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COMPARISON OF HIERARCHICAL NETWORK DESIGN SHAPE GRAMMARS FOR ROADS AND INTERSECTIONS

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1 INTRODUCTION

Travel has always been the lifeline of urban systems, in their economic and social aspects. The economies of urban systems depend and benefit substantially from efficient transport systems, agglomeration processes and low trading costs. Considerable gains in overall productivity of urban systems are achieved with coherent infrastructure and low construction, user and maintenance costs (Venables, 2007; Graham *et al.*, 2009). With increasing travel possibilities during the last two centuries, also the experience of different places increase for the people. Meanwhile, e.g. the share of leisure trips is one of the highest shares of all trip purposes in transport surveys in an increasing number of countries.

The size of urban systems will grow as population still growths and rural depopulation continuous in the near future. More people will live in urban areas to take advantage of synergies for their work and social life. Therefore, construction and reconstruction of networks have to be planned in an adequate way to save future traveling and maintenance costs. Sufficient transport supply infrastructure is required to fulfill this growing travel demand. This research addresses urban systems of about 100´000 inhabitants, with the overall aim of even larger systems. Private car transportation in considered, with potential applications for other modes.

The literature on network design covers a large variety of topics. Firstly, there is a distinction between network optimization and network design. Network optimization deals with existing networks which are improved with respect to the benefit-cost ratio of the alternatives (Stopher and Meyburg, 1976; Yang and Bell, 1998; Vitins and Axhausen, 2009). Secondly, a large proportion concerns the historical development of network design, including various case studies, e.g. Xie and Levinson (2009). Thirdly, a major proportion of contributions is related to operational research methods. Within these contributions, there is a strong emphasis particularly on the optimization of existing networks, e.g. Guihaire and Hao (2008). Few only tackle the construction of new networks (Yamins *et al.*, 2003; Daganzo, 2010). Finally, contributions with a shape grammar approach are provided for urban planning and design. Shape grammars describe in the form of rules how different types of network elements are added to each other, e.g. if a highway can be crossed by an arterial road or if local roads can be joined with larger intersections of high capacities. The area of shape grammars is located within the field of mass optimization for urban systems. Shape grammars have a strong architectural background and also includes aspects of spatial planning, e.g. Marshall (2005). Alexander *et al.* (1977) were one of the first who stressed the importance of shape grammars in urban planning. However, contributions of shape grammars for transport network design are scarce. Besides scientific contributions, shape grammars for transport network design exist in handbooks and standards (American Association of State Highway and Transportation Officials, 2004; Institution of Highways and Transportation, 1997; VSS, 1994; Forschungsgesellschaft für Straßen- und Verkehrswesen, 2008). However, they mostly lack a fundamental research base as well as systematic evaluations, e.g. cost-benefit-analyses, and exclude explicit recommendations. Transportation network shape grammars are also in line with ongoing achievements in the field of shape grammars for building construction (Talen, 2009; Carmona *et al.*, 2006).

A key advantage of shape grammars is their ease of application in planning processes. Practitioners prefer robust and reliable methods. Shape grammars satisfy these requirements but are at the same time adaptive to different scenarios and can incorporate even spatial planning rules and interaction with other networks, like power supply or communication. Shape grammars can serve as decentralized investment rules. Moreover, the application of shape grammars needs very low computational requirements. Shape grammars are therefore increasingly applied in large scale urban modeling and simulations (Vanegas *et al.*, 2009; PROCEDURAL, 2011; Jacobi *et al.*, 2009). Thus, a scientific base for shape grammars would be an important contribution to the urban and transport planning community. Additionally, the research results are intended to serve as future recommendations in handbooks.

This paper introduces an approach independent of existing network data or case studies because existing transportation network are often biased due to history. Instead, artificial transport networks are designed that follow the shape grammars under consideration. The resulting networks are then compared with regard to an efficiency measure that accounts for infrastructure cost and generalized costs of travel. The aim is to see to which extent shape grammars influence the result of the efficiency measure and, thus, the performance of the networks.

The network design method is based on a modular approach and is suitable for the implementation of shape grammars. Network elements are exchanged between different candidate networks to generate more efficient networks regarding a given efficiency measure. The design method is a merger of a Genetic Algorithm (GA) and an Ant Colony Optimization (ACO). Both the GA and the ACO can be applied for discrete optimizations and are suitable for network generation problems. They are merged to gain efficiency regarding computation time. Additionally, the efficiency of the algorithm increases by considering characteristics of transport networks, e.g. coherence, avoidance of dead ends or detours.

In the following, shape grammars are introduced as well as infrastructure types and corresponding costs. The major findings regarding the network design method and the impact of the shape grammars are shown in the subsequent section. Afterwards, the resulting networks with the implemented shape grammars are compared and discussed.

2 TRANSPORT NETWORK SHAPE GRAMMARS

Network grammar rules describe how roads and intersections of certain types or hierarchical levels may be joined with each other; e.g. which road types are connected to each other, if a four-lane road can be crossed by a local access road, or if a roundabout can have five or more arms. Different handbooks and standards are scanned for comparison of the shape grammars. Only a few handbooks account for shape grammars in network design. Three types are presented below, including USA, England, Germany and Switzerland. Almost all of them follow a different approach regarding a hierarchical link type network constitution. The following list shows the grammars regarding adjacent link types. A, B, C, D represent different link types.

- Restrictive network design: A-A, A-B, B-B, B-A, B-C, C-B, ...; e.g. Switzerland (VSS, 1994)
- Moderate flexibility in network design: A-A, A-B, avoid A-C, ...; e.g. USA and England (American Association of State Highway and Transportation Officials, 2004; Institution of Highways and Transportation, 1997)
- Adaptive network design: A-A, A-B, A-C, B-A, B-B, B-C, B-D, ...; e.g. Germany (Forschungsgesellschaft für Straßen- und Verkehrswesen, 2008)

A strict hierarchical layout is leading to a network with joined links that differ in one level of hierarchy at most. If the recommendations are more relaxed, joined links can differ in more than one level of hierarchy. It can be seen that the considered guidelines differ in their recommendations for a hierarchical structure within network design. In Switzerland, the design rules are more restrictive than in USA or Germany. The impact of such recommendations and their differences are crucial and discussed in this work.

3 METHODOLOGY OF THE MODULAR NETWORK DESIGN APPROACH

The initial setting for the design of the road networks is described in the following section. The utility function for the assessment of the transport networks is defined subsequently. Then, the algorithm for generating optimal network design is introduced as its convergence behavior.

3.1 Initial network settings

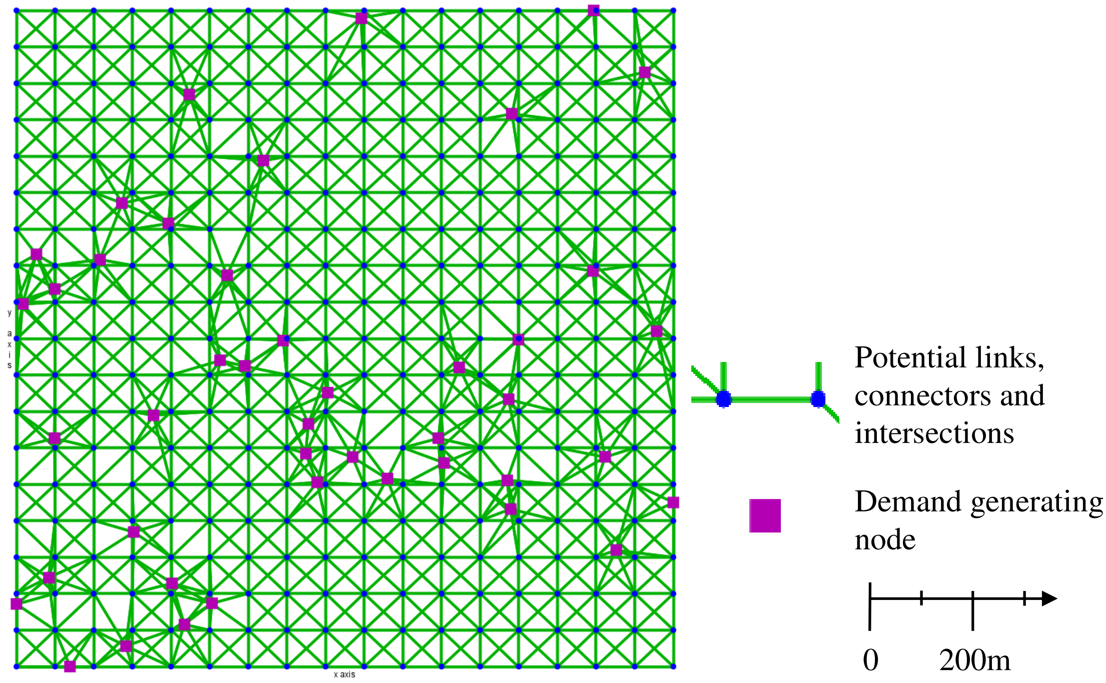
The goal is to generate a road network with a set of shape grammars in an optimal way regarding the utility function. The candidate links are initially distributed on a featureless plane of a preliminarily given size. The candidate links comprise the entire search space (see Figure 1 for an example). The advantage of the featureless plane compared to real world cases is its lack of history. Links are joined at nodes which are currently fixed in space. Overpasses are allowed to a certain extent. The demand generating nodes, also called centroids, are shown as squares, and are connected to the network using connector links. They remain fixed in space. In Figure 1, the demand generating nodes are originally derived from the city of Winterthur, close to Zurich, with about 100'000 inhabitants. Travel demand is given in advance for each pair of demand generating nodes. Travel times on links depend on the current traffic flow and are determined using the BPR function (U.S. Bureau of Public Roads, 1964). The budget constraint forces the algorithm to keep infrastructure low and therefore the number of direct paths between pairs of demand generating nodes.

Link and intersection types are assigned to the links, which are element of the proposed network. However, links and intersections types can only join if they follow the shape grammars, which are explained in more detail below.

3.2 Utility Function

The designed networks are evaluated to capture the effect of the shape grammars which are implemented in the design process. The measure to evaluate the network, i.e. the utility function, has to be defined in advance and should be independent of

Figure 1   An example network with all candidate links, nodes and demand generating nodes.



the grammars and the network design method. The most commonly used measures are travel time and cost, followed by construction and maintenance cost. Currently, the utility function adds travel time and construction costs. Calculation of total travel time is the most computationally costly measure; the function can be easily extended with further variables without adding much computation time. A penalty factor is added when the infrastructure costs exceed the budget constraint.

$$f = \left(\sum_{o=1}^{O} \sum_{d=1}^{D} demand_{od} \cdot traveltime_{od} \right) \cdot \gamma + I + p \cdot (I - B)$$

o: Origin demand generating node.
d: Destination demand generating node.
γ: Weighting factor (value of time as a recourse), extrapolated for a year.
I: Infrastructure costs as annuity.
p: Penalty factor, $p = 0$ when $I - B < 0$.
B: Budget.

3.3 Integrated Ant Colony and Genetic Algorithm (IACGA)

In the following, a short overview over the design method for the transport networks is provided. The reader is referred to (Vitins *et al.*, 2011) for a technical description of the network design algorithm. The design method employs network elements from networks of the previous iteration, called parent networks, to generate the new network.

These network elements are reassembled iteratively in an efficient way to generate new networks, which outperform the parent networks. The method is briefly introduced in the following.

The design method benefits from both the advantages of the GA and the ACO methodologies, and therefore is further called Integrated Ant Colony and Genetic Algorithm (IACGA). As in a standard GA approach, the IACGA is based on population of individuals. Each individual is representing a candidate network, which improves over time using a recombination method. The recombination of two parent individuals leads to a new offspring individual that becomes a member of the next generation. Only an offspring representing a network with an improved overall score, determined with the utility function, is transferred to the next generation. Offsprings representing networks with lower scores, compared to the parents, are rejected in the next generation.

Similar to an ACO, a learning ability is implemented in the IACGA. The motivation is to improve the weak learning ability of a standard GA. A standard GA looses the information of the previous generations, because the only information available is stored in the chromosomes of each individual of the current generation. The IACGA employs the results from all previous populations and stores this information, which is later available for further network recombination. Thus, the recombination method designs fitter individuals and simultaneously generates a lower fraction of infeasible networks. Additionally, the nature of transport networks is taken into consideration, such as assuring a coherent connected graph between the centroids, or avoiding unnecessary detours.

Methods considering both a GA and an ACO already exist, often applying both methods sequentially or in parallel. Only White and Yen (White and Yen, 2004) introduce an integrated GA which is based on very similar structures as the IACGA described here, also merging an ACO and GA. The proposed algorithm is applied to the Traveling Salesman Problem (TSP) successfully. However, the TSP excludes overpasses, cycles and only optimizes the lengths, in contrast to transport networks, which allows cycles and request a utility function that is computationally time-consuming. In the following, we introduce the IACGA step by step, an overview is given in Figure 2.

1. The initial population is generated which consists of individuals each representing a randomly designed transport networks. The initial population serves as a parent population in the first iteration.
2. Two randomly chosen individuals of the parent population are merged according to the recombination procedure. In a standard GA, the transport network is translated into a binary string code called chromosome. The recombination procedure of the IACGA however is based on the phenotype, which means that the recombination procedure is conducted in the network itself, without coding a chromosome. Additionally in the IACGA, network elements as links and intersections are not exchanged randomly but with the goal to achieve an improved offspring individual with a better score. Thus, the potential candidate network elements are chosen according to a probability function. The probability function of choosing candidate links accounts for the success of the networks, which were generated in previous generations. If a candidiate link is under consideration, which already was implemented in previous networks with high scores, it is more likely that the candidate link is chosen. This is because pheromone density

τ_{ij}^g on this link is high. Links are chosen with probability p_{ij}^g, where the scores of the previously generated networks are stored as pheromones in τ_{ij}^g (see step 5 for further details).

$$p_{ij}^g = \begin{cases} \dfrac{e^{\alpha\tau_{ij}^g} e^{\beta r}}{\sum\limits_{l_{ij} \in L_{Parents}} \left(e^{\alpha\tau_{ij}^g} e^{\beta r} \right)} & \text{, when } l_{ij} \in L_{Parents} \\ 0 & \text{, otherwise.} \end{cases}$$

p_{ij}^g: Probability of choosing link *i-j* in iteration *g*.
τ_{ij}^g: Pheromone density in iteration *g* on link *i* - *j*.
$e^{\beta r}$: Accounts for randomness.
α, β: Parameters, subject to calibration.
$L_{Parents}$: Set of links l_{ij} which are present in at least one parent network.

Links from both parents are chosen with probability p_{ij}^g until the budget constraint is depleted (step 3 for more details). Links which are not element of one of the parent networks are not implemented in the new network. Therefore, the initial population size has to be large enough to comprise all relevant links.
3. The budget constraint serves as the upper bound when generating new networks. Because the initial networks are generated randomly, they most probably exceed the budget constraint. Therefore, the budget constraint is relaxed at the beginning of a network generation run. However, individuals with networks exceeding the constraint will get penalized; they are more likely outperformed by other generated networks.
4. Step 2 and 3 are repeated four times with new parent networks and only the best offspring is added to the offspring pool. For this purpose, the parent networks are randomly chosen from the parent population. The parent individuals are returned if their candidate offspring is outperformed by another candidate offspring generated by other parents. This procedure reduces the risk of generating infeasible networks. Currently, the number of trials is set to four, which leads to only very few infeasible networks, but this parameter is subject to further calibration. Step 2 - 4 are repeated until a new population is generated with the same number of individuals as the previous population.
5. After a new population is generated, the pheromones on all candidate links are updated with the scores of the individuals of the new population. The pheromones are responsible for preserving the information of success or failure of the network individuals and are a measure of success. Therefore, the score of a network individual is used to determine the amount of the pheromones τ. The pheromone amount is saved on each links element of the network. When two network individuals contain the same link, the higher score is applied for the pheromone amount. The evaporation rate δ is responsible for the adaptive learning process, similar to an ACO.

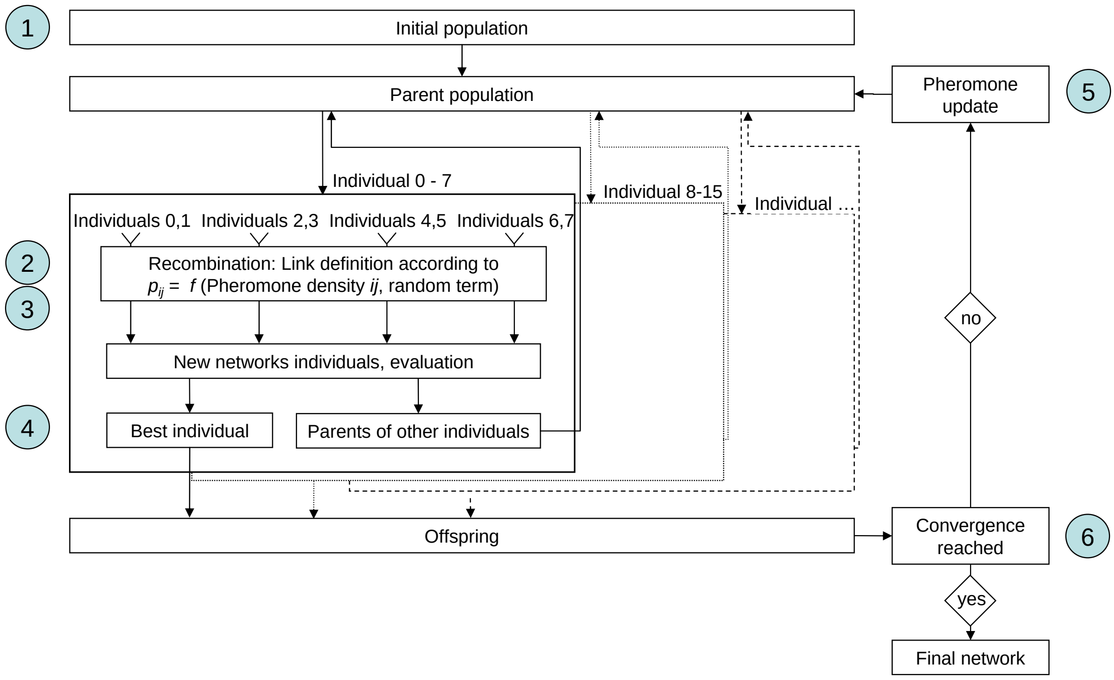
$$\tau_{ij}^g = (1 - \delta) \cdot \tau_{ij}^{g-1} + \max(\Delta\tau_{ij}^g)$$

δ: Evaporation rate.
$\max(\Delta\tau_{ij}^g)$: Score of the best individual out of all networks containing link *i* - *j*.

6. The algorithm returns to step 2 if the convergence criterion is missed. Convergence is reached when the pheromone densities on single links are not changing any more or when a substantial part of the population consists of individuals with the same

networks. The cutoff criterion is responsible for stopping the population generation when no network improvement is expected in further generations. The best performing criterion so far applies the pheromone density on links. This criterion bases on the fact that only links which are element of high performing networks with high scores can maintain their pheromone densities on a high level. Thus, when reaching the optimum network, the pheromone densities on all links are decreasing except the densities on the links of the optimum network. This behavior is a main requirement for a proper convergence.

Figure 2 Overview over the IACGA with numbers referring to the text.



3.4 Geographical contraints

The building and maintenance costs of specific network links and intersections depend on the type, length or number, but also on terrain, tunnels or building density. Depending on the infrastructure budget, the resulting network highly depend on the costs assigned to the potential network elements. Therefore, when implementing network elements with high infrastructure costs, the infrastructure budget is depleted faster and the resulting network potentially differ from the origin network with standard costs. However, each potential link is more or less relevant for the overall network design. Potential links, which are expensive in their costs, may be replaced by parallel links. So the overall relevance of the network elements can also vary in contrast to other network elements.

Specific potential network elements, which are costly, may be still crucial for the overall network performance. These elements can still be of major importance of the overall network despite their high costs, e.g. tunnels. A trade-off between the more expensive link and potential detours arise during the network design process. Elements with a high total benefit cost ratio outperform the second elements with a lower ratio. One has to consider, that not a single network element is considered and its "stand-alone" benefit cost ration, rather the entire network is evaluated in the algorithm. This is a key advantage of the proposed algorithm.

Due to the network element costs, which can be assigned on each link individually, geographical constraints like variable terrain, e.g. slopes, underground, can be easily incorporated in the algorithm. An example is given in the Result section.

4 INITIAL SETTINGS AND SHAPE GRAMMARS UNDER CONSIDERATION

Two different initial settings are provided for comparison reasons (Table 1). In initial setting 1, the demand generating points are distributed evenly on an empty featureless plane. Initial setting 2 is derived from a real-world city (see Figure 1).

Table 1 Initial settings 1 and 2.

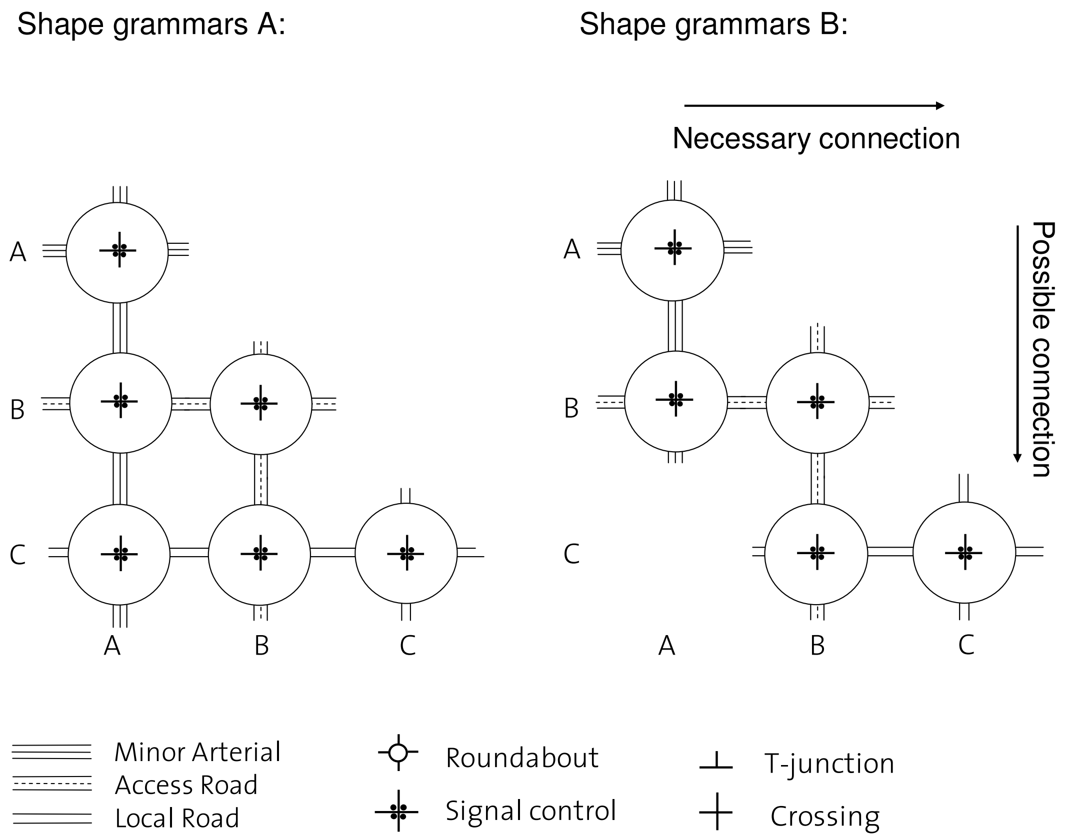
	# Centroids	# Candidate nodes	# Candidate links	Total travel demand [# vehicles/day]
Setting 1	25	225	1’624	~ 41’000
Setting 2	44	386	2’380	~ 130’000

Two different sets of shape grammars are implemented (Figure 3, derived from Marshall (2005)). Shape grammar A assumes that every link is allowed to be connected to another link of any type. When generating new networks, the different link hierarchies are distributed according to the link loadings on each link to optimize overall travel time. E.g., arterials are assigned to link with higher loadings, whereas local roads are assigned to links with lower loadings. Thus, a certain share of arterials, access and local roads is assigned to the network. The share of each link type is subject to the infrastructure budget and can not be determined in advance. That is because there is a trade of between the total length of arterial and access roads. Either more arterial or more access roads can be built, with consequences on travel times for network users. An iterative sampling determines the optimal share of each link type.

Shape grammar B is more restricted and states that links of a given hierarchy can only be jointed to links of the same or a neighboring hierarchy. Additionally, links of type X have to form a coherent network, which means that links of type X have to be connected to at least one other link of type X (indicated with arrows in Figure 3). Similar to the implementation of shape grammars A, link types are distributed according to link loadings to optimize overall travel time. Link types with higher speed limits and more capacity are assigned to links with higher loadings to minimize link travel time.

The infrastructure budgets of all networks are identical. Therefore, no scenario is created where only very expensive link types are implemented in the network. Shape grammar B is especially helpful in structuring the transport network due to a clear overview for the road users due their hierarchical setup.

Figure 3 Shape grammars under consideration.

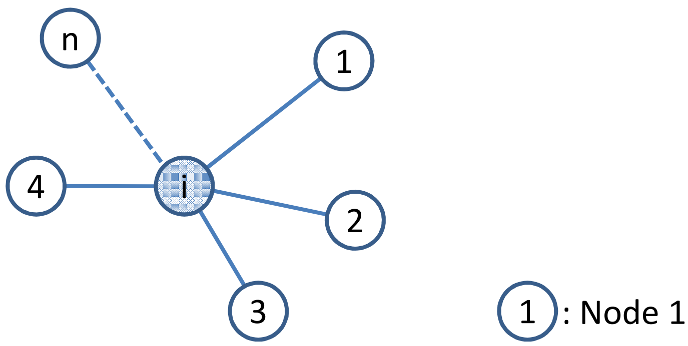


5 GEOMETRIC OPTIMIZATION

So far, the alignment of the intersections in space is maintained fixed during network design. Fixed link and intersection alignments are leading to a major reduction of the search space when designing a transport network. A fixed intersection alignment contrasts flexible, floating intersection alignment. The definition of link and intersection types still remain discrete, while the definition of the link alignment in space, including the node alignment, turns into a continuous decision. Floating intersection alignment encompasses flexible positioning of intersection in space. This accounts for more realistic network design. However, floating intersection alignment escalates the search space due to the additional degrees of freedom. Due to the growing complexity, this research currently applies the alignment optimization sequentially after network desing. The proposed alignment algorithm is described in the following.

In terms of transport networks, the lengths of the links have to be reduced, and therefore travel time and the outcome of the objective function have to be minimized to further optimize the transport network. The higher the network loading on a given link, the higher are the performance gains when the link is shortened in a further optimization process. The higher the construction costs on a given link, the higher is the overall cost reduction when the link is shortened in an optimization process. Two general cases can be observed in node alignment. The first case is rather simple and tackles all detours in a network. The detour is replaces with a direct link and therefore the rest of the network is not affected directly, except for the special case of a Braess Paradoxon (Braess, 1969). The second case accounts for nodes with at minimum three arms and needs to be elaborated in more detail. The optimal state is not defined a priory. Potentially, more than the shortest connection between the nodes is possible. Figure 4 refers to an abstract network example and the optimal alignment of node *i*.

Figure 4 Abstract example for further geometric alignment of node *i*.



Methods to tackle floating intersection alignment are scanned, emphasizing network and graph theory and application. The current implementation resembles Brandes (2001) and Kamanda and Kawai (1989) who contributed within graph theory. They apply a spring analogy for a network graph and therefore are situated in the field of forced based algorithms. Springs forces add up when springs are connected to each other. The forces have to cancel each other out. From an energetic perspective, each spring contains an internal potential energy. So the sum of the potential energies has to be minimized to reach a stable and most relaxed state.

Graph drawings cannot be immediately applied for transport networks. The links have certain variables like loading, speed, utilized capacity, which are not mirrored in spring properties accurately. Therefore, spring analogy is replaced with a more comprehensive approach, more suitable for transport networks. In the following formula, the volume delay function is approximated with the BPR function (U.S. Bureau of Public Roads, 1964) and complemented with a link cost term c_t.

$$f(x_i, y_i) = \sum_{l_{ij},\ j \in J_i}^{J_i} \left(\left(v_{l_{ij}} \cdot \frac{1 + \left(\frac{v_{l_{ij}}}{c_{l_{ij}}}\right)^4}{s_{l_{ij}}} \cdot VTTS + c_t(l_{ij}) \right) \cdot \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \right)$$

x_i, y_i: Coordinates of node i.
J_i: The set of adjacent links considering node i.
l_{ij}: Link $i - j$.
$v_{l_{ij}}$: Traffic volume on l_{ij}.
$v_{l_{ij}}$: Capacity of l_{ij}.
$s_{l_{ij}}$: Free flow travel speed of l_{ij}.
$VTTS$: Value of travel time savings.
$c_t(l_{ij})$: Infrastructure costs as a function of the link type of l_{ij}.

The geometric alignment problem and $f(xi, yi)$ are a nonlinear optimization problem of the following form:

$$\boldsymbol{x}^* \in \mathbf{R}^n \quad \text{with} \quad f(\boldsymbol{x}^*) \leq f(\boldsymbol{x}) \quad \text{for all} \quad \boldsymbol{x} \in \mathbf{R}^n$$

$f(x_i, y_i)$ is a nonlinear, twice continuously differentiable function. Several algorithms can be found in literature for solving nonlinear, twice continuously differentiable functions, e.g. in Fletcher (1987). Because of the Hessian matrix, which is positive semidefinite at each point, $f(xi, yi)$ is clearly convex and therefore has a minimum. $f(x_i, y_i)$ is expected to be convex for three adjacent links. However, $f(x_i, y_i)$ has a single minimum for an arbitrary number of adjacent links and also for any kind of network. These properties allow an application of a variety of optimization algorithms.

Due to lack of space, the descriptions and proofs for the optimization of $f(x_i, y_i)$ are kept scarce. The reader is referred to Fletcher (1987) for a more comprehensive overview. The very common steepest descent method starts at an initial starting point and applies the first derivative multiplied with a negative scalar as an initial direction. The optimal relaxed state cannot be determined a priori, so the procedure is applied in a sequence. Known as a very fast algorithm, the iterative Newton method is applied instead (Fletcher, 1987). There are no technical limitations regarding the search space and the function, so calculation time can be kept very low. The Newton method starts at an initial starting point with the help of a quadratic approximation of $f(x_i, y_i)$. Again, an iterative procedure is applied to reach the minimum of $f(x_i, y_i)$. A major advantage of the algorithm is the fast convergence, which lead to the assumption that in general settings the algorithm converges faster than the steepest descent method. A comparison of the Newton method compared to the steepest descent method is tested on two examples and summarized in Table 2. The threshold is set to an accuracy of 0.01m. The distance between the starting point and the final solution is in both cases 200m. The differences between the two methods are considerable.

In more complicated and realistic networks, several node positions have to be optimized to improve network performance. The alignment algorithm to implement the network optimization follows an iterative procedure, similar to the Newton method and the spring analogy above. Iteratively, the network needs to be improved to reach the most relaxed state. The necessary steps are described in the following:

Table 2 Example runs of geometric optimization

Method	Vector	Number of iterations	
		3 arms	4 arms
Steepest descent	$-\nabla F(\mathbf{x}^k)$	66	109
Newton	$-(\nabla^2 F(\mathbf{x}^k))^{-1}\nabla F(\mathbf{x}^k)$	6	5

1. The correction vector is determined according to the Newton direction at the starting point.

2. The net correction forces are applied on the nodes in consideration, resulting in $\boldsymbol{x}^{k+1}$.

$$\boldsymbol{x}^{k+1} = \boldsymbol{x}^k - \left(\nabla^2 F(\boldsymbol{x}^k)\right)^{-1} \nabla F(\boldsymbol{x}^k)$$

3. The demand is assigned again to calculate the new network loadings.

4. Start at 1. again, until results are achieved which are precise enough.

A major advantage of the alignment algorithm above is the distinction between Euclidean distance and the network and link properties. The alignment algorithm considers the volume-delay function for optimization, and excludes approximation similar to graph drawings. When reducing only the link length to a minimum, the network's performance would eventually decrease. Another advantage is the arbitrary closeness to the optimal state when repeating the algorithm often enough. A major advantage of the approach is the implementation of the first and second derivatives of the volume delay function, which are defined for a variety of volume - delay functions.

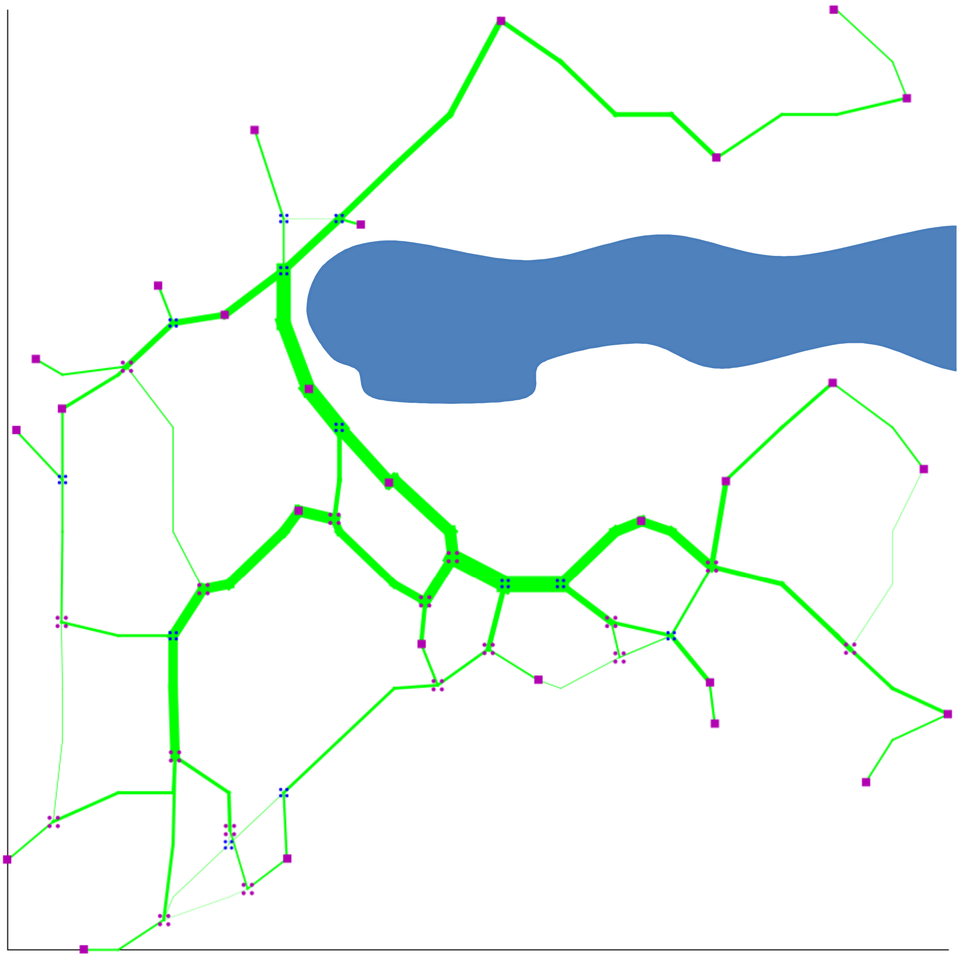
The alignment algorithm can be applied in larger networks. Currently, the algorithm is applied sequentially after the discrete network design (IACGA) has determined a most favorable network. The most favorable network is additionally improved by the algorithm to gain additional network performance.

6 RESULTS

6.1 Algorithm

The IACGA network design algorithm is applied on a variety of networks. To further verify the IACGA, a geographic boundary is implemented and the outcomes of two different cases are compared against each other. Unlike a featureless plane, a randomly defined bay is included in the algorithm as a terrain boundary for testing purposes. Regarding the implementation in the IACGA, the bay is define in two ways. In the first case, the costs of the bay crossing links are increased (penalty factor of 20.0) in the second case, the bay crossing links are excluded already in the initial setting. The results of both cases are similar. Also the first case exclude bay crossing link in the final network. The exclusion is due to the fact that the cost increase lowers the benefit cost ratio of the entire network considerably. The average difference of the network performance, assessed with the objective function, is 1.5 % for a sample size of four. Figure 5 shows the implemented geographic boundary and, as an example, the resulting network, generated with the second setting.

Figure 5 Implementation of the high link costs for bay crossing links.



6.2 Shape grammars

Networks are designed with the IACGA and shape grammars A and B. Two initial settings are provided for comparison reasons (Table 1). Unlike in Figure 5, the initial settings are empty featureless planes. Initial setting 2 refers to Figure 1 whereas setting 1 is reduced in size for calculation time savings (Table 1). Table 3 shows the results of the average transport network scores and a comparison of the different shape grammars. Table 3 lists the results of the shape grammars which account for the adjacent links corresponding to shape grammars A and B in Figure 3. It is crucial that the scores of the resulting networks are compared to scores of other network which were built up in a different manner. In Table 3, the scores of the networks generated with shape grammar A and B are compared against each other. Due to the long calculation times, the sample sizes vary, and a Wilcoxon test (Mann and Whitney, 1947) is not applicable for setting 2.

Table 3 Relative difference between the shape grammars under consideration.

	Initial setting 1 (n=20)			Initial setting 2 (n = 3)	
Shape grammar	Average score	Relative difference	Wilcoxon rank-sum	Average score	Relative difference
A	-143'200	-		-300'192	-
B	-147'132	2.75%	0.009%	-317'145	5.65%

Independent of any shape grammars, coherent network structures are found in the generated networks, which means that links of the highest hierarchy type A is always joined with another link of type A. This finding is in line with Yerra and Levinson (2005) stating that networks are often built of routes with continuous attributes.

The application of shape grammar B, which is more restrictive regarding the link joining, decreases the average network score, relative to shape grammar A, a finding that is replicated with both initial settings. This finding can be expected, since the fact that the reduction of flexibility in shape grammar B is obviously leading to a decrease in network efficiency. However, especially in initial setting 1, the impact of shape grammar B is remarkably low. Therefore, shape grammar B is not affecting the overall network performance substantially. This is an advantage for standards which stress the importance of hierarchical network designs, which are normally clearer in their constitution.

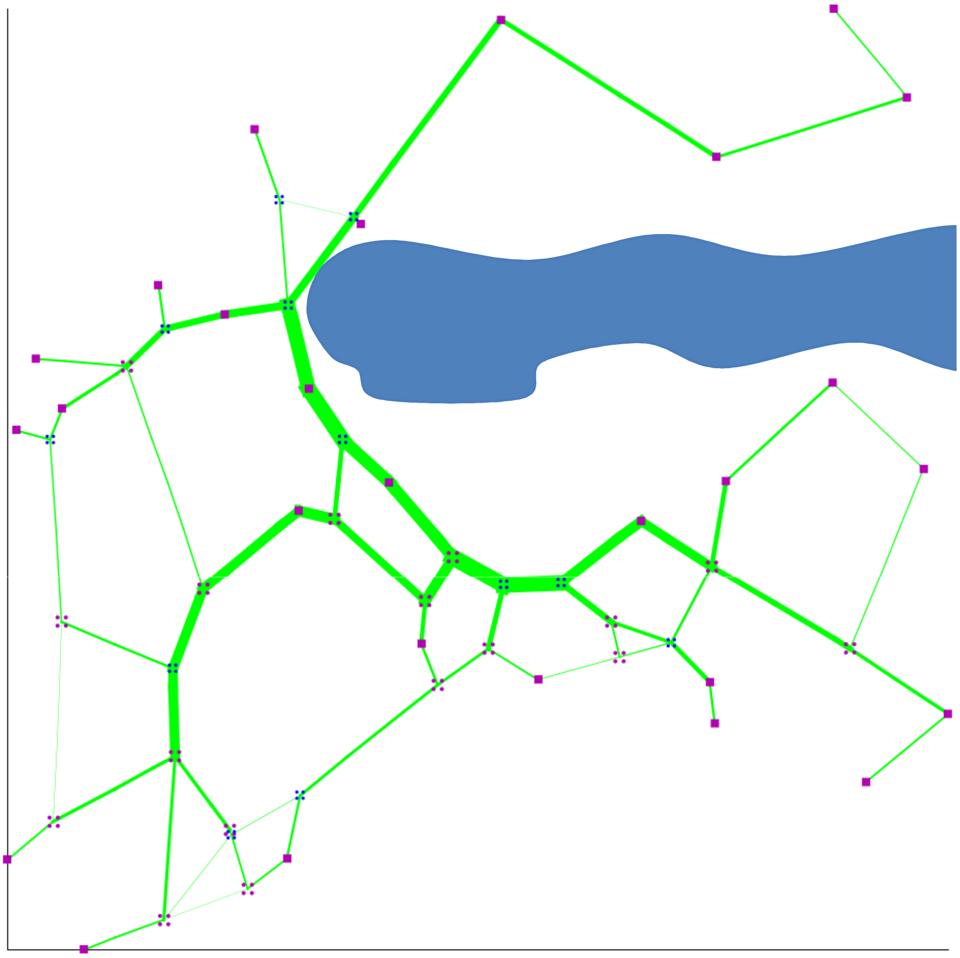
6.3 Alignment algorithm

The alignment algorithm is applied on the network shown in Figure 5. Figure 6 shows the outcome of the discrete network design (IACGA) after the application of the alignment algorithm. The algorithm stopped after the objective function increased again due to the fact that there is no need for further network changes. The score improves of 7.3 % due to geometric alignment.

7 CONCLUSION AND OUTLOOK

To our knowledge, a first systematic methodology to assess the impact of shape grammars in transport networks is proposed and successfully implemented in this research. While a large body of literature exists about discrete and continuous network optimization, the impact of shape grammars on network design is not thoroughly investigated so far. Following the planners needs for sound planning tools, this paper offers the opportunity to assess shape grammars including a corresponding evaluation function. The assessment of the shape grammars does not rely on case studies and are therefore independent of historical development. The shape grammars takes place on networks built up on featureless planes. Two different initial settings are tested which vary in size, the number of candidate links and the travel demand. The results are replicated in both settings. The design process of the transport networks relies on an Integrated Ant Colony and Genetic Algorithm (IACGA). The IACGA reassembles

Figure 6 Implementation of the geometric alignment.



network elements in an iterative way, while maintaining the shape grammars under consideration. The performances of the emerging network designs are compared using a utility function, which includes travel time and infrastructure costs.

It could be shown that the shape grammars have an influence on the overall efficiency of the network. Two shape grammars affecting link distribution are compared against each other with significant differences. However, hierarchical link distribution seems to have a significant but low impact on network performance. This finding supports a hierarchical layout in network design, as proposed in some standards. Minor losses in performance are acceptable, in return for a structured network design. The findings have to be confirmed with additional shape grammars including intersection delays, and eventually a traffic microsimulation to account for more details in intersections.

The IACGA can be applied on featureless planes. However, the IACGA is able to cope with terrain constrains. Different spatially dependent link and intersection costs can be implemented in the algorithm. Spatially dependent network costs can then affect network design. This is especially useful for applications in urban simulations, e.g. PROCEDURAL (2011) or Vanegas *et al.* (2009). The geometric considerations are based on a theoretical foundation, but are in line with the volume delay functions often used in macroscopic models. The discussed geometric alignment method is currently applied sequentially after the IACGA. Possibly, the geometric alignment algorithm can be coupled with the algorithm, but further research is needed here.

A new method of designing transport networks is applied successfully by this work, which opens numerous possibilities for future research. Promising is the modular approach, with allows expansions of the method, the shape grammars and simultaneously keeps complexity low. More shape grammars can be evaluated with the IACGA, especially focusing on intersections. Moreover, a more variable link and node alignment in space should be addressed to design more realistic networks. The aim is to reduce travel times by adjusting the intersection types. Additionally, variable travel demand, and transport and land use interdependencies will be addressed in the future. Transport and land use interactions, e.g. different land use types, can be modeled with the IACGA and corresponding shape grammars. This is relevant because of the absence of appropriate planning guidelines. A comparison with existing case studies of new or reconstructed urban areas will provide additional insights.

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