mamada et al. (2005) consider an evacuation problem on tree dynamic networks with the property "all the supplies going through a common vertex are sent out through a single arc incident to it toward a single sink" (Mamada et al., 2005, p. 196). That means the flow is not allowed to diverge on different arcs. They consider a continuous time quickest transshipment problem.

For evacuation from regions, the following approaches which optimize traffic flows that have to leave the network due to a specific objective have been developed: Yamada (1996) investigates shortest path and the minimal cost flow problem on static networks for city emergency evacuation. Lu et al. (2005) propose a heuristic approach to solve the problem of the minimization of evacuation egress time with time-dependent node and arc capacity for large-scale instances. The heuristic algorithm calculates evacuation plans that provide evacuation routes and evacuation schedules without using the time-expanded network, i.e. using the static network. Kim et al. (2007) improve the heuristic proposed in Lu et al. (2005) in terms of the runtime using the min-cut max-flow theorem. Time-dependent travel times and capacities are allowed. Lim et al. (2009) apply the maximum dynamic network flow problem for the case of hurricane evacuation to determine an upper bound of the total amount of evacuees that reach a safe zone within a given time horizon. Analog to the approach of Burkard et al. (1993) for the single source and sink case, a binary search is executed until the minimum time horizon is found such that the model is feasible. Kamiyama et al. (2006) suggest an algorithm for an evacuation problem modeled as a quickest flow problem with single sink. The algorithm is constructed for a grid network with uniform inflow capacity.

Evacuation Models Based on Dynamic Traffic Assignment Problems

A simple traffic assignment model defined on a static network is used for a regional evacuation approach in Han et al. (2006a,b). The assignment model is based on a system optimum traffic assignment model of Sheffi (1984). Amounts of flow

of the demand of sources is assigned to routes leading to a super sink with the objective to minimize the total travel cost for all travelers in the network. Ng and Waller (2009) suggest a slightly different problem. They consider a two-stage stochastic programming network design model for transportation networks that take all possible evacuation scenarios into account. Capacity extensions for the transportation network of a certain region are determined in the first stage. In the second stage, a system optimal static traffic assignment problem is considered to achieve a solution for the evacuation traffic flow. The trade-off of the minimization of the total evacuation time, total distance and traffic congestion is intended by Stepanov and MacGregor Smith (2009) with a multiobjective evacuation routing model on the static network that considers the demand of the origin nodes and the capacities of the destinations as well as of the links. Exactly one route is assigned out of a set of k-shortest paths to an origin-destination pair such that the weighted sum of the three objectives is minimized.

Ziliaskopoulos (2000) developed a linear model for a system optimum dynamic traffic assignment problem with a single destination that is based on the cell transmission model of Daganzo (1994, 1995). The cell transmission model (Daganzo, 1994, 1995) is a discrete approximation of the Lighthill, Whitham, Richards hydrodymatic model used to model traffic evolution. The street network is divided into cells such that in one period a vehicle can travel trough the cell in light traffic. The time horizon is divided into time periods of equal length. These cells are connected with connectors through which flow can change a cell. Every period, the network situation is updated regarding flow conservation, inflow capacity in and out of cells and total capacity within cells. The travel time is implicitly modeled in the construction of the cells and the length of the period. It is not explicitly used like, for example, in the flow conservation constraint of a dynamic network flow model. The model of Ziliaskopoulos (2000) itself builds the basis for some evacuation models in the regional environment: The linear optimization program presented in Chiu et al. (2007) models a mass evacuation problem using a dynamic traffic flow optimization model that is based on the formulation of Ziliaskopoulos (2000). The loading pattern is not given a priori, it is determined with the model. Liu et al. (2006b) model a staged evacuation process on a network with a predefined evacuation zones, where the starting time to begin the evacuation of each zone has to be determined. With the start of the evacuation in a certain zone, the predefined loading pattern loads the flow onto the network of an evacuation zone. They present in Liu et al. (2006c) a revised cell transmission model that is designed for large-scale networks. This model uses a revised flow propagation formulation and allows different cell sizes. Liu et al. (2006c) propose two evacuation models: a model that maximizes the number of evacuees reaching the sinks within a given time horizon and a model that minimizes the total time a given amount of evacuees are within the evacuation network, respectively.

Uncertainty aspects are incorporated in the following cell transmission framework: Road capacities may be uncertain in an evacuation situation. The capacities may decrease for example by flooding. Yazici and Ozbay (2007) take link capacity changes into account by introducing probabilistic capacity constraints. Additionally,

they use the solution of the model to determine the capacity of shelters that are associated with the given sinks. Ng and Waller (2010) suggest an evacuation route planning model that takes the uncertainty of demand as well as the uncertainty of road capacity into account. The parameter values of a cell transmission-based evacuation model are adjusted such that a more conservative plan is generated than without the manipulation of the values. The values of the demand are increased and the capacity values are decreased subject to certain assumptions. A robust optimization approach for evacuation planning is developed by Yao et al. (2009). They focus on demand uncertainty. A "threat level" weight is introduced into the objective function that is used to penalize a solution where evacuees are still in the evacuation area at the end of the time horizon.

In all above-presented approaches, the capacities are known in advance. That means, the evacuation routes or traffic routing for the case of the evacuation of a region is already determined. In Sect. 2.2, we will give a survey on optimization models that incorporate traffic management strategies like the temporally reversal of lane in the case of an evacuation.

2.2 Evacuation Models with Traffic Management Strategies

Traffic management strategies that are used for evacuation planning like lane-reversal operations are modeled with optimization models. The temporary reversal of lanes of certain street segments are also known in rush-hour traffic. Zhang and Gao (2007) present for example a bi-level programming model that reallocates lanes for rush-hour traffic.

Traffic conflicts within intersections are the crossing of lanes and the merging of lanes. Cova and Johnson (2003) developed a mixed integer programming model that minimizes the total travel distance while forbidding intersection crossing conflicts and allowing a fixed number of merging conflicts. The network is constructed lane-based, i.e. each lane of every considered street segment, also every lane within intersections, are depicted by an arc. The intersection subgraphs consist of nodes that represent the access of every lane. That means, if four lanes access an entrance of an intersection then four nodes are generated for this entrance of the considered intersection.

Certain network flow problems with the goal to determine an optimal arc reversal are NP-hard. Rebennack et al. (2010) investigated the complexity of network flow problems, where the possibility of arc reversal is given. They show that the maximum dynamic flow problem with arc reversal capability having a single source and a single sink is polynomial solvable. In contrast, the maximum dynamic network flow problem with arc reversal with only an additional source or sink turns out to be NP-complete. Moreover, they show that the dynamic transshipment contraflow problem is NP-complete, even with only two sources and one sink or only one source and two sinks. A directed network with sets of sources and sinks, capacities and symmetric travel times on arcs is given. Then the dynamic transhipment

contraflow problem asks, if there exists a feasible flow within a given time bound T, where it is allowed that each arc is reversed once at time 0. The dynamic network flow problem of minimizing the total cost resulting from arc switching costs proves to be NP-hard. Kim and Shekhar (2005) consider a similar dynamic contraflow problem, where a network with sets of sources and sinks is given (each source has a initial occupancy) and each arc has a capacity and a travel time. The contraflow problem asks, if there exists a fixed contraflow network configuration such that the minimal evacuation time is lesser or equal to a given time bound T. They give a sketch of a proof that the contraflow problem is NP-complete.

The following models restructure the traffic routing for the case of an evacuation with traffic management strategies like lane-reversal, addition of lanes or the consideration of traffic conflicts and describe the traffic flow over time.

Tuydes and Ziliaskopoulos (2006) propose a linear optimization model based on the cell transmission model for traffic flow that includes the capability of the reversal of lanes for the case of evacuation. The decision variable corresponding to the number of lanes is assumed to be continuous. The proposed solution method is a tabu search-based heuristic algorithm incorporating results of simulation.

A linear cell transmission-based optimization model is also investigated by Kimms and Maassen (2011b). The optimization model incorporates the level of danger of different parts of the network in the objective such that it is more preferable to use streets with a lower "danger" level. The direction of lanes is assigned afterwards depending on the result of flow using a cell. Kimms and Maassen (2011a) extend their model introducing different cell sizes as well as incorporating continuous decision variables representing the numbers of lanes. The goal is to achieve an optimized traffic routing consisting of one-way streets. Crossing conflicts, "touching" conflicts and the merging of lanes are prohibited, and the number of turning directions within an intersection that can be used by traffic are bounded. "Touching" conflicts are understood as conflicts that may be caused due to a limited amount of space within intersections (see for a detailed explanation Kimms and Maassen 2010b): Consider the four directions that are generated if two disjunct pairs of entrances of an intersection are chosen and each of the pairs generate two directions. Then exactly one direction out of the four can be traveled by flow to avoid a "touching" conflict. Kimms and Maassen (2010a) present heuristic approaches that are based on a shortest path approach and the computation of a feasible solution based on the solution of an auxiliary model defined on the static network.

The cell transmission-based mixed integer programming model of Peeta and Kalafatas (2008) gives the opportunity that predefined network design options like lane-reversal, lane addition on certain street segments are chosen and prohibits crossing conflicts while minimizing the cumulated sum of total time spent in the network. The network load (demand per time interval) is given, the costs of network design options are included and the total costs of implementing the network design options are restricted by a given bound. The costs of implementing e.g. a lane-reversal operation are understood as the cost of special equipment like electronic variable signage or the cost of training the personnel. They (Peeta and Kalafatas, 2009) propose a similar model considering just lane-reversal operations

and investigate a test network varying the values of the parameters population size, number of contraflow operations and the distribution of the origin-destination demand.

Xie et al. (2010) and Xie and Turnquist (2011) introduce a lane-based evacuation problem with a bi-level model that determines a reallocated fixed traffic routing for the evacuation case. The capability of lane-reversal is integrated, crossing conflicts are prohibited and merging of lanes is allowed. The traffic management operations are presented for the case of two lanes for each street segment. The upper level problem seeks in both cases to optimize the system-wide evacuation performance. The lower level problem assigns traffic flow to the corresponding network components building a user-equilibrium. In Xie et al. (2010) the model describing the traffic flow is realized with a mixed integer linear cell transmission-based model, in Xie and Turnquist (2011) the traffic flow is described by a mixed integer linear dynamic network flow problem. For both approaches a corresponding integrated Lagrangian relaxation and tabu search approach is suggested.

Kim and Shekhar (2005) solve a quickest transshipment problem with lane-reversal heuristically. They propose heuristic approaches: a greedy algorithm that assigns lanes depending on the optimal values of flow of a minimum cost flow defined on the time-expanded network, a heuristic based on simulated annealing metaheuristic and a bottleneck heuristic (Kim et al., 2008). The basic idea of the latter one, is to identify bottlenecks and increase its capacity by lane-reversal iteratively.

2.3 Further Problems in Evacuation Planning

In an evacuation scenario, there are not just the evacuees involved that travel by vehicle to the exits of the evacuation zone, but there are also pedestrians and also emergency response vehicles that have to travel to the evacuation zone and within the evacuation zone in counter direction to the evacuees to reach places where they are needed. These are services like the transportation of emergency equipment into the evacuation zone or buses and emergency ambulances that support evacuees that are not able to self evacuate. The buses and ambulances may have to travel multiple time into and out of the evacuation zone.

Liu et al. (2006a) present an approach for the evacuation of pedestrians caused by flood. The objective is to determine the evacuation route to minimize the evacuation time taking the time-varying travel time on arcs into account. In the case of a flood disaster the water depth varies over time and influences the walking speed of people.

Chiu and Zheng (2007) study a cell transmission-based dynamic traffic assignment model that models different groups of evacuees and emergency response vehicles. A priority factor is included in the objective that minimizes the priority weighted sum of total travel times of vehicles to the corresponding destination. Xie and Turnquist (2009) consider in the presented evacuation problem flow of evacuees and flow of emergency vehicles. They propose an optimization model

with bi-level structure that needs the number of lanes assigned for the emergency vehicles in advance and determines the traffic routing for the evacuation flow on a static network. Crossing conflicts are prohibited and the reversal of lanes is allowed. But they do not discuss, if there exists a feasible solution without crossing conflicts for every network and demand pattern of evacuees and emergency vehicles. Indeed there are simple examples, where no feasible solution without a crossing of two lanes exists. Such an example is presented in Chap. 7. A similar problem consider Kimms and Maassen (2010b). They incorporate the flow of rescue teams that may travel to a place within the evacuation area or commute between a safe and an endangered place. A street segment can be either used for evacuation traffic or for rescue traffic in different time periods. I.e. in certain time periods street segments have to be closed for evacuation traffic. The assignment of lanes is static, but the permission of flow to use the corresponding street section may vary over time. The rules of traffic routing are the same as introduced in Kimms and Maassen (2010a) and have to be valid for the rescue flow and evacuation flow separately.

There are also multicommodity problems that provide in the same time evacuation planning activities as well as disaster response activities: Özdamar and Yi (2007) suggest a location-distribution model for the coordination of logistics support and evacuations in disaster response activities. Here, evacuation is understood as the evacuation and transfer of wounded people to emergency units. The distribution of commodities like medical materials, medical personnel or food to locations in the affected area, the transportation of wounded people to hospitals or emergency centers and the determination of temporary emergency centers is formulated in a mixed integer capacitated location-routing model. It minimizes the delay in satisfying demands of prioritized commodities. In Özdamar and Yi (2008), they present the problem of the evacuation from affected areas to medical centers during the initial response phase and logistic transport from supply centers to distribution centers in affected areas and they suggest a heuristic based on greedy neighborhood search. Also Osman et al. (2009) incorporate the evacuation problem in a disaster response problem. They present a general transportation routing problem for disaster areas that considers the transportation of materials and people out of a disaster area and the transportation of materials and people into the disaster area.

Services like the amount of provided beds of shelters are restricted. Hence, the decision what shelters in the safe zone are operated may be incorporated in the formulation of traffic assignment problems for evacuation scenarios. A location-allocation model that captures both, the choice of shelters and the network flow problem, is presented by Sherali et al. (1991). They propose a non-linear mixed-integer programming problem that takes the available shelter staff into account and describes the evacuation flow on a static network, where flow is assigned to capacitated links from sources to destinations. Kongsomsaksakul et al. (2005) propose a location-allocation model for evacuations planning with a bi-level programming formulation. With the upper level the locations of shelters are chosen among a given set, and the lower level determines the allocation of sources to shelters and assigns the traffic of the evacuees to routes to the corresponding shelter. A genetic algorithm is presented to solve the proposed model heuristically. Saadatseresht et al.

(2009) suggest a multiobjective optimization problem that assigns building blocks to safe areas regarding the distance, the population size of the building block and the capacity of the corresponding shelters in the safe areas.

Besides the reallocation of people to safer locations due to a disaster, people may need help of emergency services of ambulances or of firefighters. During a disaster some of the facilities like ambulances or fire stations may be damaged. Huang et al. (2010) consider the problem of choosing locations for emergency service facilities taking large-scale disasters into account, where some facilities may become inoperable. They propose a variation of the p-center problem.

Another problem is the decision if to order an evacuation. For example, Regnier (2008) investigates the problems of evacuation decisions concerning whole regions or cities due to hurricanes. Evacuation decisions because of the risk of hurricanes are based on uncertain data. The forecasts cannot predict with 100% certainty if a hurricane will strike a special region. False evacuation alarms can cause costs like the costs for preparation or the "cost" of non compliance of people in the future. Therefore a trade-off between the danger to residents and the costs of false evacuation has to be made. To improve the quality of these decisions, the uncertainty of the forecasts can be measured and incorporated in the decision process. To support the evacuation decision, Regnier (2008) develops a decision support model that estimates the uncertainty of the forecasts based on historic hurricane tracks.

Cova and Church (1997) consider a problem that evaluates the maximal "vulnerability" of a community in potential evacuation regions that are endangered by moving hazards with a high level of uncertainty. As examples for that kind of hazards urban firestorms or toxic spills on highways are mentioned. The vulnerability of a node representing an intersection in the considered network is described by the average population per exit lane. The developed model is a nonlinear binary optimization problem and has to be applied for every node in the network. To solve the problem for arbitrary large networks in adequate time, Cova and Church (1997) propose a heuristic algorithm.

2.4 Simulation Approaches

Simulations are used to evaluate given traffic networks under a certain or under different scenarios. Simulation methods are also applied to decision support in evacuation planning. In the considered traffic networks, bottlenecks are identified and the evacuation time is estimated. Based on these results, traffic operational strategies can be implemented. Macroscopic simulation models for regional evacuation planning are for example NETVACI (Sheffi et al., 1982) or MASSVAC (Hobeika and Jamei, 1985) and microscopic simulation models are for example CORSIM (e.g. used in Theodoulou and Wolshon, 2004) or VISSIM (e.g. used in Edara et al., 2010). More simulation models, macroscopic as well as microscopic models, that are constructed for regional evacuation are listed for example in Pel et al. (2010) or Edara et al. (2010).

Frameworks for regional evacuation modeling are reviewed and proposed e.g. by Southworth (1991) and Barrett et al. (2000). Southworth (1991) considers a framework of regional evacuation modeling as a five step approach: traffic generation, traffic departure times, destination selection, traffic route selection and implementation of traffic management controls. He summarizes necessary data like the estimation of population, the estimation of the number of vehicles or the determination of the traffic loading curve. Difficulties arise for example for the estimation of day time population.

Barrett et al. (2000) consider an evacuation modeling framework for hurricane evacuation to determine short range strategies during the storm. A goal is to determine real time operational strategies and to develop a model that can analyze large regional networks in real time that incorporates traffic conditions based for example on the data of road sensors or law enforcement personnel.

Simulation tools provide generally various possibilities of alternative scenarios like different weather conditions or lane management strategies (see e.g. Sheffi et al. 1982, or the "knowledge based mode" in TEDSS, Hobeika et al. 1994). Measures are e.g. the estimated evacuation time (network clearance time) or congestion on links. Components of traffic simulation models are generally the network loading, trip generation, traffic assignment and the update of the traffic condition like travel times. These components are iteratively operated until all vehicles have left the network (see e.g. Hobeika et al., 1994).

There are different approaches of simulation tools for different disasters like nuclear accidents, hurricanes, floods or wild-fires:

The simulation approach of Sheffi et al. (1982) was motivated by the requirement of estimating the clearance time for areas surrounding sites of nuclear power plants. Sheffi et al. (1982) provide a macroscopic traffic simulation model called NETVACI to simulate traffic patterns during a mass evacuation of an area. Also Hobeika et al. (1994) present a decision support system TEDSS (transportation evacuation decision support system) for the development of evacuation plan around nuclear power plants. The proposed model is based on the simulation tool MASSVAC that simulates the dynamic movement of traffic on the highway network. The proposed evacuation policy is that evacuees have to leave the danger zone (10 mile zone) first before they can drive to the proper shelter somewhere in the safe area. Traffic management strategies like the permission to use shoulder lanes or lane-reversal operations may be implemented in a scenario and may be evaluated. An update of the above introduced tool is presented in Hobeika and Kim (1998). An user equilibrium assignment algorithm is incorporated. The user equilibrium requires that the travel times are equal on all used paths for each origin-destination pair and that no other path leads to a lesser travel time.

Southworth and Chin (1987) use MASSVAC to investigate alternative traffic routings for the case of an emergency evacuation due to flooding that results of a dam failure. Pel et al. (2010) consider time-varying networks that map the progress of a moving hazard. They investigate evacuation scenarios due to flooding with the simulation model EVAQ in a case study of the Dutch city Rotterdam.

Farahmand (1997) presents a simulation model applied for hurricane evacuation planning in the US-state of Texas in the Rio Grande Valley. Different

scenarios depending on hurricane categories are investigated. Williams et al. (2007), Theodoulou and Wolshon (2004) and Edara et al. (2010) use microscopic simulation models to evaluate freeway networks for the case of a hurricane evacuation in North Carolina, Louisiana and Virginia, respectively. Traffic management strategies like lane-reversals are taken into account and scenarios depending e.g. on storm categories are investigated. Edara et al. (2010) considers especially large-scale hurricane networks.

Cova and Johnson (2002) use microscopic traffic simulation to study evacuation plans in the urban-wildland interface. An urban-wildland interface is an area "where urban growth encroaches into fire-prone wildlands" (Cova and Johnson, 2002, p. 2211). This approach is applied to the Emigration Canyon in Utah for different scenarios in terms of the number of vehicles per household and the possibility of the usage of second access road.

Different evacuation strategies are investigated for different road patterns by Chen and Zhan (2008). They study the performance of simultaneous and staged evacuation strategies using agent-based simulation. For the staged strategies the evacuation area is divided into zones, and these zones are evacuated in different sequences. The evacuation strategies, the simultaneous and all possible staged strategies, are applied to three different types of road network structures, i.e. a grid road structure, a ring road structure and a real road structure from the City of San Marcos (Mexico). The results of the study of Chen and Zhan (2008) are that no evacuation strategy is the most effective strategy across the analyzed network structures and that the effectiveness measured by the overall evacuation time of a strategy depends on the network structure and the density of the population.

2.5 Summary

The literature review indicates that evacuation planning is an important research topic. Simulation approaches are developed for various situations like hurricanes, floods or nuclear accidents that may cause the need to evacuate a certain area (compare Sect. 2.4). These hazards may endanger a population and an evacuation may be the best choice to protect the affected population.

Dynamic network flow models that describe evacuation problems like the reallocation of evacuees to a safe zone in the minimum amount of time (the quickest flow problem) or the reallocation of the maximal amount of evacuees in a given amount of time (maximum dynamic network flow problem) are studied and investigated with different properties of the attributes. The optimization models are applied to evacuation planning for buildings as well as regions with time- and flow-dependent attributes. Dynamic traffic assignment models are applied to optimize evacuations from regions incorporating also aspects of uncertainty. The evacuation of a region may be the evacuation of a district of a city, a whole city or may affect multiple cities. All these problems and models (presented in Sect. 2.1) consider the capacities of the arcs, and hence the traffic routing, as fixed. The traffic routing of the considered street network is known and is not part of the optimization.

With the incorporation of the possibility of lane-reversal operations for street networks, traffic routing becomes part of the optimization. Scarce capacity has to be allocated to the two different directions of street sections or, if only one-way streets are intended, the capacity has to be allocated to exactly one of the two directions. Additional decision variables are necessary to model the traffic routing for example with integer number of lanes or indicator variables that determine which direction of a street segment is permitted to be traveled by traffic flow. Dynamic network flow problems become harder to solve if there are more than one source or more than one sink.

Studies on the optimization of traffic networks that intend to optimize the traffic routing with the capability of lane-reversal and the prohibition of crossing conflicts are rare. There are recently Kimms and Maassen (2010a,b, 2011a), Peeta and Kalafatas (2009), Xie et al. (2010) as well as Xie and Turnquist (2011). Each of them considers the progress of traffic flow over a certain time horizon, whereas each of them takes different definitions of crossing conflicts into account. Peeta and Kalafatas (2009) only mention that the crossing of flows is prohibited. Kimms and Maassen (2011a) consider one-way streets and allow a limited number of chosen directions within intersections. Xie et al. (2010) and Xie and Turnquist (2011) lean upon the definition given in Cova and Johnson (2003). They present lane-based models for only two lanes per street segment and intersections with four entrances/exits.

The work of Bretschneider and Kimms (2011a,b) can be cited in Sect. 2.2 (Evacuation Models with Traffic Management Strategies). The traffic re-routing measures lane-reversal, certain restrictions of merging of lanes and the measure prohibition of crossing conflicts are considered in dynamic network flow models. In this work and in the articles Bretschneider and Kimms (2011a,b) which build the basis of parts of this work, a direction-based network will be investigated. I.e. not every lane is modeled in the network like in Xie et al. (2010). But the idea of crossing conflicts is based on the lane-based definition given in Cova and Johnson (2003), too. The lanes within the network can be allocated such that no crossing conflict occurs if the assigned number of lanes is feasible with respect to the proposed constraints. A notation for the network will be introduced such that all crossing conflicts can be determined generally for all intersections such that the determination of directions which cross is comprehensible. Contraflow operations that allow the partly reversal of lanes and contraflow operations that lead to one-way streets are studied which have an effect on the number of crossing conflicts.

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