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# **Shape Grammars for Hierarchical Transport Network Design**

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## Abstract

Urban systems are growing fast in many countries today, and therefore face the task to build efficient transport networks. Significant productivity gains are due to infrastructure investments in urban systems. A shape grammar based approach is proposed to contribute to more efficient networks by reducing the enormous and complex search space in the design of a new transport network. This paper sheds light on impacts of different shape grammars in network design.

The proposed approach applies a network generation algorithm based on the integration of ant colony optimization (ACO) and a genetic algorithm (GA). For network design applications, the proposed algorithm is able to overcome restrictions of both ACO and GA, e.g. in network size and computational time, and is concurrently computationally fast. The algorithm generates best transport network layouts given a defined objective function, including demand weighted travel times. A budget constraint provides an upper bound for infrastructure investment. Shape grammars for hierarchical network design are respected during the generation of the network layouts. Different initial network layouts are tested. It can be shown that shape grammars can affect the resulting transport networks. Future research is proposed, including additional shape grammars, variable demand and growth processes, to verify and complete the results gained.

## Keywords

Shape, Grammars, Rules, Transport, Transportation, Network, Design, Generation, Integrated, Ant Colony Optimization, Genetic Algorithm.

## 1. Introduction

Generation and expansion of transport networks are major tasks of transport and urban planning. Economies rely and benefit substantially from efficient transport systems, agglomeration processes and low trading costs. Urban systems will continue to grow considerably in emerging and in developed countries and therefore also the need for efficient transport systems. Network design is especially demanding in complex systems where major interactions between demand and supply exist. Requirements for transport systems are high accessibility, low generalized costs of travel, low construction, operating and maintenance costs and low environmental impacts. Additionally, new technologies and travel behavior change necessitate reconstruction of existing transport systems. These challenges require a sound basis of knowledge of how to construct and to adapt transport networks.

This paper suggests a methodology targeting the rules for transport network design, which are currently under-researched, with the aim to support and improve passenger transport infrastructure planning. The examples presented focus on networks for an entirely new transport system. However, using the method for restructuring an already given transport infrastructure is possible as well.

The motivation of this research is to establish a methodology, which supports the planning of a transport network that is favorable for transport users and constructed under an infrastructure budget constraint given in advance. Additionally, the methodology should be able to address shape grammars. Different shape grammars have to be considered in the network design process, so the resulting final network meets shape grammars given in advance. Different shape grammars can be implemented directly in separate network design processes which may lead to different final networks. The resulting network designs can be compared regarding an objective function.

The objective function includes the total demand weighted travel time of the network users as the major component of the generalized costs of travel. Demand weighted travel times can be monetarized before adding to the generalized costs. However, the calculation of travel times is computationally costly due to the time expensive determination of the Wardrop User equilibrium (Wardrop, 1952). Infrastructure costs are included as an additional element in the objective function. A given budget constraint serves as an upper boundary in an investment process and prevents an oversupply of network infrastructure.

The starting position of the algorithm is an exhaustive set of candidate links distributed over the urban area under consideration. Zones are given in advance and have to be joined to the network. Travel demand is also predefined. This assumption leads to the question, which subset of links forms the most favorable network given the objective function. The large number of candidate links constitutes a very large search space. There are many existing algorithms for the combinatorial network design problem. After an extensive search, Ant

colony optimization (ACO) and genetic algorithm (GA) seems to be the most suitable and straightforward algorithms for the combinatorial network design problem. Both are highlighted in the following paragraph for the reason of completeness

ACO is a metaheuristic to solve combinatorial problems and approximates ants' foraging characteristics. The main principles are collective guided behavior of the individuals and the implementation of a memory strategy, which accelerates convergence behavior. The probability of choosing an alternative in a set of candidates increases when the previous selections of the considered alternative were successful. Considering the construction of a new transport network, the search room is the set of all candidate links and is very large already in a medium sized case study. It is expected that the construction of a medium sized network would rise the computational time of a standard ACO to find the optimum in reasonable computing time. Vitins and Axhausen (2009) applied an ACO for a smaller optimization problem when searching for the best network improvement infrastructure.

The GA was originally developed for combinatorial problems and mimics evolutionary processes in populations of a virtual species. Its concept is based on random recombination of several individuals. The offspring is evaluated according to a fitness function, also called objective function, and only the fitter individuals are members of the next generation, leading to an overall fitness increase over several iterations and finally to the optimal individual regarding the fitness function. A standard GA is not suitable for very large and discontinuous search spaces because of exponentially increasing calculation times. This is due to the large population which is necessary for proper convergence. Vitins and Axhausen (2010) showed that for network design a standard GA can be applied for networks up to about 225 nodes, mainly due to the computationally costly objective function.

This research is motivated to find an algorithm combining advantages from both approaches, especially the learning ability of the ACO and the statistical advantages of the GA, and simultaneously keeping calculation times low. Regarding a merged algorithm, many methods are applied where GA and ACO run sequentially, parallel or iteratively (e.g. Kuan, Ong and Ng, 2006; or Silva, Faria, Abrantes Sousa, Surica and Naso, 2005). This paper applies an Integrated Ant Colony and Genetic algorithm (IACGA), fully joining both approaches in a single algorithm. The algorithm is also capable of implementing shape grammars in the design of the new network. Due to the iterative nature of the IACGA, each generated network has to fulfill the shape grammars given in advance, making it possible to implement the shape grammars in each iteration and in the intermediate results. Therefore, the final result meets the shape grammars considered.

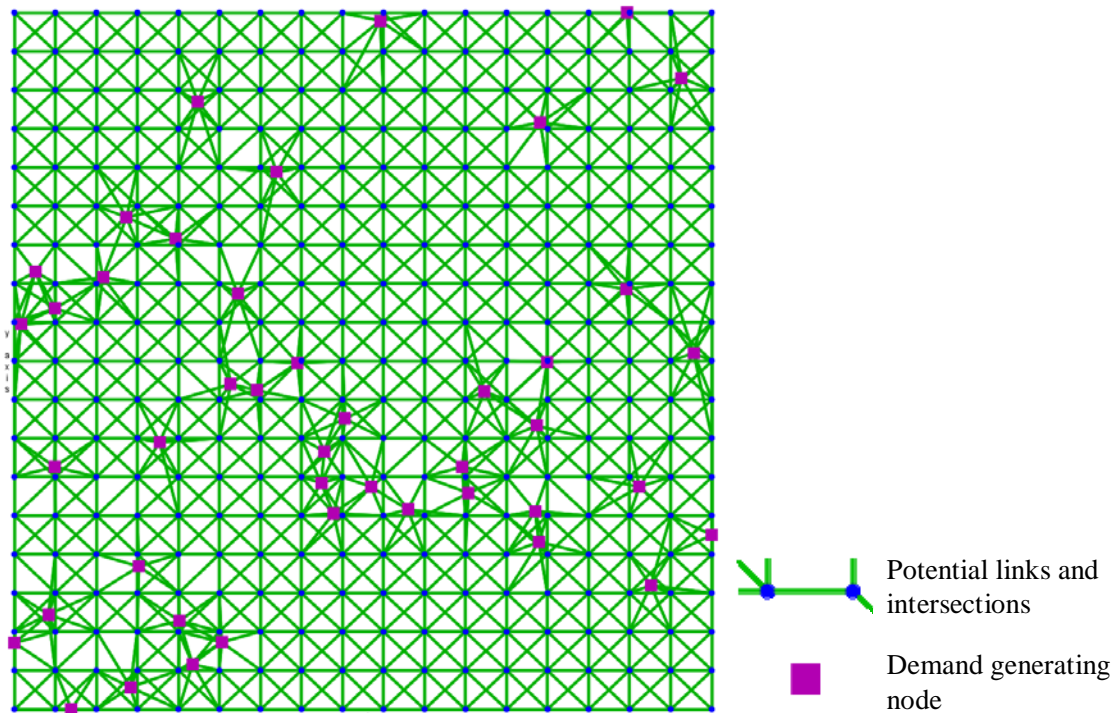
Section 2 explains the problem statement, the initial settings, and the objective function. The IACGA is described step by step in Section 3 focusing on technical details. Convergence behavior of the IACGA for one network scenario shown in Section 4. Grammars are

introduced in Section 5, including a summary of different handbooks. Final networks with different shape grammars implemented are evaluated and compared against each other. A conclusion and outlook including proposed future research are discussed in Section 6.

## 2. Problem statement

The goal is to generate a road network in an optimum way given the objective function, which is described in more detail below. The planar distributed candidate links are initially distributed on a featureless plane and define the entire search space (see Figure 1). Links are joined at nodes, candidate intersections. The demand generating nodes, shown as squares, have to be connected to the network in order to guarantee paths from and to each node. In Figure 1, the demand generating nodes are originally derived from the city of Winterthur, close to Zurich. Travel demand is given in advance for each pair of demand generating nodes. The amount of travel demand is artificial and given in advance. Each OD pair has a given demand. The amount of travel demand is stated in the relevant tables. Travel times on links are dependent on current traffic flow and are determined with BPR function (Bureau of Public Roads, 1964). The budget constraint is given such that the algorithm has to significantly reduce the number of direct connections between pairs of demand generating nodes. Variable demand responsive to the network services is possible to implement in the future, e.g. with the four-stage transport model, e.g. Ortuzar and Willumsen (2001), or an agent based approach, e.g. Nagel and Flötteröd (2009). Figure 1 shows a basic grid structure; nevertheless, the algorithm is not restricted to a grid. Xml-files with any coordinates of nodes and demand generating nodes can be read initially.

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



The search space is increasing more than quadratically with the number of nodes in a quadratic network structure, which means  $T(n) > O(n^2)$  in  $\Omega$  notation. 100 intersections lead to a search space of  $10^{103}$  possibilities, 400 intersections to a search space of  $10^{446}$  possibilities and 625 intersections to  $10^{708}$  possibilities. Budget constraints reduce the number of possibilities because potential network solutions can be sorted out when the maximum budget of the network solution is exceeded and the demand generated nodes are still unconnected.

The interval scale objective function evaluates a given network. The objective function is detached from the core of the IACGA, so it can be exchanged with other chosen functions; the planner is able to set up its own function according to the local urban planning requirements. Currently, demand weighted travel time, which is fundamental to transport planning, and infrastructure costs are included in the objective function (F 1). The determination of travel times is very costly computationally and therefore leading to a computationally expensive objective function.

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

$O$ : Number of origin demand generating node

$D$ : Number of destination demand generating node

$\gamma$ : Weighting factor (value of time as a recourse), extrapolated for a year

$I$ : Infrastructure costs as annuity

In this paper, the demand assignment is solved with the algorithm proposed by Dijkstra (Dijkstra, 1959) for shortest path determination and the MSA algorithm for the equilibrium search. These algorithms can be replaced by faster algorithms proposed by Frank and Wolfe (Frank and Wolfe, 1956) or origin based algorithms (e.g. Bar-Gera, 2002), but in most cases, computation time savings can be expected to be low (Jourquin and Limbourg, 2003; Zhan, Yang and Chen, 2010).

The amount of travel demand is distance-related to mirror the higher number of shorter trips. In the current stage of research, the demand is approximated linearly to the distance of the network, increasing for shorter distances. The lengths between demand generating nodes vary because of the variable links in the networks and the paths between the demand generating nodes. Therefore, the amount of travel demand is related to crow-fly distance, to avoid demand, which depend on the network, and to reduce calculation times. This assumption is an early estimate and can be replaced with a much more comprehensive demand calculation, e.g. a four-stage model.

### 3. Methodology

The IACGA combines the advantages of both the GA and the ACO methodologies. The GA and ACO methodologies themselves have already been widely used in different applications. Explanations are kept minimal; the reader is referred to the introduction or to the literature for more details, e.g. Dorigo and Stützle (2004), Holland (1975), Goldberg (1989).

White and Yen (2004) introduce a hybrid GA which is based on very similar structures compared to the IACGA described here, also merging ACO and GA. They apply their algorithm on a Traveling Salesman Problem (TSP) successfully on test cases up to 318 cities. Similarities and differences exist between the TSP and the transport network design problem. Both problems generate graphs, and mainly planar networks occur in both cases. Additionally in the current network design approach, we kept candidate nodes fixed in space, like in the TSP. The differences are the objective function and the constraints. The TSP excludes overpasses, cycles and only optimizes the lengths, contrasting the transport network design, which allows cycles and has an often time-consuming objective function. In the following, we introduce the IACGA and refer to the hybrid GA of White and Yen (2004) when necessary.

From the GA, the population approach is inherited in the new algorithm as well as an evolution over time with a recombination approach and breeding populations. A single population consists of several individuals each representing a single network. Recombination

of two parent individuals leads to a new offspring, becoming a member of the next generation. In line with Goldberg (2002) and others, the IACGA is not allowing for mutation. It is assumed that mutation destroys complex networks and that too few feasible networks are generated with random mutation. This approach contrasts with White and Yen (2004) who applied a specific mutation procedure. A local search approach may be applied in the IACGA and is subject to further research.

The IACGA is, like standard ACO, a metaheuristic with strong learning ability. Learning techniques are adopted to support recombination. The motivation is the weak learning ability of a standard GA. Employing the results from previous populations, recombination is able to generate fitter individuals and simultaneously a lower fraction of infeasible offspring. Also the nature of a transport network is taken into consideration, such as assuring a necessary connected graph between the zones, or unnecessary detours.

### 3.1 Detail description of the IACGA

The following paragraphs explain the IACGA step by step. An overview is given in Figure 2.

1. The initial population is generated containing individuals each representing a randomly generated network. A candidate link is chosen with a probability  $q = 0.5$  and all links are checked. Dead ends are removed, but links with no traffic flow after demand assignment remain for completeness. They eventually can still be used in following generations.
2. Two individuals, member of the parent population, are the starting set for the recombination procedure. Links from both parents are chosen with probability  $p_{ij}^g$  as a function of the pheromone density and a random term (F 2), until the budget is depleted (step 3 for more details). Other variables like score of the parent networks, number of chosen neighbors or others can be included in (F 2). The scores of the parent networks, as they may be used in a standard ACO algorithm, are disregarded in the decision making process because they are indirectly present in the pheromone densities. The Logit structure  $\frac{e^{V_i}}{\sum_j e^{V_j}}$  is applied successfully in an ACO by

Poorzahedy and Abulghasemi (2005).



$$F 2 \quad p_{ij}^g = \begin{cases} \frac{e^{\alpha\tau_{ij}^g} e^{\beta r}}{\sum_{l_{ij} \in L_{Parents}} e^{\alpha\tau_{ij}^g} e^{\beta r}}, & \text{when } l_{ij} \in L_{Parents} \\ 0, & \text{otherwise} \end{cases}$$

$p_{ij}^g$ : Probability of choosing link  $i$ - $j$  in iteration  $g$ .

$\alpha, \beta$ : Parameters of pheromone density  $\tau_{ij}^g$  and the random term  $r$ .

$L_{Parents}$ : Set of links  $l_{ij}$  which are present in at least one parent network.

The first link is chosen out of the entire set of candidate links from the initial set of two parent individuals. To prevent the link determination process of generating many single and unconnected links, a path is generated to the next common node: If the first link got chosen by the formula described above, adjacent links are selected until a common node, which exists in both parent networks, is reached. This stepwise procedure generates a path including the link above and all neighboring links. It reduces the chance of generating many stand-alone links with no connection to the network.

3. The budget constraint serves as the upper bound when generating new networks. It determines total links lengths in the network. Because the initial networks are generated randomly, they most probably exceed the budget constraint. Only at the beginning, also more expensive networks are allowed as solutions. Therefore, the budget constraint is relaxed at the beginning, and also networks are generated with total expenditures above the budget constraint. The relaxation is undone gradually in the first 20 iterations, and network expenditures are limited to the budget constraint. Nevertheless, more expensive networks are penalized and achieve a lower score, because the objective function remains the same. To reduce initially high infrastructure costs, dead ends and unused links (detours) are removed to increase the score.
4. Step 2 and 3 are repeated four times with different parent networks and only the best offspring is added to the offspring pool. All other parents return to the ancestor pool except one parent of the chosen offspring. This procedure reduces the risk of generating infeasible networks and improves the merging results. The number of trials leads to only a very few finally infeasible networks, but is subject to further calibration. In all examples below, four trials seem reasonable. This inner loop is not shown in Figure 2 due to lack of space. Step 4 also is responsible for changing the positions of individuals in the population, as extremely important to the overall success of a GA (Goldberg, 2002). Due to the risk of generating subpopulations,

containing a reduced pool of candidate links, individuals should change their position in the population to recombine always with individuals with different candidate links.

5. The pheromones are updated as soon as an entirely new generation is generated from the parent generation. The pheromones on all candidate links are updated with the scores of the individuals of the new population. It can be possible that several individual networks implemented the same link in their network, but differ in their overall score, derived from the objective function, because other parts of the networks distinguish between each other. If this is the case, currently only the highest score are considered in the update of the pheromones on the link in consideration. This approach is similar to White and Yen (2004), updating only the pheromones on link corresponding to the very best individual. It is assumed that averaging the scores across all individuals reduces the convergence rate.

$$F 3 \quad \tau_{ij}^g = (1 - \delta) \cdot \tau_{ij}^{g-1} + \max(\Delta \tau_{ij}^g)$$

$\tau_{ij}^g$  : Pheromone density in iteration  $g$  on link  $i - j$ .

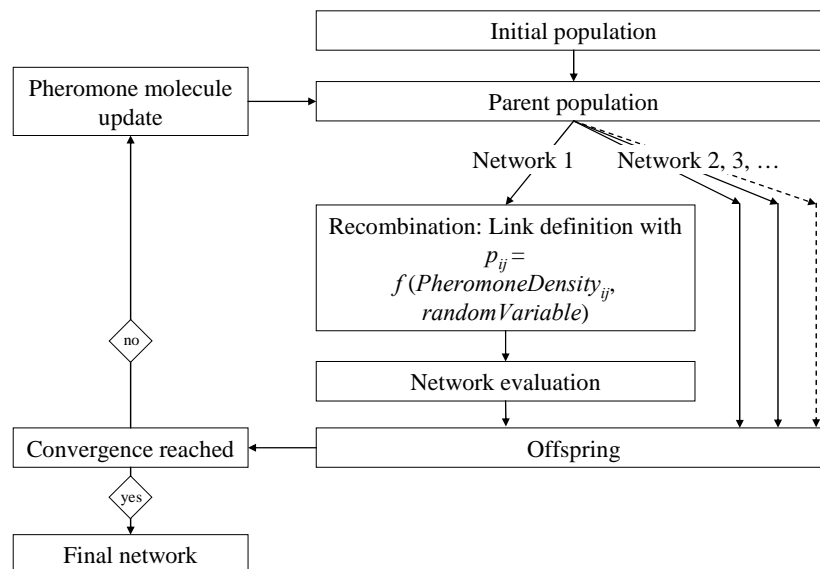
$\delta$  : Evaporation rate.

$\max(\Delta \tau_{ij}^g)$  : Score of the best individual out of all processed network individual.

$\tau_{ij}^0$  is initiated with the scores of the first iteration.

6. Convergence is reached when the pheromone densities are not changing any more or when a substantial part of the population consists of the same members. The algorithm returns to step 2 if no convergence is reached. The cutoff criterion is responsible for stopping the population generation when no better individual is expected in further generations. Different cutoff criteria have been tested. The most promising criterion considers the pheromone densities, which vary over the generations. Overall, pheromone densities on the links mainly decrease, because the algorithm ignores an increasing number of links. Only links which lead to networks with high and competitive scores can maintain their pheromone densities. According to the characteristics of the algorithm, when reaching the optimum network, the pheromone densities on all links decrease except densities on the links of the optimum network. Therefore, the criterion requests decreasing pheromone densities during a given time period of  $n_{cutoff}$  generations expect on links of the optimum network. After  $n_{cutoff}$  generations, no other networks are supposed to replace the so far best individual.  $n_{cutoff} = \left( \frac{\text{assumed total generation number}}{15} \right)$  is still subject for further calibration, but applied successfully.

Figure 2 Overview over the IACGA



A major difference between the IACGA and a GA is the missing distinction between the genotype and phenotype. The IACGA recombines the networks directly in the phenotype structure still following the idea of the building block hypothesis (e.g. Goldberg, 2002; Holland, 1975), which says that successful parts of the network should be maintained with a higher probability during recombination processes.

#### 4. Convergence behavior

As in a standard GA, average scores of the members of a population should increase during the process. Figure 3 displays the convergence result of a test case network of 386 nodes, and 44 demand generating nodes, consistent with Figure 1. The highest and lowest score occurring in each generation is displayed for each generation during an optimization run.

Figure 3 Typical convergence behavior of the IACGA

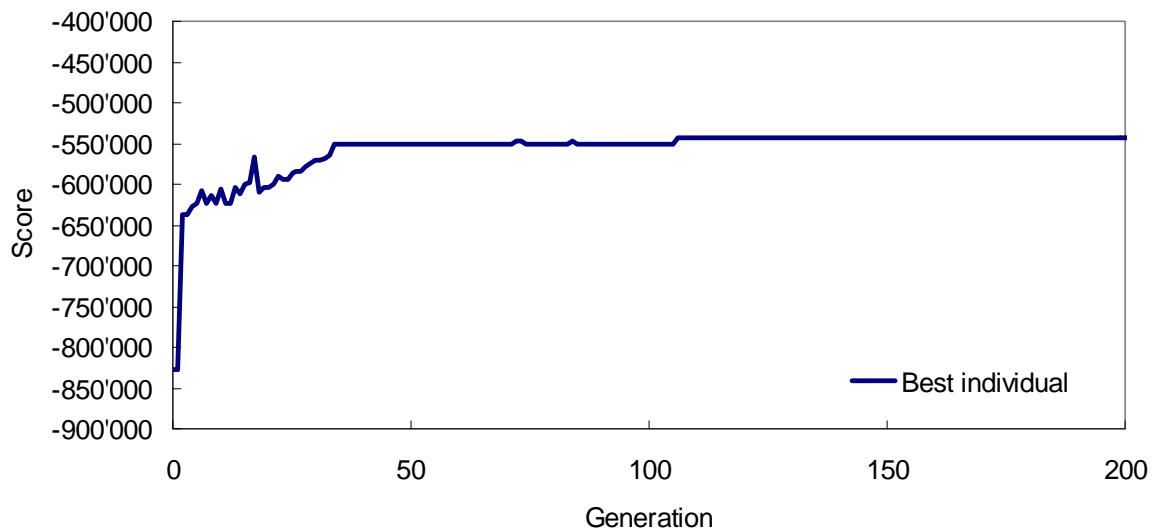
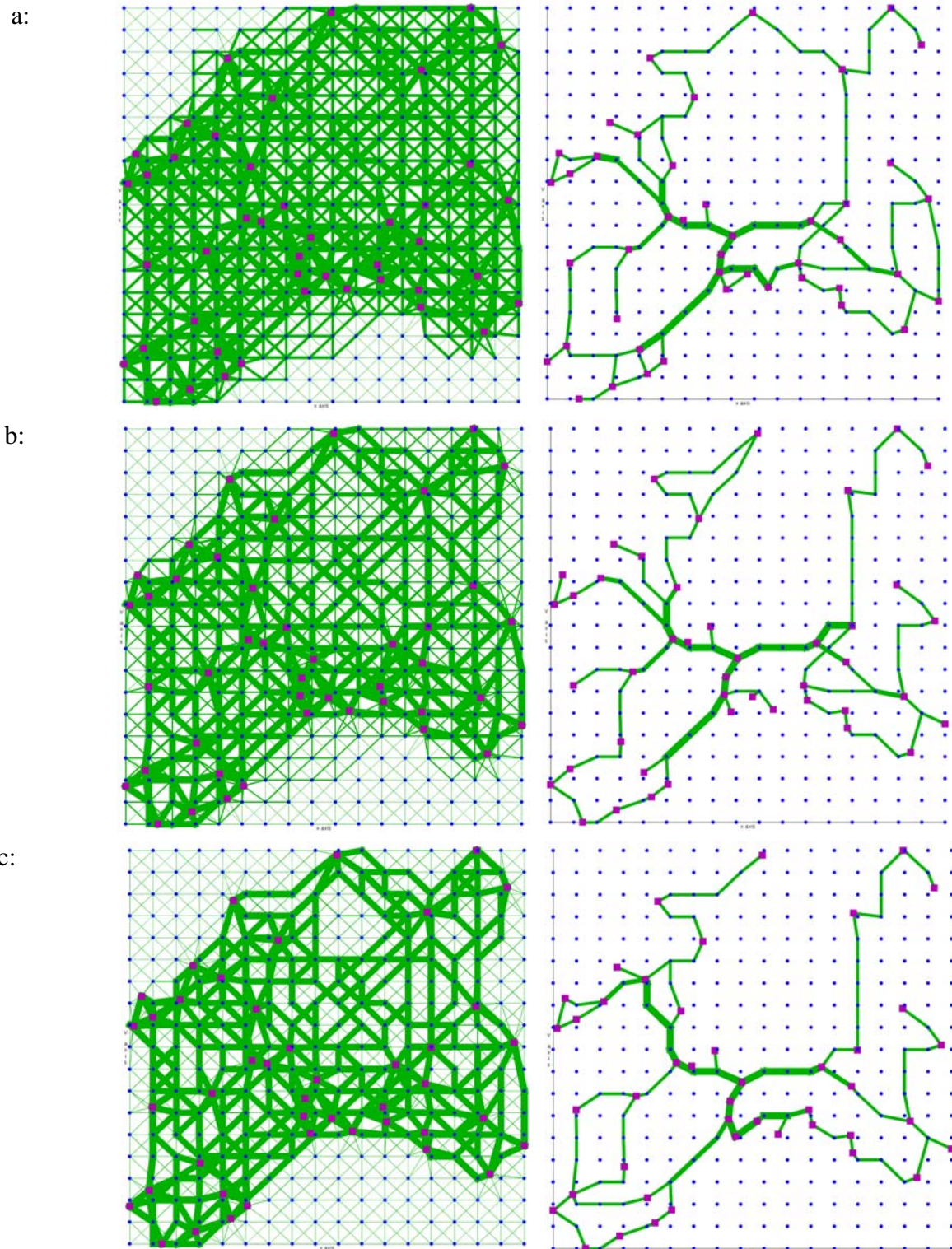


Figure 3 shows the effect of an exclusion of the saving of elite individuals because of the discontinued increasing of the best network score. If the population size is large enough, elite saving is assumed to be not necessary. Fast reduction can be seen at the beginning. Low scores at the beginning are due to the initially randomly generated individuals. They have very high infrastructure costs because of the randomly chosen candidate links. Because of the decreasing costs of network individuals in the first generations, the scores also decrease as well as the score of the best individual. A slower reduction of score is expected after 40 generations, because only minor changes occur in the network design.

The pheromone density on each link can be stored after each pheromone update. The shifts in the pheromone densities can be used for validation of the convergence behavior. Due to lack of space, the shifts of the pheromone densities between different generations are shown only exemplarily in Figure 4 (left) for generation 100 (Figure 4 a), 200 (Figure 4 b) and 300 (Figure 4 c), as well as the best scoring network individual of the corresponding generation (right).

Figure 4 a, b, c      Pheromone densities on each link of an example network of generations 100 (a), 200 (b) and 300 (c) with the best networks for each corresponding generation.



The problem of near optimal solutions is illustrated in Figure 4. Improvements on a local level are still possible when looking at the pheromone densities of the last picture in Figure 4, e.g. with local search methods (e.g. in White and Yen, 2004). But they are not leading to large changes in the overall score. The overall picture is very reasonable. As stated above, smaller changes are expected at the end of the convergence. Even after iteration 100 (Figure 4 a), only minor changes are expected. Indirect connections with intermediate intersections occur in the network, leading to Y-patterns.

Test runs are conducted for global convergence. Since the algorithm is of heuristic nature, and a complete enumeration is too time-consuming, it never can be guaranteed that the global optimum is reached in a given run. Therefore, the algorithm is tested for a special case where the optimum is known in advance. The alignment of nodes and zones is arranged in a way that only one optimum can be generated. The test case is a square network structure, similar to previous figures, but only with one demand generating node in each corner, four in total. The minimum network infrastructure encompasses both diagonals with a node in the center. This setting is challenging because direct paths following the sides of the initial square network structure are shorter and are seemingly more favorable, but leading to a local minimum. The budget constraint is the minimum network size, two diagonals with one node in the center of the network.

Considering the test network layout described before, it is measured how many times the algorithm reaches the optimum. Two evaluations were conducted with different initial populations. The population in the first evaluation is generated randomly (step 1 in Section 3). A second test run is conducted for reliability reasons. Here, the size of the initial population is doubled, and half of the initial networks with an initial score above average were deleted, leading to a population of the initial size, but with individuals of lower scores. Parameters remain the same. The results are in Table 1.

Table 1 Testing the global optimum without and with a degraded initial population in a network of 121 nodes and 420 candidate links and a sample size of 73 each.

Best possible score	Share of networks reaching the known optimum	Standard deviation	Standard error
Without degraded initial population:			
-2'432	51%	0.67%	3.37
With degraded initial population:			
-2'432	55%	0.79%	3.90

The global optimum is reached in 51%. This rather low rate is due to the difficulty of the initial network setting. Nevertheless, the nearly global optima, which were reached in the other cases, are only little different from the global optimum. With degraded initial population, the global optimum is reached even in 55% but with higher deviation and error. This underlines the cutoff method described below as well as the robustness of the algorithm. The results coincide with the results of Dorigo and Blum (2005) where the ACO is an approximate algorithm for good enough solutions in reasonable amounts of time.

Performance tests were conducted to compare a standard GA and the IACGA. The standard GA is described in Vitins and Axhausen (2010). Table 2 shows the comparison between the GA and the IACGA for different test cases, based on the work of Vitins and Axhausen (2010). The runs were calculated on different computers applying different number of parallel threads. The total calculation time is scaled down or up for comparison reasons. The up- or downscaling assumes linearity, which is an approximation in reality but justifiable when considering high parallelization capabilities of the IACGA.

Table 2 Difference between a standard GA and the IACGA.

Network size [nodes]	Number of evaluations of the objective functions			Total calculation time [h] of a single CPU machine		
	GA	IACGA	Difference	GA	IACGA	Difference
100	200'000	54'000	- 73.00%	6	0.75	- 87.50%
225	$1.7 \cdot 10^8$	140'000	- 99.92%	5'100*	2	- 99.96%
400	$\sim 1.1 \cdot 10^9$ **	700'000	- 99.94%	33'000*	124	- 99.62%

\* It is assumed that in the case of GA, calculation time grows linearly with the number of objective functions evaluated.

\*\* Estimated using the conclusions of Goldberg (2002), and based on the results of smaller networks.

Table 2 shows a drastic reduction of the necessary number of objective function evaluations. This is due to the learning ability of the IACGA, the less random merging of new networks and the reduced chance of generating individuals with low scores, compared to the GA which generates random individuals during reproduction. Nevertheless, elements of the IACGA algorithm also use more calculation time compared to the GA. This is mainly due to the more computationally expensive link determination. In the IACGA, the formula (F 2) requires more calculation time compared to the GA, in which the new networks are determined randomly in the genome structure.

The separate processing of many individuals benefits from the recent development of large multi-threading architectures. The largest scenario is calculated on a Sun Fire X4600 with 8 CPUs (AMD Operon 2.66 GHz dual core) and 128GB RAM. The scenario consists of 625 links and 29 demand generating nodes and requires about 5 days of calculation time with 100% working load. The scenarios in Table 2 are conducted with 50% of working load of the above mentioned computer. These rather high hardware requirements are reasonable especially with the current development, which is pointing toward an increasing availability of even more cores for multi-threading architectures. This development makes the algorithm even more suitable also for computing time expensive objective functions.

## **5. Shape grammars for transport networks**

The following three subsections describe different hierarchies for transport network design as well as potential shape grammars, which can be found in handbooks and standards. Shape grammars are implemented in the IACGA. The evaluations of the resulting networks generated by the IACGA are explained at the end of Section 5.

### **5.1 Network hierarchies**

Network hierarchies describe ordered types of nodes and links, i.e. junctions, roads, and transit lines including their characteristics, e.g. designated speed, capacity/hour or number of lanes. For example, for residential access the rules of the hierarchies specify links with small widths, sideways, speed bumps, parking areas as opposed to links in industrial zones or interurban connections with less parking, wider widths, less and smoother curves and higher designated speed limits. Each attribute or characteristic can be classified in different ranges. Network elements can be assembled in groups or hierarchies with certain attribute classifications. Table 3 divides in different hierarchical classifications.



Table 3 Link hierarchies and characteristics in Swiss norms

Link type	Level	Function	German translation
Highway	international to regional	major carrier for through traffic	Hochleistungsstrasse (HLS)
Expressway	national to inter-municipal	major carrier for connection purposes	Hauptverkehrsstrasse (HVS)
Arterial	regional to inter-municipal	minor carrier for connection purposes	Verbindungsstrasse (VS)
Collector	municipal	collecting traffic	Sammelstrasse (SS)
Local	district	access	Erschliessungsstrasse (ES)

Source: VSS (1994)

Special care has to be taken in the German - English translation, due to the official classification in the USA. In the USA, the official classification distinguishes between urban and rural roads and therefore differs from the table above. The following list explains the hierarchical classification in the USA (AASHTO, 2004):

- Principal arterial street
  - Freeway
  - Interstates (only in urban classifications)
  - Others
- Minor arterial street
- Collector street
  - Major (only in rural classifications)
  - Minor (only in rural classifications)
- Local street

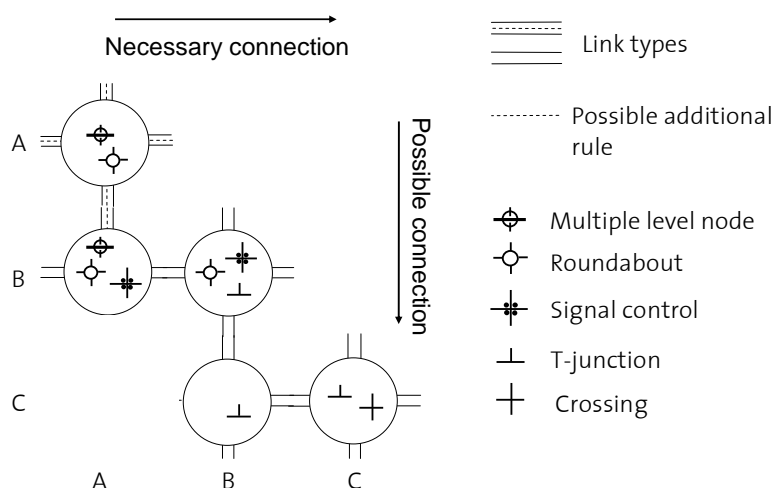
Care has to be taken of the broad class of arterial streets, which ranges from freeways (principal arterial street) to intracommunity streets (minor arterial street). Details can be found in AASHTO (2004) and ITE (2008). The classes of collector and local streets are similar to the Swiss classifications.

## 5.2 Shape grammars in consideration

Shape grammars for transport networks describe in the form of rules how network elements like links and nodes have to be added to each other. The shape grammars implemented in this

work are explained in Marshall (2005). Marshall (2005) suggests a street network approach based on shape grammars for hierarchical layout, as shown in Figure 5.

Figure 5 A schemata of a hierarchical approach of three levels.



Source: After Marshall (2005)

Figure 5 describes necessary and possible connections between link and node types of different hierarchies. It is stated that links can be added to each other only if the adjacent link is of the same type or one type lower or higher. Candidate links cannot be added to each other if they differ in more than one hierarchy level. Additionally, it is stated that a link of a given hierarchy has to be joined with another link of the same hierarchy in order to maintain a coherent network. On the right side of Figure 5, different node types are proposed with different specifications. Nodes of a given type have to match the adjacent links and their types. Similar to the shape grammars for links, nodes can be implemented only if the types of the adjacent links are consistent with allowed hierarchies, as shown on the left side of Figure 5. In the following, shape grammars for node types are listed here only for the sake of completeness and are not considered further.

### 5.3 Handbooks and Guidelines

Several guidelines provide shape grammars about link joining, similar to the shape grammars above, and are mainly described in handbooks and technical standards. Different handbooks and standards are scanned for comparison of the shape grammars and for possible implementation in the IACGA. An overview of the scanned guidelines is given in Table 4. The table only considers the grammars regarding adjacent link types, other shape grammars for street design are ignored.

The considered guidelines differ in their recommendations for a hierarchical structure within network design. Regarding the grammars of joining links described above, both restricted and relaxed recommendations can be found in the guidelines. A strict hierarchical layout is leading to a network with joined links which only differ in one level of hierarchy at most. If the recommendations are more liberal, joined links can differ in more than one level of hierarchy. A summary is given in the list below. A, B and C are different level of hierarchies, consistent with Figure 5.

- Restricted grammar rule: A-A, A-B, B-B, B-A, B-C, C-B....
- Moderate grammar rule: A-A, A-B, avoid A-C, ...
- Relaxed grammar rule: A-A, A-B, A-C, B-A, B-B, B-C, B-D, C-A, ...

Table 4 Overview of the hierarchical shape grammars of the different guidelines

Country	Explicitness	Number of hierarchies	Description and special focus	Source
Switzerland	restricted	5	Transport or settlement divided Type-approach	VSS (1994)
USA	moderate	5 - 6	Land-use related Extra transitions	ITE (2008), AASHTO (2004)
Germany	relaxed	5	Rural and urban subdivision Functional levels	FGSV (2008)
England			No rules found so far	IHT (1997)

Table 4 emphasizes a hierarchical network design as found the scanned handbooks. The similarity in the levels of hierarchies is notable and is mainly due to comprehensiveness and understandability for the planner and road network user. It also can be stated that only a few recommendations exist for hierarchical network layout. The guideline of Switzerland recommends a strong hierarchical design, but does not list any detail about the completion in practice. The opposite is found in the handbook “Transport in the Urban Environment” of England (IHT, 1997) which gives advices on street appearance, but no advices on hierarchical structures in network layouts and transitions.

## 5.4 Costs of link types

For planning purposes, costs of the link types have to be known in advance. Depending on the budget, different link types can be allocated differently in the network. E.g. a lower total

budget may lead to a higher share of links of lower hierarchies, which result in a less expensive network design. Table 5 shows the costs for six different link types. Additionally, costs of nodes are added for the sake of completeness, but are not considered further in this work.

Table 5 Costs of network elements in the USA (year 2000)

Network elements	Costs [Mio \$/lane-km]		Costs [Mio \$/junction]	
	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	-	-
Local street	-	-	-	-

Source: \*Litman (2009), \*\*Alam, Timothy and Sissel (2005)

As expected, considerable differences occur between links in built-up and outlying areas. The costs of intersections tend to differ more between different levels of hierarchies, compared to the differences of costs for links. This is due to over- and underpasses and larger radiuses for curves for freeway and highway nodes. The costs of the major arterial roads are considerably higher compared to the next lower level, the collector roads, because the major arterial still historically functions as a major carrier, compared to the collector road which only carry locally generated traffic. For local streets, no reasonable values are found so far. Costs tend to increase over time because the cheaper projects are always built first (DOT, 2008; Gätzi, 2004).

Shares of link types are a relevant topic for planning purposes and when allocating the link types for network design purposes. The distribution of street type mainly depends on the traffic flows of the links under consideration, and also on the costs, and on the land usage. Therefore the choice of an appropriate link type often is a trade-off between costs, traffic flow and function of the street in the urban environment. Table 6 compares the shares of link types in the United States (excluding Alaska and Hawaii) and in Switzerland.

Table 6 Share of the link type lengths in the USA

System	Share of link type [%]	
	Urban	Rural
Principal arterial system	5 – 10	2 – 4
Minor arterial system	10 – 15	4 – 8
Collector road system	5 – 10	20 – 25
Local road system	65 – 80	65 – 75

Source: \*AASHTO (2004) p.10, 12

Table 6 distinguishes between principal and minor arterial system. Compared to the principal arterial system, which carries mainly through traffic, the minor arterial system emphasis more on land access and provide intracommunity continuity (see above or in AASHTO, 2004). In the Swiss context and referring to Table 3, major arterial roads are highways and interstate roads (HLS und HVS). Minor arterial, collector and local road system are considered in this work due to the urban focus. Therefore, the average shares are 14% for minor arterials, 8% for collector and 78% for local roads in the network design application of this work.

## 5.5 Implementation of shape grammars

The attributes of the link types, e.g. speed and capacity limits, differ between the recommendations. Therefore, the attributes represent different hierarchies in a way to distinguish the levels clearly (Table 7). Higher hierarchy levels, like highways and freeway / expressway, are not considered because of the urban focus of this work. A restricted shape grammar is applied, which states that joined links are allowed to differ in one level of hierarchy at most.

Table 7 Currently implemented link types

Link type	Hierarchy	Max. capacity [veh./h]	Speed [km/h]
Minor arterial system	A	1'200	68
Collector road system	B	800	46
Local road system	C	500	28

The shape grammars are applied in the IACGA described in the previous sections. The shape grammars are implemented in the generation process of each individual. Because the shape grammars are considered in the generation process of each individual, every individual

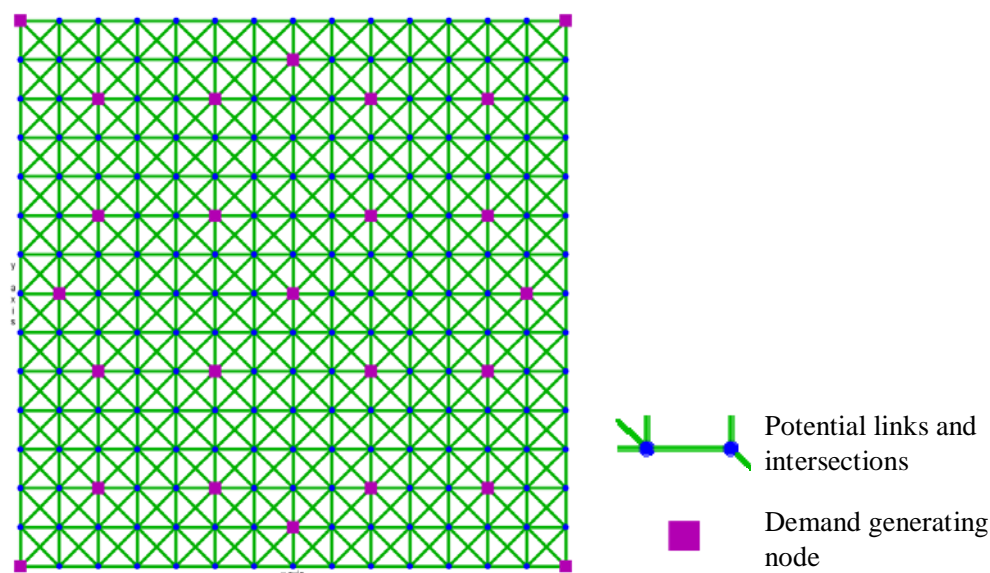
generated in the IACGA meets the designated shape grammars. When implementing the shape grammar in a network layout, the link types under consideration have to be allocated to the network links in such a way that a maximum reduction in generalized costs of travel is achieved. At the same time the relevant shape grammar rules have to be fulfilled. The generalized costs are approximated currently by the travel times. To reach a maximum reduction of travel time, the street types are allocated according to the distribution of traffic flow on the links. A higher link type hierarchy is allocated to a link with a higher traffic flow to minimize travel time. A top-down approach is implemented at this point, which starts at the highest hierarchy and allocate the link type to the links with maximum flow and simultaneously building up a coherent network. If the share of the highest link type, which remains fixed, exceeded, the next lower link type is allocated to the remaining links. The methodology is repeated for each link type until the lowest hierarchy. The allocation of link types to the network links is implemented in the travel demand assignment iteratively. The allocation is leading to a minimum travel time for given shares of link types. Simultaneously, the shape grammars are maintained. The method also is able to generate a coherent network regarding the shape grammar in consideration. Until now, the shares of the different link types are kept fixed. Nevertheless, the shares can be variable too, which is described below.

When implementing variable link type shares, an algorithm searches for the most optimum link type distribution. Depending on the link type distribution, the score of the network might be higher or lower regarding the objective function. The aim is to achieve a maximum overall network score, regarding the objective function  $F$ . E.g. part of a network may be more suitable for local streets due to its lower travel demand, leading to a lower share of arterial roads. Or another network only consists of arterial and local and no collector streets. To find the optimal shares of link types, a stepwise procedure is applied where the share of each link types vary, maintaining a total share of 100%. The algorithm is of iterative nature; because the most appropriate shares cannot be determined in advance. Therefore, the algorithm scans through the possible combination of link type shares. Within each combination of different link type shares, the network is evaluated regarding its score. Only the network with the link type combination leading to the best score is considered further in the evaluation process. To lower computational time, the step size is set to 2%, which means that the possible shares differ in a multiple of 2%. Therefore, the combination of different share of link types is limited to a maximum number of combinations and a reduced calculation time. A cost limit has to be met in the optimization process to avoid applying only links of the highest hierarchy with the highest speed limit. The networks generated have to have the same maximum infrastructure costs. Currently, the link types are distributed independently of the overall link budget mentioned in the sections above. Networks differ in the allocation and shares of link types. But the average costs of the links of all types are identical with the average link costs in real networks. Interaction of the budget for the link type distribution and the network budget is subject to further research.

For comparison, shape grammars can be disregarded during the optimization process of the IACGA. If shape grammars are disregarded, the network elements are arranged in the most optimal way regarding the score of the objective function. In the current IACGA, the link types have to be distributed to minimize the total travel times. Therefore, higher hierarchy levels are allocated to links with higher traffic flows, independent of any shape grammars.

Two network examples for testing purposes are conducted to validate the shape grammars described above. The first network example A is a synthetic example of a symmetric distribution of centroids, shown in Figure 6. The second network example B comprised centroid allocation originally derived from the city of Winterthur (Figure 1).

Figure 6 Synthetic network example A for testing shape grammars



## 5.6 Results of the grammar implementation

Three different optimal network layouts are determined with the IACGA for each of the two network examples. The first network design results when no shape grammars are considered during the optimization run of the IACGA. The street types are allocated in a most optimal way, described in the section above. The second network design results of an IACGA optimization implementing a standard hierarchical approach, where jointed links have to differ in one level of hierarchy at most. In both the first and second network design, the shares of link types are given in advance, in contrast to the third network design. In the third network design, the shares of link types are optimized during the IACGA to additionally improve the scores of the networks. Shape grammars still have to be met in the third case. The scores of

the resulting networks are shown in Table 8. Due to longer calculation times, the sample size of the calculations with the network example B is lower (n=2).

Table 8 Different scores of the grammar implementation

	Network example A		Network example B	
	Average score (n=4)	Difference	Average score (n=1)	Difference
No hierarchical shape grammar	-126'843		-512'246	
Hierarchical shape grammar, fixed type share	-135'242	+6.6%	-589'209	+15.0%
Hierarchical shape grammar, optimized type share	-135'044	+6.5%	-597'808	+16.7%

All scores are negative because of the negative impact of the generalized costs of travel and the infrastructure costs. The scores of the network with and without hierarchical shape grammars differ clearly for the synthetic network example A. The scores of the networks are higher when the networks include hierarchical shape grammars. The scores remain when the share is optimized during the network design. The resulting networks of example A with variable link type share (last line in Table 8) show similar link type shares compared to observations (Table 6), with about 2% deviation.

In example B, derived from real world example, a similar pattern can be found. The score is the highest when implementing no grammar rules in the network design process. When considering network grammars, the score lowers. As in network example A, the optimized shares are similar to the shares observed in real networks. This fact gives the impression that the share is optimized already in average in real world networks. Further validation is required.

## 6. Conclusion

This research motivated by the need of providing planning tools for developing urban systems in many different countries around the world. Urban planners face interacting and complex systems and therefore require sound methods for planning purposes. Especially shape grammars are a promising toolbox for planning purposes. Yet, unclear is the impact of the shape grammars in transport planning. Following the planners needs, an Integrated Ant



Colony and Genetic algorithm (IACGA) is presented to solve the transport network design problem, which chooses the network out of an initial set of candidate links, to connect all predefined neighborhoods or demand generating nodes. Simultaneously, shape grammars can be met in the design process. The major achievements of the metaheuristic are the integration of both the genetic algorithm (GA) and the ant colony optimization (ACO) and concurrently keeping calculation times low. The major characteristics of the IACGA are improved recombination methods of the individuals and the ability of learning from previously generated networks. The IACGA optimizes large scale networks within reasonable times. Additionally, hierarchical shape grammars are included in the network design process, including cost considerations and optimized shares of the different hierarchies. The approach of implementing shape grammars in the network design process is promising. The implementation of hierarchical shape grammars show that hierarchical shape grammars affect the overall gain of the generalized costs of travel, when comparing networks without meeting shape grammars. This fact gains relevance when considering the increasing application of shape grammars in urban planning.

Additional link shape grammars as well as node types have to be included in the optimization process. Improved parameter adjustment, also during convergence, may reduce calculation time for very large networks. For further research, more shape grammars, public transportation and land use aspects can be included in the algorithm. Other fields beyond transportation also offer potential applications for the IACGA. Different test cases are required, e.g. applications in other graph generating problems in operations research, like shortest path problems. Telecommunication, gas pipeline network design or more general applications in operations research are assumed to be suitable for the IACGA as well.

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