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Comparison of heuristic methods for the design of edge disjoint circuits

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ABSTRACT

In this paper heuristics are studied for the design of edge disjoint circuits. We formulate the Edge Disjoint Circuits Problem (EDCP) in the context of a telecommunication network design problem: the roll-out of Fibre to the Cabinet. This problem setting can be represented by a graph. A small subset of the vertices are cabinets and one vertex is the central office. The objective is to minimise the sum of the circuit costs to connect all street cabinets to the central office, while satisfying capacity restrictions and edge disjointness within each circuit. In the studied graphs inexpensive paths are present with available ducts, which complicate the analysis considerably. The problem is NP-hard, so an insertion heuristic is developed. After the construction of an initial solution, local search is used to improve the solution. Finally, the performance of the insertion heuristic is compared to a cluster first-route second heuristic. The insertion heuristic clearly shows better performance for almost all types of instances that were studied while taking just a bit more time.

1. Introduction

In this paper we present the Edge Disjoint Circuits Problem (EDCP) in the application of the design of a telecommunication network. The question here is how to connect a collection of access points. Due to reliability constraints, in the Netherlands the choice is made for rings. But even broader [32,33,13] sketches the need for redundancy in the network, even in access networks. The question then is which access point is served by which fibre optic ring. Each ring that is constructed should meet a capacity constraint and should be edge disjoint to guarantee the desired reliability. In other words, it is not allowed that a trench or pipe is used twice within one ring.

The example used in this paper is the roll-out of Fibre to the Cabinet (FttCab) for the network of a telecom operator. As stated in Phillipson [28] the problem also occur in planning of FttCurb, using G.Fast. The design of the FttCab network has to satisfy certain properties and restrictions:

1. A ring-shaped network structure is used to guarantee a high reliability.
2. Each ring has a maximum capacity, in our example a number of customers that can be included in one circuit.
3. Each access point, cabinet in our example, will be included in only one cluster. This is a logical property of the network design, since it would just be too expensive to include every cabinet in multiple circuits.
4. Each ring that is constructed should be edge disjoint. In other words, it is not allowed that an edge is used twice within one ring. Note further that between rings, no edge disjointness is required. Multiple rings can, therefore, make use of the same pipe. Another remark to be made is that a ring is not required to be node disjoint.

This problem has been investigated before in Phillipson [26,27]. There a cluster first-route second approach is used, i.e. first the cabinets are clustered and only afterwards is determined where the fibre cables are to be put (below which street). The clustering is based solely on minimising the distance between the cabinets. These distances are not based on the street pattern or the ditches that can be used to put the cables in, but are as the crow flies (a straight line). This has the advantage that it is easy, but at the same time it has an important disadvantage. The chosen clusters may be cost-inefficient when taking into account the real street patterns and ditching restrictions.

The objective of the research of this paper is to develop a method for the EDCP that integrates the cluster and routing decision in one algorithm to avoid the above mentioned disadvantage. Now information of routing challenges can be taken into account when making the clusters and vice versa. We expect this to give

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better results. However, we are combining two problems that are both NP-complete as proven in Phillipson [29].

The computation time of the method is targeted to be in the order of magnitude of minutes. This is the reason that the focus is on the development of heuristic methods, since exact methods will exceed the preferred computation time very soon as instances grow in size. It may seem counter-intuitive that short computation times are preferred over very high solution quality, since the planning takes place only once and not an continuous basis. Often in such situations computation time is of less importance. However, we found that in practice the situation is a bit different. Firstly, network planners prefer a tool that is able to find a good solution quickly. Not all practical constraints and decisions can be included in the model and the data will not be 100% reliable, so in that sense it is much more important to get a good solution quickly than an optimal solution that took days or even weeks to calculate. Some adaptations will need to be made to the solution anyway. Ideally, planners could use the tool to play around a bit with the solution to come to a really practically implementable network design plan using their knowledge and experience.

This paper is innovative in the use of Suurballe's algorithm in network design problems with edge disjointness restrictions. To the best of knowledge of the authors, all previous work focussed either on exact approaches that require very large computation times for large instances or on heuristics that can seriously affect the routing quality by iteratively constructing a route or using a greedy method to solve conflicts in the paths.

In the next section the related literature is reviewed. In Section 3 the problem outlined in this section is described more formally and some prerequisites methods are discussed. Next, in Section 4 the approach is discussed to construct an initial feasible solution to the problem and to improve the initial solution. Then in Section 5 the instances are described that are used to test the developed methods and the test results are outlined. Finally, in Section 6 the conclusions of this paper are given.

2. Literature overview

In this section we give an overview of the literature of three important areas. First related papers in the field of Ring Network Design are discussed, followed by papers in the field of Edge Disjoint Shortest Paths. The last part consist of an overview of different Vehicle Routing Problem (VRP) heuristics to construct initial solutions. Their advantages and disadvantages are mentioned and in particular their suitability to the problem studied in this paper is analysed.

2.1. Network design problems

For a completer overview, the interested reader can consult e.g. Laporte and Martín [22] or Beasley and Nascimento [3]. Here we look at the Ring Network Design Problem and the Capacitated m-Ring-Star problem, since these are closest to the problem studied in this paper.

2.1.1. Ring network design problem

Gendreau et al. [12] and Fink et al. [10] formulate heuristics for the (General) Ring Network Design Problem. However, this problem deals with the construction of one single ring only.

The problem studied by Henningsson et al. [14] deals with the construction of edge disjoint rings covering all nodes at least once. Also included is the constraint on the maximum number of connected nodes in a ring. Although they require edges of the ring to be disjoint, this does not at all prohibit using a duct multiple times as is desirable from reliability perspective. They do not consider a street or duct pattern, so edge disjointness is not necessarily satisfied on the detailed level that is studied in this paper. The computation times they present for instances with up to 100 nodes are up to half an hour.

Kalsch et al. [16] develop a mathematical model and a heuristic that looks how to embed a ring structure in a fibre network. Apart from some small differences, the mathematical model developed in Kalsch et al. [16] is almost directly applicable to the problem studied in this paper. However, no computation times are mentioned in the paper for this model, which might indicate that they are too large. They quickly continue with the development of a heuristic based on a decomposition and solving multiple integer programming models. The description of this heuristic is quite brief and some details are not given.

2.1.2. Capacitated m-Ring-Star problem

The Capacitated m-Ring-Star Problem was introduced by Baldacci et al. [2]. The Ring Star Problem (RSP) without the capacity constraint was already introduced earlier by Labbé et al. [21]. The CmRSP deals with the design of rings (circuits) that connect customers to a central depot. Customers can either be situated on the ring itself or they can be directly connected to a visited node on the ring. In this way, a ring-star network is formed. Restrictions taken into account are that the rings need to be node-disjoint (for reliability) and that each ring has a maximum number of customers that it can include. Furthermore, next to the customers, transit points (Steiner nodes) are considered, which are intermediate points that can be included in a ring, but do not necessarily have to. Because of the requirement that the rings need to be node-disjoint, each transit point can at most be included in one ring. The objective in the CmRSP is to minimise the sum of two cost types: routing costs (costs of the ring) and allocation cost (cost of connecting customers to the ring).

The CmRSP differs from the problem studied in this paper in several ways. Firstly, in the CmRSP it is implicitly assumed that no pre-existent pipes are available which can be used against significantly lower cost compared to new pipes. In this paper these pre-existent pipes are explicitly taken into account, since in quite a lot of situations they are in fact available. Naji-Azimi et al. [24] recognise the importance by stating that the cost of excavations to lay down the pipes is the most important cost, but at the same time they do not take these existing pipes explicitly into account, because in their case study there were No. Including discounts based on availability of pipes into their data might be possible. However, this is not so easily done since it might lead to ending up with a star-shaped network instead of the from a reliability perspective required ring network.

After the introduction of the CmRSP by Baldacci et al. several papers have investigated the problem, see Hoshino and de Souza [15], Mauttone et al. [23], Naji-Azimi et al. [24], Naji-Azimi et al. [25]. Some of them, like Hoshino and de Souza [15] focus on exact IP-based solution methods, whereas others, like Mauttone et al. [23], Naji-Azimi et al. [24] choose a heuristic approach. However, the calculation times are too long for our purpose.

2.2. Edge disjoint shortest paths

One important restriction in the problem definition in Section 1 is the edge disjointness of a ring. A ring consists of shortest paths between cabinets that each consist of possibly several edges. Therefore, in this section relevant literature on the disjoint shortest paths literature is discussed.

Many papers have been published from the 1950s onwards that deal with all kinds of versions of disjoint path problems (see e.g. the surveys in Korte et al. [20]). For some versions an algorithm is found that can solve the problem in polynomial time, whereas