Comparison of Hierarchical Network Design Shape Grammars for Roads and Intersections

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ABSTRACT

Urban systems are growing fast in many countries today and depend essentially on efficient transport networks. Significant productivity gains in urban systems can be achieved by improving transport infrastructure and thus reducing overall costs of travel. Shape grammars provide a solid foundation for coherent transport network design, and concurrently reduce complexity of planning processes. Shape grammars describe how network elements are joined with each other. However, only a few are listed in standards for network design without any fundamental research basis. Therefore, shape grammars remain vague and the standards lack of clear recommendations.

In this paper, shape grammars for hierarchical network design are examined for different transport networks. The investigated shape grammars include different link and intersection types. The network models are artificially created to avoid a bias in the results due to history. The networks are optimized regarding an infrastructure and user cost function. Shape grammars significantly affect transport network performance. As expected, the distribution of link types affects the network efficiency. However, intersection types and the corresponding delays in travel time have a remarkable and even larger effect on network performance. In the future, more shape grammars will be examined to shed light on the impacts of relevant grammars for transport network design and to derive clear recommendations for urban planners.

INTRODUCTION

Today, the construction of transport networks is still a major concern for governments and planners. Because of rural depopulation and migration, the population in existing urban systems will double between 2005 and 2050 *(1)*, which will increase travel demand and transport infrastructure requirements. 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 *(2, 3)*.

The literature on network design covers a large variety of topics with an overall classification in network optimization and network design. Network optimization deals with existing networks which are improved with respect to the benefit-cost ratio of the alternatives *(4, 5, 6)*. An extensive number of contributions addresses the bi-level network optimization approach. Optimization methods applying a bi-level approach separate the two optimization problems, namely network design and demand assignment *(6, 7, 8)*. A major proportion of contributions is related to operational research methods, e.g. *(9)*. Additionally, a large proportion concerns the historical development of network design, including case studies *(10)*.

The construction of new networks is normally following different methods, compared to the optimization of existing methods. Especially urban planning and design aspects as well as interactions between transportation and land use issues are crucial when designing new networks, e.g. *(10, 11, 12)*. The degrees of freedom and the search space are growing substantially when building or expanding new districts and urban systems, compared to network optimization mentioned above.

For network design, shape grammars are increasingly applied in transport and urban planning and corresponding software solutions *(13, 14, 15, 16, 17, 18)*. Besides scientific contributions, shape grammars for transport network design are often found in handbooks and standards *(19, 20, 21, 22)*. 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 rules depict how an existing planning state and geometry is extended to a more desirable state. However, scientific contributions of shape grammars for transport network design and urban development are scarce despite their wide application. So far, shape grammars mostly lack a fundamental research base as well as systematic evaluations, e.g. cost-benefit-analyses, and do not remain explicit in their recommendations. For a profound application of shape grammars in urban development, research is needed to support planning guidelines.

Shape grammars have a strong architectural background *(23)* but are also able to include aspects of spatial planning *(24)*. An early approach is provided by *(25)*. Alexander and his colleagues *(23)* were one of the first who stressed the importance of shape grammars in urban planning. *(26)* focuses on patterns, link arrangements, link lengths and scaling in larger cities. In *(26)*, quality of streets depends on the context of space and adjacent buildings and shops. *(26)* does not directly define grammar rules, but introduced regularities between different network elements. *(27, 28)* developed guidelines and prescriptions for general urban development in a qualitative way. Their work can be related to the movement of New Urbanism *(29, 30)*.

A key advantage of shape grammars is their ease of application in planning processes *(15, 17, 18)*. Shape grammars can be applied for both network optimization and network design purposes *(31)*. Practitioners prefer robust and reliable methods. Shape grammars satisfy these requirements but are at the same time adaptive to different scenarios and are able to incorporate spatial planning rules *(24)*. Shape grammars can serve as decentralized investment rules. Moreover, the application of shape grammars needs very low computational requirements *(13, 17, 18)* and can be implemented in interactive planning tools, e.g. *(15)*. This is especially relevant since e.g. bi-level network optimization is limited in application due to high computational requirements and hence the wide application of heuristics in network optimization *(7)*.

The aim is to see to which extent shape grammars influence the result of the efficiency measure and, thus, the performance of the networks. Only if the influence of the shape grammars for network design is known, clear recommendations for design standards can be made in the future. This paper introduces an approach independent of existing network data or case studies because existing transportation networks and patterns are often biased due to history. Instead, artificial transport networks are designed that follow different shape grammars under consideration. The advantage of the application of artificial transport networks are their independence of history and politically driven decisions. The results are valid detached from existing case studies. The implementation in artificial networks is similar to e.g. *(11, 32, 33)*.

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. This work is a major extension of *(34)*, and additionally comprises variable intersection types and more detailed shape grammars. This research focuses on areas with about 100´000 inhabitants and on different link and intersection types. This work focuses on private car transportation, but is extendable for other modes.

TRANSPORT NETWORK SHAPE GRAMMARS

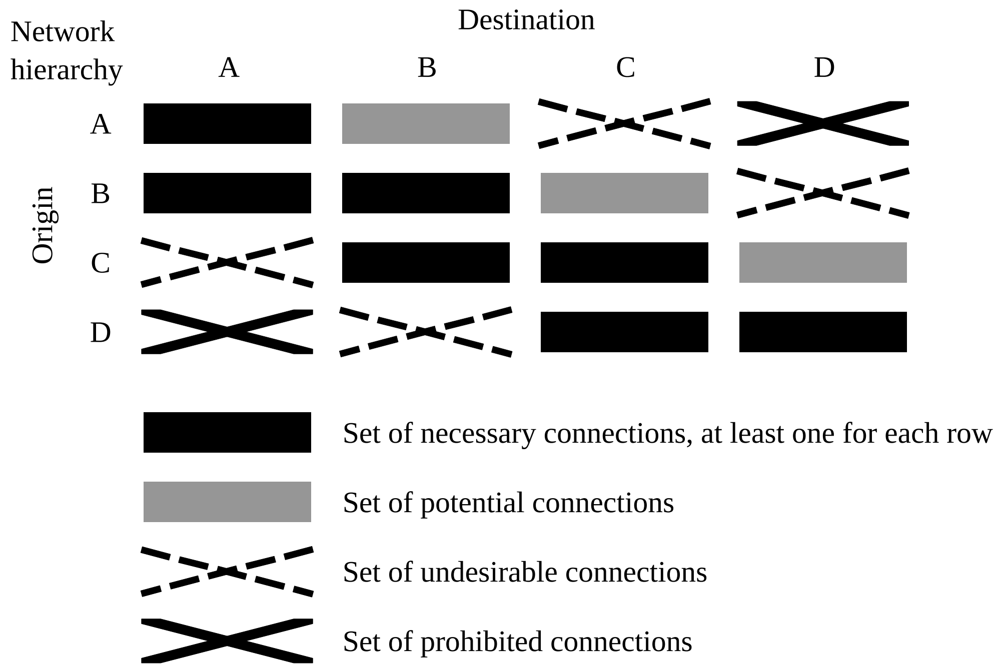
Network grammar rules describe how roads and intersections of certain types or hierarchical levels may be joined with each other. A general example of a set of possible shape grammars is shown in Figure 1. On the left, the hierarchy of the considered network element is listed. The potential (at least one), undesirable and prohibited adjacent network elements are listed row-wise for each hierarchy class.

In this example, network elements can only connected with each other if the adjacent link is of the same type or one type lower or higher. Additionally, it is stated that a link of a given hierarchy level has to be connected with another link of the same hierarchy level or of one hierarchy level higher in order to maintain a coherent network. For intersections, the types of the adjacent links have to be consistent with the considered intersection types.

Different handbooks and standards are scanned for comparison of the shape grammars. 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 *(21)*
- Moderate flexibility in network design: A-A, A-B, avoid A-C, ...; e.g. USA and England *(19, 20)*
- Adaptive network design: A-A, A-B, A-C, B-A, B-B, B-C, B-D, ...; e.g. Germany *(22)*

FIGURE 1 Example set of shape grammars for joining network elements of different hierarchical levels



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. The impact of such recommendations and their differences are crucial and discussed in this work.

INFRASTRUCTURE COST

Depending on the budget, link and intersection types can be allocated differently in the network. E.g. a lower total budget may lead to a higher share of links and intersections of lower capacities, which result in a less expensive network design. Table 1 shows the costs for five link types and three intersection hierarchies *(35, 36)*.

As expected, considerable differences occur between links in built-up and outlying areas. The costs of the major arterial roads are considerably higher compared to collector roads, because the major arterial still historically functions as a major carrier, compared to the collector road which only carries local traffic. The costs of highway intersections are remarkably high, also in comparison to costs for links. This is due to over- and underpasses and larger radiuses for curves. A large variety of data can be found for costs of intersections in urban areas. This is due to the fact that intersections differ in many aspects, e.g. number of lines, pedestrian and bicycle paths and public transportation. Additionally, costs tend to increase over years because the cheaper projects were generally built first *(37)*.

TABLE 1 Costs of network elements in the USA (year 2000)

Network elements	Links [Mio $/lane-km]		Intersections [Mio $/intersection]	
	Built-up area	Outlying area	Built-up area	Outlying area
Freeway	1.6	1.3	9.3	6.2
Highway	1.4	1.2	1.2	2.5
Interstate	1.3	0.8	-	-
Major arterial	1.3	1.1	0.3	0.1
Collector street	0.8	0.6	-	-

METHODOLOGY OF THE MODULAR NETWORK DESIGN APPROACH

The initial setting for the design of the road networks is described in the following section, followed by the description of the utility function. Subsequently, the algorithm is introduced for generating networks under given shape grammars.

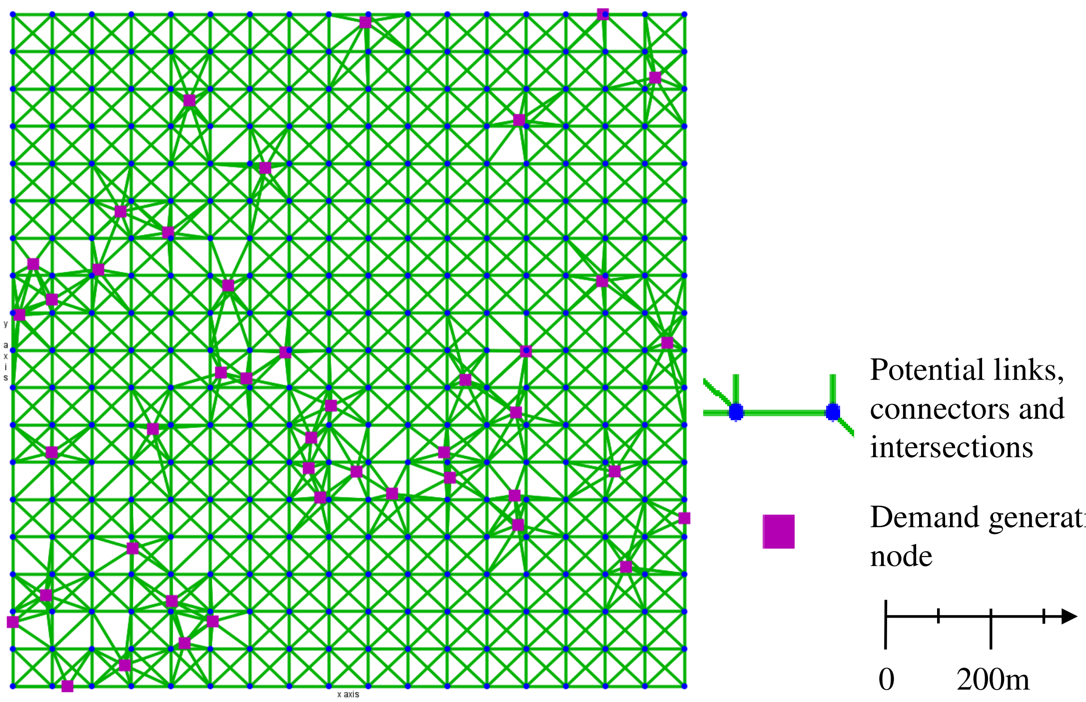
Initial network settings

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, e.g. Figure 2. The advantage of the featureless plane compared to real world cases is its lack of historical development and politically motivated decisions. Links are joined at nodes which are currently fixed in space. 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, but can be relaxed in space in the future *(38)*. In Figure 2, the alignment of the demand generating nodes are originally derived from the city of Winterthur *(39)*, close to Zurich (Switzerland) with about 100'000 inhabitants. Hence, existing potential shape grammars are ignored in the example networks. 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 *(40)*. User equilibrium is determined according to the method of successive averages. The budget constraint forces the algorithm to keep infrastructure low and therefore the number of direct paths between pairs of demand generating nodes.

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 is independent of the grammars and the 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, usually the most relevant cost factors. 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.

FIGURE 2 An example network with all candidate links, nodes and demand generating nodes.



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

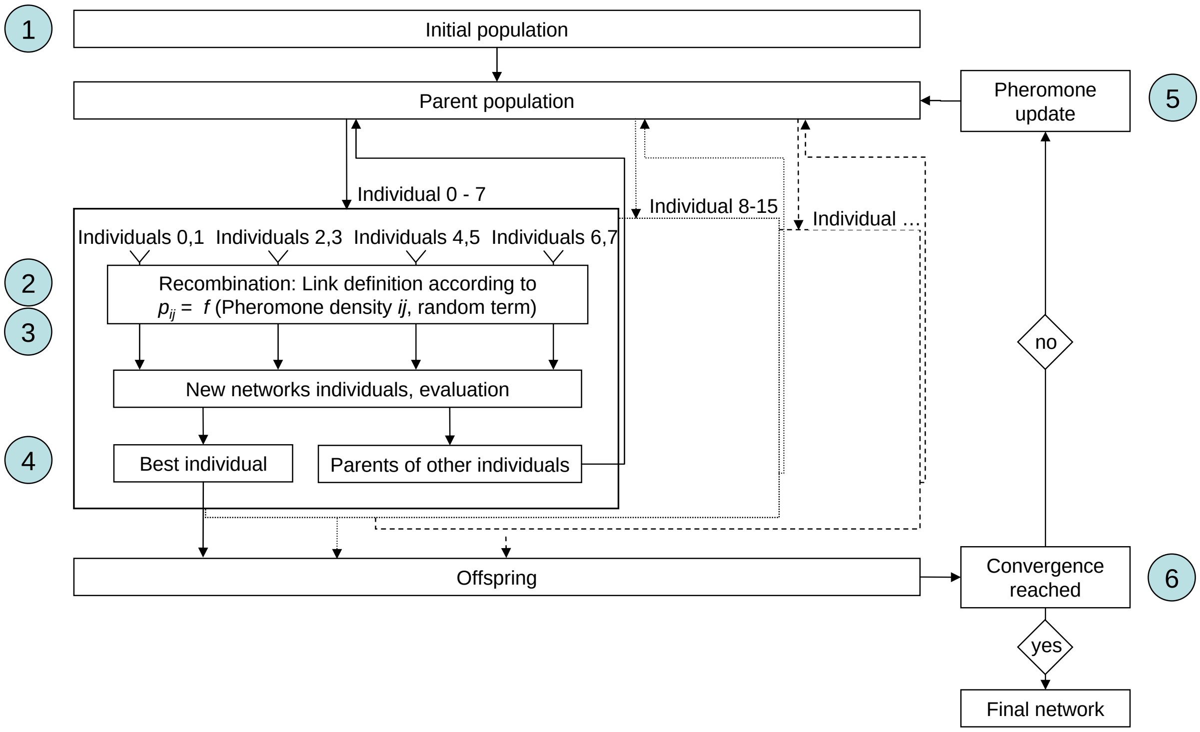
o: Origin demand generating node.
d: Destination demand generating node.
γ: Weighting factor (value of time as a recourse), extrapolated for a year.
I: Infrastructure costs as annuity.
p: Penalty factor, $p = 0$ when $I - B < 0$.
B: Budget.

Integrated Ant Colony and Genetic Algorithm (IACGA)

In the following, a short overview is provided over the design method for the transport networks. *(34)* refers to additional details. The design method benefits from both the advantages of the GA and the ACO methodologies, and therefore is called Integrated Ant Colony and Genetic Algrithm (IACGA). E.g. *(41, 42, 43)* describe the GA and ACO in details. Derived from a standard GA, the IACGA is based on population of individuals. Each individual is representing a candidate network, which improves over time using a recombination method. 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. As a standard ACO, the IACGA employs the results from all previous populations and stores this information, which is later available for further network recombination. 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 alternately. Only White and Yen *(44)* introduce an integrated GA and ACO which is based on very similar structures as the IACGA described here. The proposed algorithm is applied to the Traveling Salesman Problem (TSP) successfully. However, the TSP contrasts to transport networks in many aspects. In the following, we introduce the IACGA step by step, an overview is given in Figure 3.

FIGURE 3 Overview over the IACGA with numbers referring to the text.



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. Unlike a standard GA, the recombination procedure is conducted within the network, but without coding a chromosome. Additionally, 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 candidate link is under consideration, which already was implemented in previous networks with high scores, it is more likely that the candidate link is chosen again. 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).

$$p^g_{ij} = \begin{cases} \dfrac{e^{\alpha\tau^g_{ij}} e^{\beta r}}{\sum\limits_{i\text{-}j \in L_{Parents}} \left(e^{\alpha\tau^g_{ij}} e^{\beta r}\right)} & \text{, when } i\text{-}j \in L_{Parents} \\ 0 & \text{, otherwise.} \end{cases}$$

p^g_{ij}: Probability of choosing link i-j in iteration g.
τ^g_{ij}: 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 i-j which are present in at least one parent network.

Links from both parents are chosen with probability p^g_{ij} 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 hierarchical shape grammars are applied in the design process according to the following two consecutive rules. Firstly, the link and intersection types are distributed according to the shape grammars in consideration. A secondary rule accounts for the current link and intersection loadings. The higher the loadings, the link and intersection types with the higher capacities are allocated to the link and intersections in consideration. Both rules simultaneously maintain the budget restriction. Therefore, both rules follow an optimized type alignment.

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.

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

δ: Evaporation rate.
$\max(\Delta\tau^g_{ij})$: Score of the best individual out of all networks containing link ij.

6. The algorithm returns to step 2 if convergence is not reached yet. Convergence is only 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 best performing cutoff 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.

Convergence behavior

The intermediate results of a sample network design run of the IACGA are shown in Figure 4. Both pheromone densities and their changes over time can be seen in the left part of Figure 4. Each link bar represents the pheromone density on a network link. The wider the bar, the more relevant is the link. On the right, the corresponding intermediate network results are shown. Here, the link bars represent the link types. The wider the bar, the higher is the hierarchy of the link type. A node with more than two arms represents an intersection, indicated by the intersection symbol.

The global minimum is reached in 50% or more in test networks *(34)* with a low standard deviation of 0.67%. The standard deviation can explained by the heuristic nature of the IACGA. The convergence speed mainly depends on the size of the scenario and the number of demand generating points. The IACGA clearly outperforms a standard GA, because of the advanced recombination procedure with learning ability *(34)*. A scenario of 1’624 candidate links and 25 demand generating nodes (setting 1 in Table 2) takes about 5 hours on 16 parallel threads with 2.66GHz. The high parallelization capabilities of the IACGA is an advantage, especially because of the recent advances in parallelization.

INITIAL SETTINGS AND SHAPE GRAMMARS UNDER CONSIDERATION

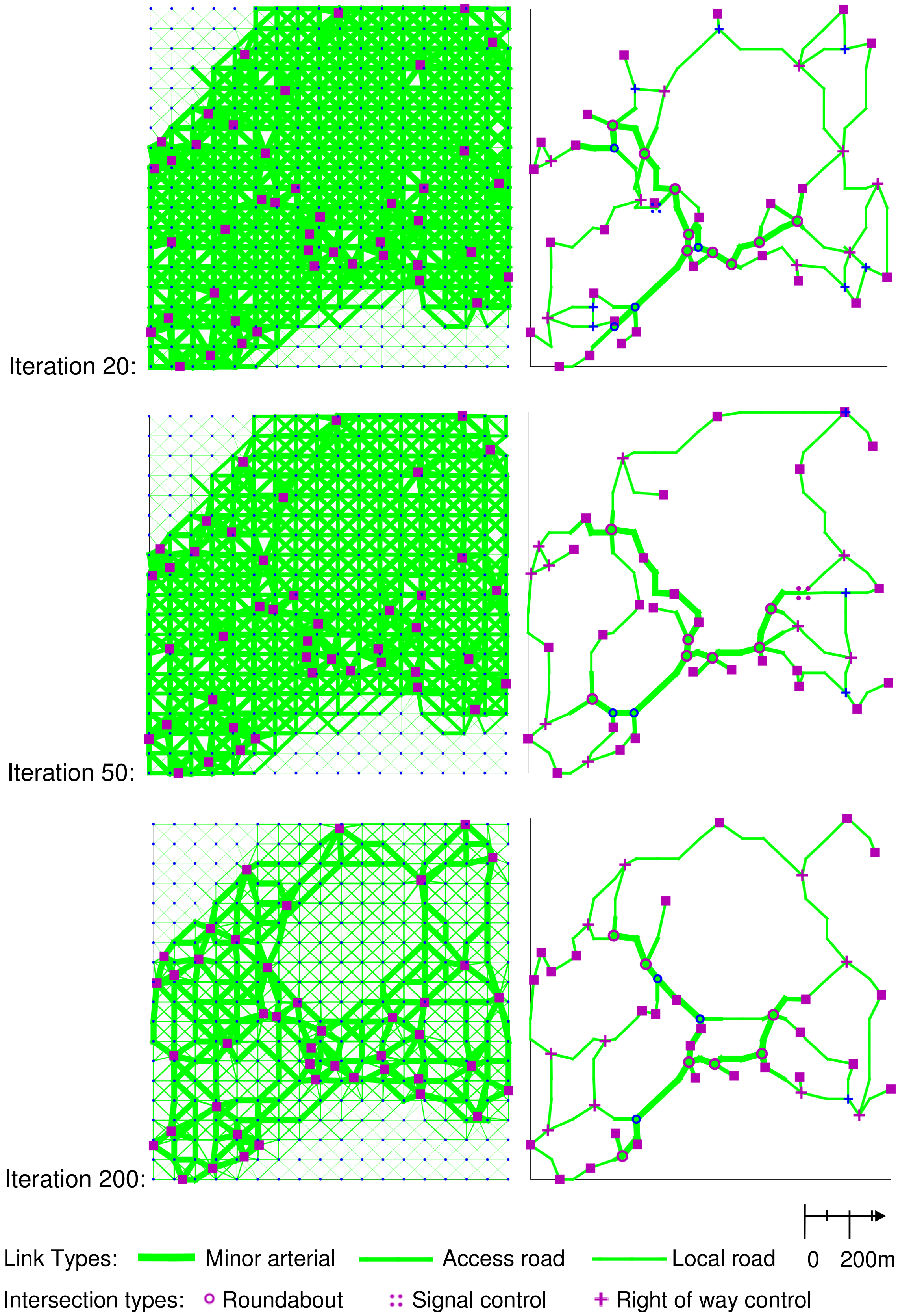
Two different initial settings are provided for comparison reasons (Table 2). In initial setting 1, the demand generating points are distributed evenly on an empty featureless plane. Initial setting 2 is identical to Figure 2.

TABLE 2 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

The intersection delays are calculated for roundabouts, signalized intersections and two-way stop-controlled intersections (TWSC) according to *(45)* considering turn movements and their delays, but ignoring adapted cycle times for each intersection. TWSC include a right of way penalty in the case of unequal link types. Reliable data for intersection costs are scarce, also because of many different types. However, the costs of the three intersections types correspond to the data of Table 1. The intersection type also should reflect the size of the intersection. Therefore, 0.6, 0.3 and 0.2 Mio Dollars are assumed for roundabouts, signal control and TWSC

FIGURE 4 Convergence of IACGA. On the left, pheromone densities are shown of selected generations, on the right, the link and intersection types of the best network is shown of the corresponding generation.



intersections.

Four different sets of shape grammars are implemented (Figure 5), derived from *(24)*. Shape grammar A and B focus only on link alignment, whereas shape grammar C and D also include intersection alignment.

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. An iterative sampling determines the optimal share of each link type, accounting for budget restrictions.

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* (indigated with arrows in Figure 5). Similar to the implementation of shape grammars A, link types are distributed according to link loadings to optimize overall travel time.

Shape grammar C resembles shape grammar B regarding the link types. Additionally, different intersection types are distributed according to the intersection loadings. Currently, three intersection types are implemented in the approach: Roundabouts, signal control and TWSC intersections. The total infrastructure budget can be invested in both intersections and links, adding an additional degree of freedom to the network design. Because the optimal share can not be predicted in advance, it is part of the iterative sampling procedure.

Shape grammar D resembles shape grammar C, but differs in the allocation of intersection types. In shape grammar D, the allocation of intersection types is restricted to the distribution of link types according to Figure 5.

Shape grammar B and D are especially helpful in structuring the transport network due to a clear overview for the road users due their hierarchical setup. However, the structuring of a network also can have disadvantages, especially regarding travel times and performance. This effect of the shape grammars is discussed in the following.

RESULTS

Networks are designed with the IACGA and shape grammars A, B, C or D. Two initial settings are provided for comparison reasons (Table 2). Table 3 shows the results of the average transport network scores and a comparison of the different shape grammars. The upper half of Table 3 lists the results of the shape grammars which account for the adjacent links corresponding to shape grammars A and B in Figure 5. Shape grammars C and D also include intersection types. 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 as well as shape grammar C and D. Shape grammars A, B and C, D are not compared against each other because of the large impact of the variable intersection types in shape grammars C and D. Due to the long calculation times, the sample sizes vary, and a Wilcoxon test *(46)* is not applicable for setting 2.

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 *(32)* 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,

FIGURE 5 Shape grammars under consideration.

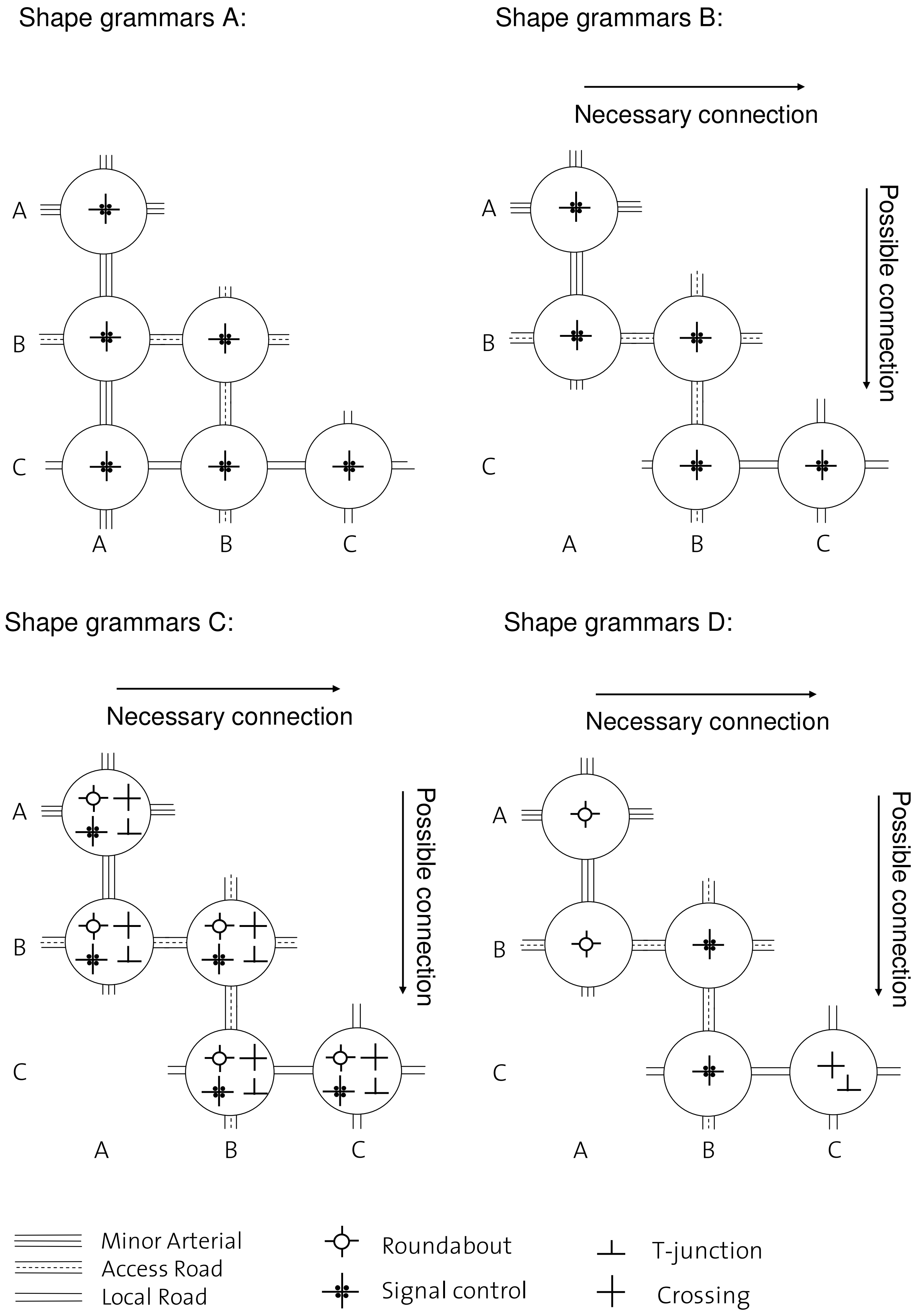


TABLE 3 Relative difference between the shape grammars under consideration.

	Initial setting 1 (n = 53)			Initial setting 2 (n = 11)	
Shape grammar	Average score	Relative difference	Wilcoxon rank-sum	Average score	Relative difference
A	-143'200	-		-300'192	-
B	-147'132	2.75%	0.0087%	-317'145	5.65%
C	-144'798	-		-297'301	-
D	-157'690	8.90%	0.048%	-466'909	57.05%

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.

In contrast to the results above, the lower half of Table 3 summarized the results gained with shape grammars C and D, considering three different link and intersection types. The distribution of intersection types, accounted in shape grammars C and D, affects network performance considerably. The application of shape grammar D decreases the average network performance significantly relative to the application of shape grammar C. The lower average score with shape grammar D is due to the restrictive shape grammar D. Therefore, the restrictions lead to increasing travel times and decreasing the overall network performance. The findings show that the intersection type distribution is essential. Therefore, shape grammars on how to allocate intersections are of major importance. This findings are especially relevant, since investments in new intersections are discussed less often than in new roads. There is strong evidence that intersections play a major role especially in urban areas. Total travel times can be saved and performance improved when reducing the intersection delays.

CONCLUSION

To our knowledge, a first systematic assessment of the impact of shape grammars in transport networks is conducted in this research. While a large body of literature exists about network optimization, the impact of shape grammars on network design is not thoroughly investigated so far. This paper establishes shape grammars and includes a corresponding evaluation. The evaluation does not rely on case studies because of their bias due to history. The evaluation 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 design process of the transport networks relies on a new Integrated Ant Colony and Genetic Algorithm (IACGA). 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. However, the implementation of different intersection types, which are included in additional shape grammars, affects the network efficiency considerably more. There is strong evidence that the intersection types play a central role in maximizing network performance. This finding is crucial for further planning purposes, especially in urban areas with a high density of intersections. The findings have to be confirmed with additional shape grammars, and eventually a traffic microsimulation to account for more details in intersections.

A new method of designing transport networks is applied successfully by this work, which opens numerous future possibilities. Promising is its modular approach, with allows expansions of the method, the shape grammars and simultaneously keeps complexity low. More shape grammars can be evaluated with the applied method, especially focusing on intersections. Moreover, 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 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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