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Efficient Algorithms for Infrastructure Networks: Planning Issues and Economic Impact

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5 Summary

Electricity and telecommunications network providers operate in a turbulent period. The market is open for competition and the demand of their customers is changing dramatically, causing huge challenges for the network providers.

Information is reaching us more and more digitally. Mobile and fixed networks have to deal with this explosive growth of data traffic. The end of this is not yet in sight, mainly due to the increase in video services at higher resolution. For fixed networks this means that the default internet connection via ADSL (up to 8 Mb per second) is no longer sufficient. Providers using coaxial cable brought the fibre connection already far into the direction of their customers, so they can already offer 100 Mb per second, but this will soon no longer be sufficient. The incumbent telecommunications networks using twisted pair copper cables are not there yet. Mostly they are working on the rollout of VDSL, where the fibre connection is brought to the cabinet (Fibre to the Cabinet, FttCab) and also a speed of about 100 Mb can be achieved. That may be sufficient for now but this is also not future proof. In addition, they offer Fibre to the Home (FTTH) in certain areas. The latter roll out is not fast enough. In the past five years about 25% [138] of the Netherlands is reached, which was likely to be the easiest part to connect. Such a FttH connection costs around 1,000 euros which means a huge investment for the operators. This sketches the huge dilemma for the operators: bring a solution quickly that is not future proof or bring a future proof solution slowly and lose a part of your customers to the competition. In this thesis, we provide a systematic solution for this dilemma.

Electricity networks have to handle another dilemma. They face an increasing demand due to, e.g., electric cars, and they see their customers (households) partly generate their own electricity. They are called *prosumers*, a combination of producer and consumer. Solar panels are common, but also more and more electricity generating boilers (known as micro-CHP) and small wind turbines are placed in residential areas. This production is also highly variable, while they are depending on sun and wind. These trends lead for the network managers to the challenge how to keep their network in balance. Create your own flexible generation, using (price) incentives to influence the demand of consumers and smart grids are all investigated and you always have the very expensive solution to strengthen and renew the network cables. In this thesis we looked for a solution that is at the tactical level. How many of each type of local generator do you need and where do you place them to minimize transmission losses and the losses by demand-supply mismatch?

For both problem areas we studied (tactical) planning issues, all of which are very

complex to calculate. The operational application of our algorithms also determine the scope of the presented solution in this thesis. The focus is on efficient yet fairly accurate methods rather than methods that generate an optimal solution in long calculation times.

5.1 Telecom infrastructure

The above mentioned dilemma for telecom operators requires a deployment strategy that satisfies customer demand as much as possible, but is also economically feasible. Responding to the customers needs all the time may be too expensive, however, a cheap deployment neglecting these needs can cause that there are no customers left at a certain moment, as all of them have switched to a competitor that can offer the demanded bandwidth. In this thesis we presented an economic model that can calculate the effect of all kinds of strategies. Analyses led to the conclusion that a migration of Full Copper via FttCab (VDSL-based) and FttCurb (G.Fast-based) to FTTH is both cost effective and retains the customers.

For this migration, it is important to build up the network configurations considering the next one. When planning the current roll-out, you should take into account as much as possible the successive infrastructures. We gave an example of this in this thesis. Then we presented for each of the migration steps (Full Copper to FttCab, FttCab to FttCurb and FttCurb/Full Copper to FttH) a planning methodology.

For the first migration step, FttCab planning, we presented a planning methodology, primarily based on three steps. First was determined which street cabinets should be provided with active equipment. The aim is to chose a minimum number of cabinets from a cost point of view, which cover, e.g., 95% of the connected houses. Then the activated cabinets must be connected via a fibre optic ring. To this end, in step 2, first clusters of activated cabinets are created of a certain maximum size, respecting the capacity of the fibre optic ring. Next, in step 3, the route of these rings is determined. All three problems are already difficult to solve (NP-hard). For all three problems, we proposed a heuristic approach and showed how well they work. It is important here that we are not so much interested in the best solution, but in a good solution very quickly, preferably within seconds, minutes at most. For step 1 a greedy heuristic was developed that gave a good solution for all test cases within one second. For step 2 we developed a variant of Lloyd's algorithm for solving k-means clusters, taking seconds to solve bigger problems. In step 3 it is important to create fibre rings that do not use the same piece of track twice. For this, we developed a heuristic that is based on Dijkstra's algorithm and a Insertion Algorithm for solving Travelling Salesman Problems which creates an initial solution quickly and then solves the double used tracks in a greedy way, also within seconds.

To see how well the three-step approach works, we then created a method that solves the second and third step simultaneously. As expected, this method provides better solutions, since the routing information is included in the clustering. Also as expected, the computation time of this method was longer, but less longer than expected.

For the second migration step, FttCurb planning, we identified three main choices that you have to make if you want to create such a network, based on the technology G.Fast. First, the network operator must decide whether or not he wants to connect all the houses within a certain distance, for G.Fast the desired distance is 200 meters, or a certain percentage of the houses. Then he has to determine whether the new active nodes have a capacity limitation, or whether this location can be expanded unlimited. Finally, he must decide whether you want to connect the new active nodes via a fibre optic star or tree or via a ring structure. If every choice has two options, then there are a total of eight possible configurations of the network. In this thesis we described for each of the eight options the planning methodology. Then we elaborated the planning for two Dutch cities, Amsterdam and The Hague, to estimate the cost of the network. The results of this study have also acted again as validation of the aforementioned (simplified) economic model.

Finally, the third step involves the migration to FttH. Here we showed how the location of the new central node (PoP) can be determined. We extended a simple heuristic, called JMS heuristic, on a number of points to bring more details in this method. We then considered the real path of the fibres to the homes starting at this PoP locations. This seems like a trivial question, but you can get much profit here. We described a new method to determine these paths and developed an addition to incorporate ‘smart co-laying’. In the method the social costs of inconvenience, turn-over loss etc. are taken into account and can be minimized together with the investment costs. The ‘smart co-laying’ options give the possibility of a phased construction to use other infrastructural project as much as possible to lay the fibre in the ground together with other planned work as street maintenance and sewer renewals, all minimizing the social costs.

5.2 Electricity infrastructure

The producers of electricity and the managers of the networks have to deal with increasing demand and an increase in highly variable production by local generators such as solar cells and wind turbines. In this thesis we described two studies that study the tactical planning of these generators. How many of which kind and where do you have to place them to minimize losses. Local generation can reduce transmission losses because it does not have to be transported far. On the other hand, this local generation introduces large variability in supply, which also need to be transported again, needs to be stored (not efficiently) or will be lost through lack of demand. When the wind turbines are spread, they have lower variability due to a lower correlation between the wind at different places. If the wind blows in Middelburg, then it will also blow in Vlissingen. That it blows that hard in Groningen is a lot less certain.

The first question that we had to answer here was: What is an optimal mix of DGs in a district so that energy loss is minimized? We developed a Mixed Integer Quadratic Programming formulation (MIQP) that we had to simplify to solve it. We obtained several solutions in the case studies each under different assumptions. However, the results indicate that implementing an optimal mix of DGs in the district can reduce energy loss substantially. Next to this we could show that using our optimal solutions will not cause problems with overload. For the use of heat pumps and electric vehicles it is, unfortunately, more problematic. Most problems with overload come from the use of electric vehicles, which demand so much electricity that not even one electric vehicle can be charged at home without overloading the cables. Finally we saw that however both micro-CHP systems and PV solar panels generate electricity during the same period of the day, each type of DG has a positive characteristic that can be used in specific situations. Because PV solar panels generate a relatively small amount of electricity, they can be used as a supplement to other generators. And, because micro-CHP systems generate a lot of electricity, they are useful when there is a large increase in demand for example due to heat pumps and electric vehicles. Using the optimal solutions with different input configurations we found that in all cases there is a big improvement compared to the grid without DGs. So our solutions can be used as a guideline for incorporating DGs in a district. These results also show that instead of arbitrarily deploying DGs in the district, it may be better to promote collaboration between home owners to invest in DGs such that large reductions in energy loss can be achieved. In this way it will be more profitable for the whole district.

In the second problem we studied a normal load situation of a High Voltage (HV) network and tried to find the optimal locations to build a given number of new wind turbines, in order to minimize the expected energy transportation losses. Here we had to manage two trade-offs: (1) local or central placement and (2) spreading or concentration. A mathematical model was formulated in order to capture the wind power Generation Expansion Planning problem for loss minimization in a so-called two stage stochastic program. Network flow duality was applied such as to arrive at a NLP formulation for the stochastic Generation Expansion Planning problem for loss minimization. Rigorous solution algorithms for this NLP problem were outside the scope of this thesis. Therefore a simple heuristic was presented, together with a procedure to simulate appropriate scenarios for steady state wind power studies in multiple areas. This implementation of the model was used to generate results for the Dutch HV network. From the computational results it was possible to conclude that the effect of reducing transmission losses by placing DG units is significantly weaker for stochastic than for deterministic units. Next to this, in order to achieve high transmission efficiency, stochastic DG units should be placed further apart than deterministic DG units, but this interesting effect occur only for higher penetration. From the specific Dutch situation we learned that the optimal distribution of wind energy over the Netherlands shows a higher spreading than can be explained merely from its stochasticity. The location dependent nature of wind energy is relevant for its effect on power grid performance. Because of the load situation of the Dutch HV grid Groningen and Friesland are the only regions with both attractive wind speeds, and where placement of wind turbines would result in reduction of transmission losses in the HV grid. However at the current scale of wind energy, a spreading strategy for wind turbines does not seem to be relevant, neither from a commercial point of view (variance reduction of total output for the Dutch market) nor from a technical point of view (reducing transmission losses).