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Integrated and Real-Time Anticipatory Control of Road Networks

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Abstract

Dynamic traffic management is an important approach to minimise the negative effects of increasing congestion. Measures such as ramp metering and route information, but also the traditional traffic signal control is used. The focus in designing traffic control plans has always been on local control. However, there is a tendency to come to a more centralised and network wide approach of traffic control. The interaction between traffic management measures and the route choice behaviour of the road users then becomes an important aspect of the control strategy design. The work described in this paper shows that anticipatory control can contribute to a better use of the infrastructure in relation with policy objectives. The paper presents a framework for real-time integrated and anticipatory traffic management. It uses model predictive control including route choice to optimize traffic management. It is tested for small networks with good results. The framework can be used as a basis for further research on this topic.

Introduction

In The Netherlands transport and traffic policy heavily relies on traffic management. Building new roads is either too expensive or takes too much time due to procedures related to spatial and environmental conditions. Technically and politically road pricing will be difficult to implement the coming years, so for the Dutch Ministry of Transport, Public Works and Water Management (2004) traffic management is the key direction in which solutions for the increasing congestion problems have to be found. The reason for this is that traffic management is faster to implement and it faces less resistance than the other solution directions. In fact this is the situation since the nineties from the previous century. From 1989 on, a lot of traffic management measures were implemented, varying from a motorway traffic management system and ramp metering systems, to overtaking prohibitions for trucks, peak-hour lanes and special rush hour teams of the traffic police. In a recent policy document the Dutch Ministry of Transport, Public Works and Water Management (2008) estimates that traffic management reduced the increase of congestion (measured in vehicle hours delay) with 25% during the years 1996-2005.

In most cases traffic management in The Netherlands is used only on a local level. It lacks an integrated and network wide approach. The main reason for this is that different network types (e.g. motorways and urban roads) are operated and maintained by different road managers. In practise these road managers are only responsible for their own part of the network and normally they do not communicate or cooperate that much. To deal with this, The Netherlands has adopted a different approach, described in the Handbook Sustainable Traffic Management (Rijkswaterstaat 2003). The handbook gives a step-by-step method that enables policy makers and traffic engineers to translate policy objectives into specific measures. The method consists of clearly defined steps that can be summarised as: define policy objectives, assess current situation, determine bottlenecks and create solutions. The step-by-step plan helps to develop a network vision based on policy objectives, shared by all participating stakeholders. In addition, the handbook provides the stakeholders with a first indication of the measures required to achieve effective traffic management in line with the shared vision. To be able to say more about the effects, the Regional Traffic Management Explorer (RTME) was developed. This sketch and calculation tool supports the steps from the handbook and makes it possible to determine the effects of proposed traffic management services and measures. The effects can then be compared to the formulated policy objectives or other sets of measures. For more information on the method, the RTME and its applications, the reader is referred to Taale *et al* (2004) and to Taale and Westerman (2005).

Dynamic Traffic Assignment

To be able to calculate the effectiveness of traffic management, the Regional Traffic Management Explorer (RTME) uses a dynamic traffic assignment (DTA) model. Traffic assignment is concerned with the distribution of the traffic demand among the available routes for every origin-destination pair. It is called dynamic, because the traffic demand and the traffic situation in the network change over time and are taken into account for the distribution. The model itself consists of a control module, an assignment module and a network-loading module, which are integrated in a framework. The framework is shown in figure 1. After initialisation traffic control is optimised, then the network is loaded with the traffic demand to calculate the traffic situation and this situation is used to come to a new assignment of traffic on the available routes. This process iterates until it converges into a traffic equilibrium.

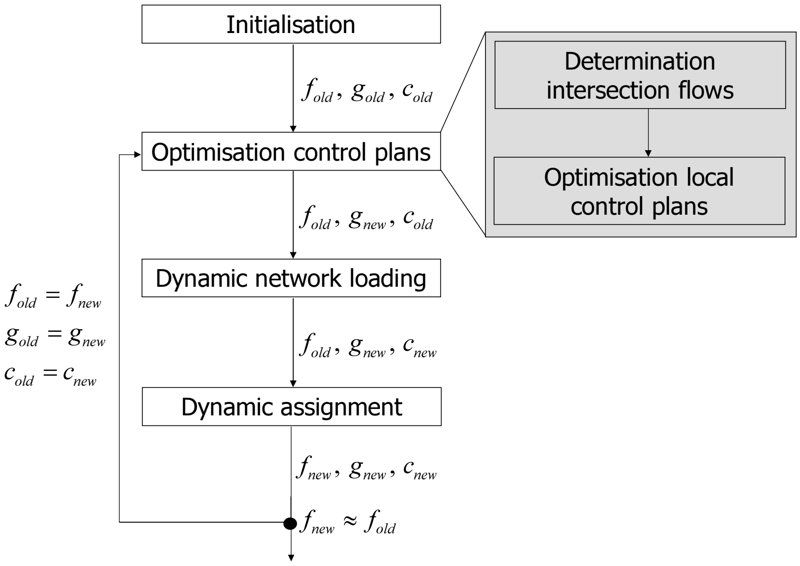

Figure 1: Framework for DTA model

The dynamic traffic assignment (DTA) module contains three different assignment methods: deterministic, stochastic and system optimal. A deterministic assignment assumes that all travellers have perfect knowledge about the traffic situation in the network and therefore chose the route that is best for them. In a stochastic assignment travellers do not have perfect knowledge and choose the route that they perceive to be the best for them. This type of assignment is the most realistic one and is used for the case studies. In a system optimal assignment everybody chooses the route that is best for the network as a whole. It is a kind of benchmark with which the results of the other assignments can be compared. All assignment methods are route based. That means that they distribute the traffic among the available routes for a certain origin-destination relation. Therefore, route searching is important. The route enumeration process searches for the k-shortest routes using a Monte Carlo approach, with a stochastic variation of the free flow link travel times and Dijkstra's shortest path algorithm.

The dynamic network-loading (DNL) model uses travel time functions to propagate traffic through the network. For different link types (normal links, signal controlled links, roundabout links and priority links) different functions are used. The travel time is used to determine the outflow of links and with that the inflow of downstream links. At decision nodes traffic is distributed from the incoming to the outgoing links according to the splitting rates, which are calculated from the route flows using the travel times. Congestion is always caused by a capacity restriction and the resulting queue propagates upstream and horizontal, which means that blocking back is taken into account. The route travel times (needed for the assignment) are calculated from the link travel times using a trajectory method.

The DTA and DNL models are calibrated and validated for a motorway bottleneck and for a network with motorways and urban roads. For both situations real-life data is used to calibrate parameters and to see of model results and data are comparable. Although comments can be made concerning the data and the method of comparison, it appears that the DNL model is capable of simulating bottlenecks fairly accurate, and that the combination of the DTA and DNL models is capable of simulating medium-sized networks with good results. In figure 2 the results for the motorway bottleneck are shown. The figure shows the speeds over time and space, measurements on the left and simulated values on the right. It is clear that the model does not produce the shock wave pattern as measured in the data. From the plots it can be also be seen that the congestion in the model starts earlier and takes more time to dissolve

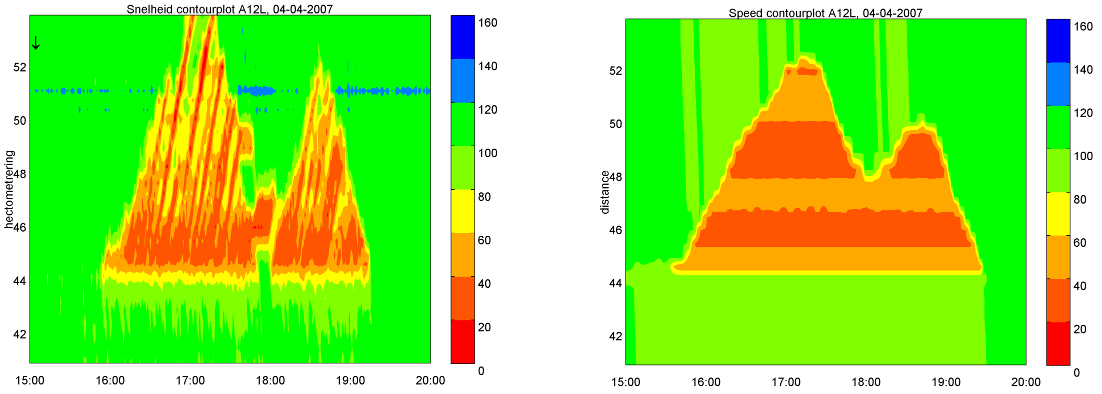

Figure 2: Measured and simulated speeds for a motorway bottleneck

Integrated Anticipatory Control

Both the assignment and network-loading modules are part of a framework for integrated anticipatory control. Integrated control means that the network is considered to be one multi-level network, consisting of motorways and urban roads. Anticipatory control means taking into account not only the current, but also future traffic conditions. For these future traffic conditions the focus is on long term behaviour of road users, such as route choice and choice of departure time. Using game theory, it can be shown that traditional, local traffic control is related to the Nash game or Cournot game, in which each player reacts on the moves of other players. Anticipatory control is related to the Stackelberg game, in which one or more players can anticipate the moves of other players if they have some knowledge about how players react.

In the research described in this article, the question was answered how traffic management should be designed and optimised and whether it is beneficial to anticipate route choice behaviour. To answer these questions, the framework from figure 1 is extended with a control module and in this control module the traffic management measures are optimised in such a way that route choice behaviour is taken into account (figure 3). This was done using the traffic assignment and network-loading modules also in the optimisation of the control plans. In the optimisation of control plans four steps are needed:

1. Generate a certain control plan by whatever method;
2. Run a simulation with the network-loading model to see how traffic propagates through the network with this control plan;
3. Based on these results run a dynamic traffic assignment to obtain a new route flow distribution;
4. And again run the dynamic network-loading model to come to a final evaluation of the control plan.

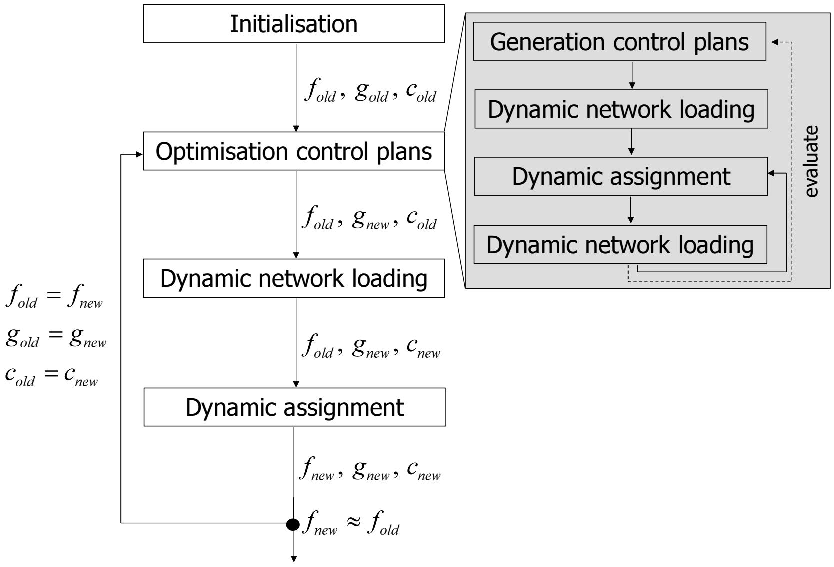

Figure 3: Framework extended with anticipatory control

Due to the nature of the optimisation problem, the number of variables to optimise and the fact that a function evaluation consists of a combined DNL, DTA and DNL run, an analytical approach would become very complex and is therefore not very suitable. That is why a heuristic approach is chosen, which uses as less function evaluations as possible. A workable method is the evolution strategy (ES) with covariance matrix adaptation (CMA-ES), as described by Hansen (2006). Evolution strategies belong to the larger family of evolutionary algorithms, just like genetic algorithms, and primarily use mutation and selection as operators.

Case studies for complete anticipatory control

Using the framework, the benefits of integrated anticipatory control can be demonstrated with two cases containing a motorway and urban roads and different types of control (ramp-metering and traffic signal control). The networks are shown in figure 4. The first network (case 5a) is quite simple with a motorway, one signal controlled intersection (black dot) and two possibilities two enter the motorway. Both on-ramps have ramp metering (grey dots). The second network (case 5b) has more origins and destinations and more routes. Also here both on-ramps are metered, but now there are two signal-controlled intersections on the urban network.

For both networks a three control strategies are tested: local control, anticipatory control and system optimum control. The results for these two networks are shown in figure 5. The figure shows the percent changes in total network delay, compared with local control. It is clear that anticipatory control is much better than local control. For the first case the results (about 40% improvement) come close to system optimum results. But also for the second case the improvements are high (about 20%).

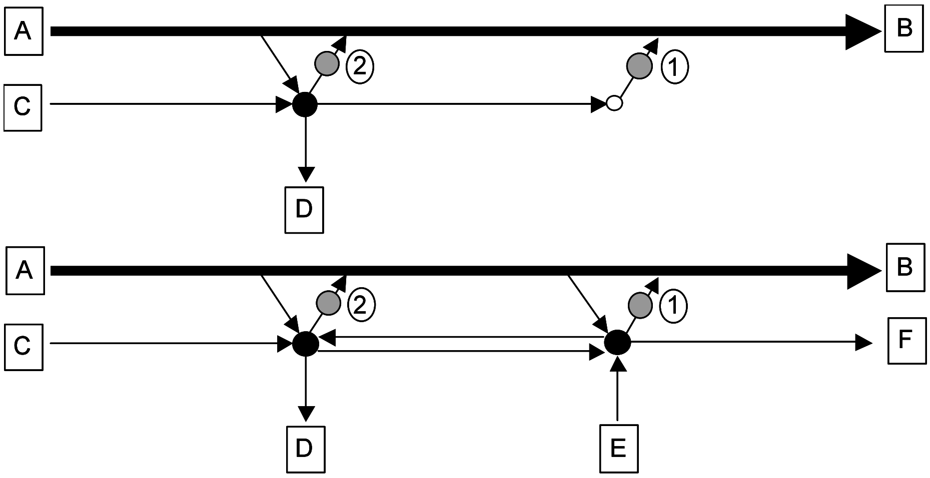

Figure 4: Networks for the case 1 and case 2

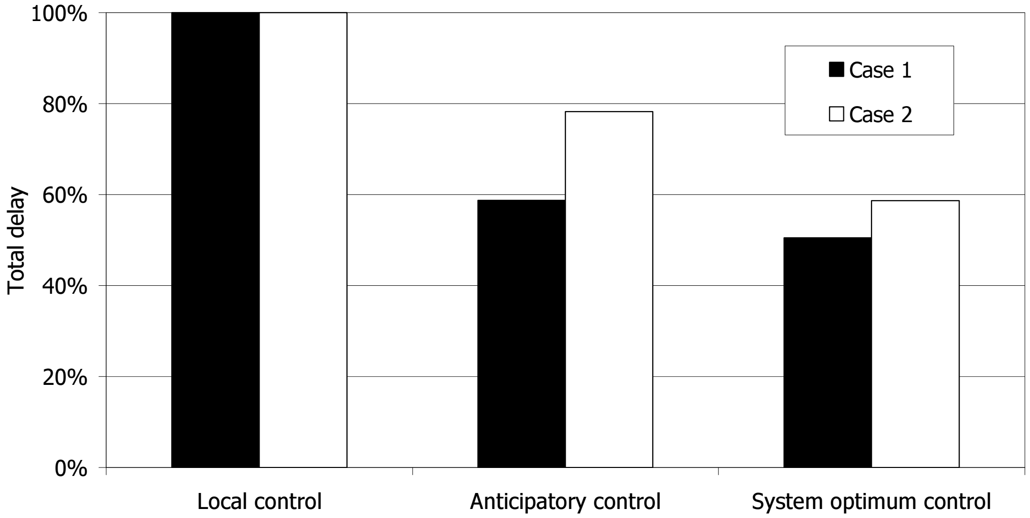

Figure 5: Results for case 1 and case 2 (relative change in total delay compared with local control)

Real-time application

For real-time application the problem can be adapted, using a rolling horizon approach. That means that for every time period the control plans have to optimized, instead of the whole simulation period at once. The advantage is that the optimization problem becomes smaller. Although it is not realistic to use an equilibrium formulation in a real-time approach, because road users have to learn from experience and are not provided with information, it is still interesting to investigate what this approach results in. For this rolling horizon approach also the framework of figure 3 is used. But now the optimization of traffic controls becomes part of the DNL model in the main loop. For every time period optimized controls are calculated for this time period, based on the results of the optimization for the next couple of time periods, as is shown in figure 6.

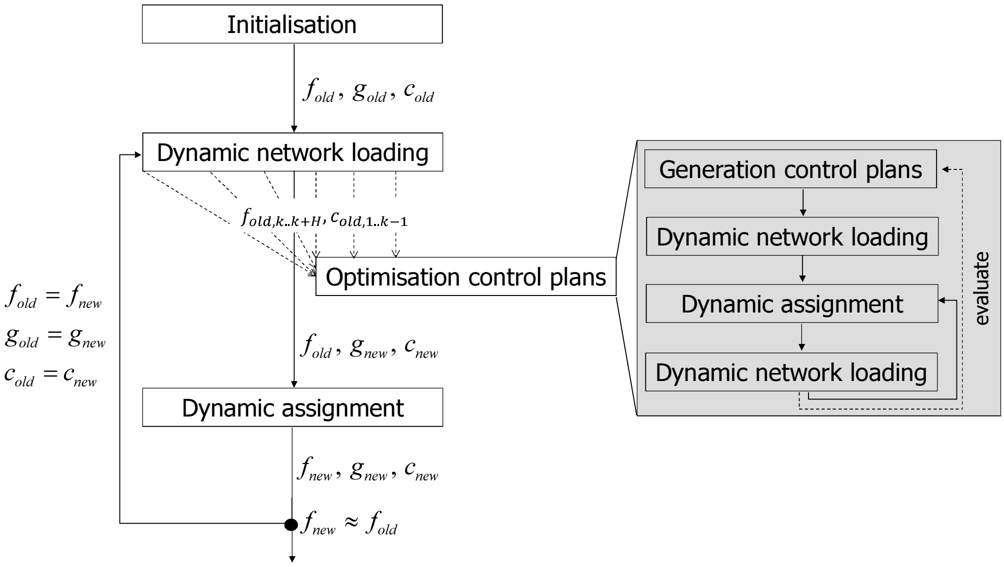

Figure 6: Framework for real-time anticipatory control

Input for the optimization of control plans is the state of the network at the start of a certain time period and the route flows of the coming periods. For these periods the optimization module generates the optimal control plans with regard to the total delay in the network, including the delay of traffic that is not able to enter the network due to spill-back.

With the framework of figure 6 (named Real-Time Anticipatory Control or RT-AC) different options with respect to the optimization process can be studied and related to the framework of figure 3 (named Complete Anticipatory Control or C-AC). The goal is to investigate whether the optimization process can be sped up and how the result are influenced by that. Two of these options are listed here and studied with the framework: *Prediction horizon*. What is the effect of the length of the prediction horizon on the final result and computation time? *Optimization criterion*. In previous work the total delay in the network was used as the variable to optimize. However with a rolling horizon approach it is possible that delay is shifted to upcoming periods with the risk that the problems are getting worse and cannot be solved that easy anymore. Therefore another optimization criterion is tested to see what the effect is.

Case study for real-time anticipatory control

The two options mentioned in the previous paragraph are tested for the network of case 1 shown in figure 4. The prediction horizon was chosen to vary between 1 period and 3 periods. In table 1 the results for the RT-AC simulations are shown in terms of total delay in the network, number of function evaluations for the optimization and calculation time. All simulations use 1 assignment iteration for the optimization. The table also includes the results for the C-AC approach. Note that a function evaluations for RT-AC takes less time than for C-AC, because the simulations needed for the optimization are for a shorter period.

Table 1: Results for the prediction horizon

	Prediction Horizon	Total Delay (veh.hrs)		# Function evaluations		Calculation time (min)	
C-AC		197.85	100	20800	100	37.83	100
RT-AC	1 period	222.97	113	16366	79	5.95	16
RT-AC	2 periods	196.13	99	69482	334	38.77	102
RT-AC	3 periods	194.92	98	132000	635	100.93	267

From the table it is clear that predicting more periods ahead gives better results for this case, which is not new and surprising. What is surprising that the further ahead the prediction goes, the less the improvement is. For two periods and longer the total delay is even somewhat better than the total delay of complete anticipatory control. But this is at the expense of more function evaluations and longer calculation times. More function evaluations are needed because more variables need to be optimized (5 for one period, 10 for 2 periods and 15 for three periods). It can be concluded that a prediction horizon of 1 period gives fairly good results and takes about 6 times less computer time.

It is possible that using a prediction horizon causes the optimization process to shift delay to next period, which then cannot be resolved. To test this, the RT-AC framework is used with 1 iteration in the main loop and 2 criteria for the optimization: total delay and queue length. The results for the delay per period are shown in figure 7. The graph shows that the optimization using the queue length has a different distribution of delay over the periods. It appears that accepting a bit more delay in the periods just before and during the onset of congestion gives less delay during congestion and during the resolving of congestion. The total delay for the total delay criterion is 236.83 veh.hrs and for the queue length criterion it is 208.66 veh.hrs, a difference of 12%. So, the choice of an optimization criterion is important for the results.

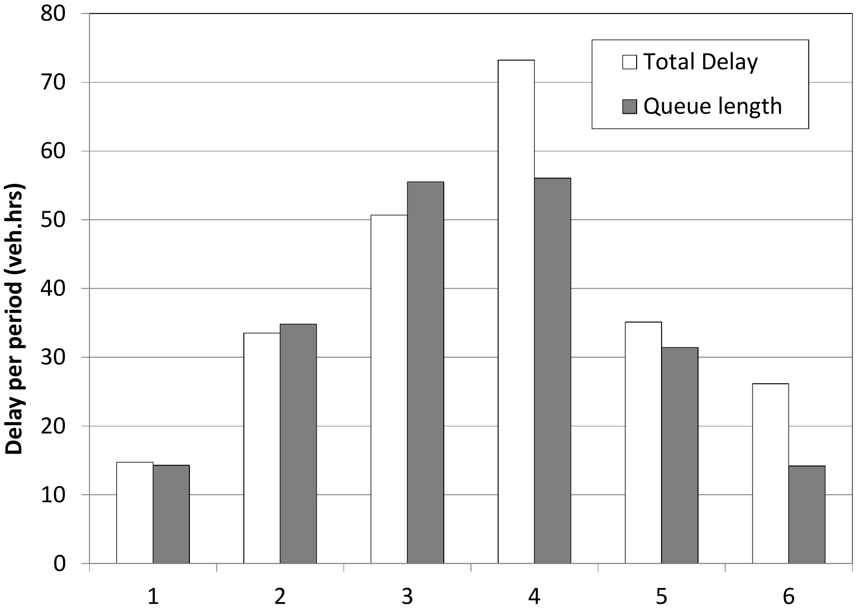

Figure 7: Delay per period for two optimization criteria

To investigate this further, 3 optimization criteria were tested with a full equilibrium assignment in the main loop: total delay, queue length and number of vehicles in the network. The results for these simulations (with a prediction horizon of 1 period and using 1 iteration in the assignment loop of the optimization) are shown in table 2.

Table 2: Results for the optimization criteria

	Optimization Criteria	Total Delay (veh.hrs)	
C-AC		197.85	100
RT-AC	Total delay	222.97	113
RT-AC	Queue length	233.83	118
RT-AC	# Vehicles in network	209.42	106

If a full assignment is used, the optimization criterion *# Vehicles in network* gives the best results in terms of total delay for the final situation of the first case.

Conclusions

We already mentioned that in many cases traffic management is reactive and local: it reacts on local traffic conditions and traffic management measures are taken to reduce congestion on that specific location. To come to an integrated and network-wide approach, the Handbook Sustainable Traffic Management describes a *process* for cooperation between the different road authorities and other stakeholders. This is a first and important step, but still a *methodological* approach to integrated traffic management is lacking. How can traffic management measures be operated to reduce congestion on a network level, taking network condition into account? In the research described in this article, and more extensively in Taale (2008), a framework for integrated and anticipatory traffic management is developed and demonstrated with good results.

For real-time applications the framework was extended and tested. More details on that can be found in Taale and Hoogendoorn (2013). The test showed that it can be concluded that the prediction horizon has an influence on the results of the RT-AC strategy. The longer the horizon is, the better the results. But it comes with the costs of longer calculation times. For the case simulated it appears that a prediction of 1 period ahead is enough to get reasonable results within a few times less calculation time as for the C-AC strategy. Which optimization criterion is the best to use, is still undecided, based on the results presented in this paper. It is clear that it is important, because results can be quite different if a different criterion is used. Which criterion is the best under which circumstances is a topic for further research. Another topic for further research that can be mentioned is the application of the frameworks to somewhat larger problems. The feasibility for these networks should be investigated, maybe together with the possibilities of faster optimization algorithms.

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