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Computer-Aided Planning of Radial and Diameter Routes in Local Public Transport Networks

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Abstract: Local public transport network planning is a complex procedure affected by many aspects (e.g., city structure, travel needs, the budget for the service, vehicle types, service frequencies, timetable optimization of parallel routes etc.). Due to the high number of possible solutions, finding the optimum is usually a problem with NP computational complexity. Although an extensive toolkit is available for evaluating specific networks, the number of versions that can be realistically examined and compared is highly limited. This implies that the routine and creativity of the network planning specialists play an important role in the selection of the examined networks. However, in some special cases, the search space can be narrowed so that all network versions can be automatically generated and compared. This paper presents such a case: when applying radial and diameter routes only, the main question is which directions should be connected to each other as a diameter route, or left alone as a radial line. The algorithm is presented on the example of the city Győr.

Keywords: Public transport, Transport network, Radial routes, Diameter routes, Computer-aided planning

Introduction

A significant element of a city's infrastructure is the network and timetable of its public transport. These have a fundamental effect on the service quality, and consequently influence the people's choice of transport mode i.e., the modal split, and they have an indirect effect on the severity of congestions as well as air and noise pollution. As a result, network development and an optimized timetable are of vital importance, so that the requirements of the passengers are fulfilled, and also the services should be realistically financeable by the responsible authorities (typically by the local governments).

In network and timetable design, human creativity, intuition and experience is highly important still to this day due to the high number of potential combinations. During the design process people who possess these traits are the ones who are able to create solutions that can be examined and analyzed by the existing transport planning systems (e.g., PTV VISUM). These software solutions can also be helpful in the design process, but they do not replace the human factor, as it is still the most important asset. As a result, finding the optimal (or as close as possible) solution is highly dependent on the professional's capabilities.

Computer-aided network and timetable planning (due to the extent of search space) is not yet fully developed, however, there is ongoing research (Owais et al., 2014). The existing solutions usually apply a heuristic approach (Ciaffia et al., 2014) as well as processes that are based on randomization, and they often result in a good solution, but in less successful cases (when they exclude certain search areas by mistake) the optimal solution might be excluded, similarly to the human intuition-based design.

The baseline of this research is that in a few special cases the search space can be narrowed so that all network variants can be automatically generated and compared. This paper presents such a case: when applying radial and diameter routes only, the main question is which directions should be connected to each other as a diameter route, or left alone as a radial line.

The structure of the paper is as follows. The next section specifies the problem and describes the theory behind it. The section after that discusses the implementation of the developed algorithm as well as the experiences gained throughout this process. This is followed by the presentation of the practical use by showing the properties of Győr's local bus network and the results of the software. The last section preceding the conclusion discusses the elements of the algorithm that still need improvement as well as the possible directions for further development.

The Specific Problem and Its Theoretical Background

As this research is at the early stages, the definition of the problem is limited in various aspects to ensure that the analysis can begin from the easiest perspective: this can naturally be extended later to best reflect reality. At this point we can specify the problem in this way: in a city, there are *n* line-ends starting in the city center and they can either operate as a radial line, or joined in pairs as a diameter route. (To simplify it, we will use one end in only one line.) In this case the number of the networks marked with *N* is given by (1) equation when *n* is an even number.

$$N_n = 1 + (n-1)(n-3)\dots\cdot 5\cdot 3 + \binom{n}{2}(n-3)(n-5)\dots\cdot 5\cdot 3 + \dots + \binom{n}{n-4}\cdot 3 + \binom{n}{n-2} \qquad (1)$$

The number 1 refers to the case when we have all radial lines, while the second part defines the number of complete pairings (meaning all diameter lines): we can find *n*–1 pairs for the first free line-end, *n*–3 for the second, and so on. This is followed by the instances where we keep some line-ends as radial routes, and we examine the number of complete pairings for the rest of the line-ends.

$$N_{14} = 1 + 13\cdot 11\cdot 9\cdot 7\cdot 5\cdot 3 + \binom{14}{2}11\cdot 9\cdot 7\cdot 5\cdot 3 + \binom{14}{4}9\cdot 7\cdot 5\cdot 3 +$$

$$\binom{14}{6}7\cdot 5\cdot 3 + \binom{14}{8}5\cdot 3 + \binom{14}{10}\cdot 3 + \binom{14}{12} =$$

$$1 + 135135 + 91\cdot 10395 + 1001\cdot 945 + 3003\cdot 105 + 3003\cdot 15 + 1001\cdot 3 + 91 =$$

$$1 + 135135 + 945945 + 945945 + 315315 + 45045 + 3003 + 91 = 2390480 \qquad (2)$$

Based on the (2) calculations, the result for case *n*=14 (that will later appear in the example from Győr), is 2,390,480 network variants, which is a significantly big number for analysis.

In order to reduce the number of network variants to be examined, we need to implement one filter: those line-end pairs that are in a very similar direction from the city center (e.g., for simplicity, towards the same compass direction) cannot be considered useful diameter lines (and in fact, not even diameter lines at all, but rather "U" shaped), since circular or transversal links between the zones they serve may provide optimal access, so that these connections can be disregarded without risking the optimum result. Naturally, the number of disregarded network variants depends on the directional distribution of line-ends so we are not able to provide a definitive formula, but some sort of reduction is definitely expected.

Another important aspect of line-ends is the minimally offered service level, so the maximum time between departures (which is required to be provided for comfort, regardless of the number of passengers), and the recommended (or in some cases required) vehicle type: these can be used to determine the default service frequency for specific line combinations as well as vehicle type.

In the model used for this research, the service frequency in given in integer numbers (typically the divisors of 60) most commonly found in local timetables and easily remembered by passengers: 1, 2, 3, 4, 5, 7 (instead of 15 / 2 = 7.5), 10, 12, 15, 20, 30, 40 and 60 minutes (but this can be changed, of course) and in the smaller and mid-sized cities mostly solo (75 passengers) and articulated buses (120 passengers) are used (Winkler, 2019). When generating line combinations, the algorithm assigns the higher frequency (i.e., less time between departures) of the two line-ends and the higher vehicle capacity to the diameter line. An exception could be in cases where a line-end must be operated by solo buses (most often due to physical restrictions such as a narrow curve where an articulated bus could not turn): in these cases, obviously only solo buses can operate on the diameter line even if it means that the frequency should be significantly higher (although this is not necessarily a bad solution).

Naturally most networks do not only consist of radial and diameter lines (Fülöp et al., 2006) but other types as well (i.e., circular, partially circular, transversal, etc.), and there are potentially elements in the network that cannot be changed for various reasons (e.g., urban sections of regional bus lines used for local service as well), so in the applied model it should be possible to specify fixed lines, which should be considered for assignment and defining frequency in the same way as line variations created by combinations.

To sum up, the goal of the implemented algorithm is to create network variants based on the criteria above, and to assign the travel demand available in the form of an origin-destination matrix onto all network variants. During this, the frequencies will also be finalized: lines where the capacity was not sufficient upon the initial assignment will be iteratively increased in frequency. From these network variants, the main operational indicators (e.g., vehicle km, capacity km) and passenger-side characteristics (e.g., number of transfers, total travel times) are calculated and stored.

Implementing the Algorithm

The implementation of the algorithm specified in the previous section was carried out in Microsoft Windows 10, GNU environment in C++. The software, called „LiMa" (=Line Matcher) consists of two parts. The first program generates all possible network variants based on line-end description, and writes their description in an output file. The output file is in a simple format, so it is easy to check and it is easy to structure (for parallel processing). The second program, after reading the detailed description of the zones, the destination matrix, the (optional) inter-zone walking times, the fixed lines and the combinable line-ends, evaluates the networks read from the output of the first program, as described in the previous section.

The assignment and the search for the required shortest paths (Winkler, 2013) is carried out in a simplified way in the current version of the program. As the origin-destination matrix describes travel demands with zone accuracy, detailed line data (route, distance, journey time) and shortest paths are not entered at stop level but at zone level to speed up the operation of the program. The assignment process is frequency-based, so when boarding or transferring to a public service, the waiting time is calculated as a function of the frequency, and is "one-way, one-step", so it assigns all passengers on the most favorable single path, and does not take into account congestion (but increases frequency if necessary).

Partly due to the above simplifications and partly due to the closed operation of the program, the running speed was favorable and suitable for practical use. Previously there were discussion that the newly developed software would only create the network variants, and the assignment itself would be done by an already existing external professional program (e.g., PTV VISUM), through inter-software communication. However, these ideas were discarded as tests showed that the simplified analysis that the self-developed software created was about 2800 times faster than using the detailed calculations of PTV VISUM that would have increased running time to an unacceptable level. In case of the Győr model that contains approximately 300,000 network variants, the running time of „LiMa" was 45 minutes (properties of the computer: ACPI x64-based PC, Intel Pentium CPU G3420 @ 3.20 GHz processor, 4 GB DDR3 memory), on the other hand, using an external program, the test could have taken several months on the same computer.

The Results of the Experiment with Győr's Example

In parallel with planning and developing the necessary software, a simplified model of public transport in Győr was developed to test the algorithm in practice. Although there are more than 60 local bus lines in Győr, it is important to note that about two thirds of these are intermittent or destination bus lines, and the core network consists of only 20 lines. Győr also has a large agglomeration (Jóna et al., 2021) which may be the topic of future research. The aim of this paper is to examine the 20 core lines in Győr and the possibilities for their reorganization, for which different solutions have been proposed in various conceptions over the years. The rest of the network can be considered unchanged. As certain areas (mainly industrial areas) are served by intermittent or destination lines only, these areas have been excluded from the analysis. Although some minor reorganizations of the network took place in April 2022, this paper starts from the service in operation at the beginning of 2022, for which complete data were available.

Table 1 shows the properties of the line-ends from (and back to) the city center (i.e., the town hall), derived from the radial and diameter lines of Győr, and Figure 1 shows their map.

Table 1. Properties of the possible line-ends in Győr

Sign	Route	Compass direction	Recommended vehicle type	Minimal service frequency
UN	Kossuth Lajos utca – Újváros, Nép utca	West	solo	30 minutes
RL	Radnóti Miklós utca – Liget utca, Nyár utca	West	articulated	30 minutes
PI	Pinnyéd	West	solo	60 minutes
SA	Városrét – Sárás	North	mandatory solo	60 minutes
BA	Bácsa, Ergényi lakótelep	North	articulated	30 minutes
LK	Likócs	East	mandatory solo	60 minutes
GS	Győrszentiván (loop)	East	articulated	60 minutes
ZZ	Zrínyi utca – Zöld utca, Szőnyi Márton utca	South	articulated	30 minutes
JK	Jereváni út – Kismegyer	South	solo	60 minutes
SK	Szabadhegy, vasútállomás – Kismegyer	South	solo	60 minutes
NM	Nagy Imre út – Marcalváros – Ménfőcsanak	South	articulated	30 minutes
KG	Kálvária utca – Marcalváros – Gyirmót	South	solo	60 minutes
TM	Adyváros (Tihanyi Árpád út) – Marcalváros	South	articulated	30 minutes
GM	Gyárváros – Adyváros – Marcalváros	South	articulated	30 minutes

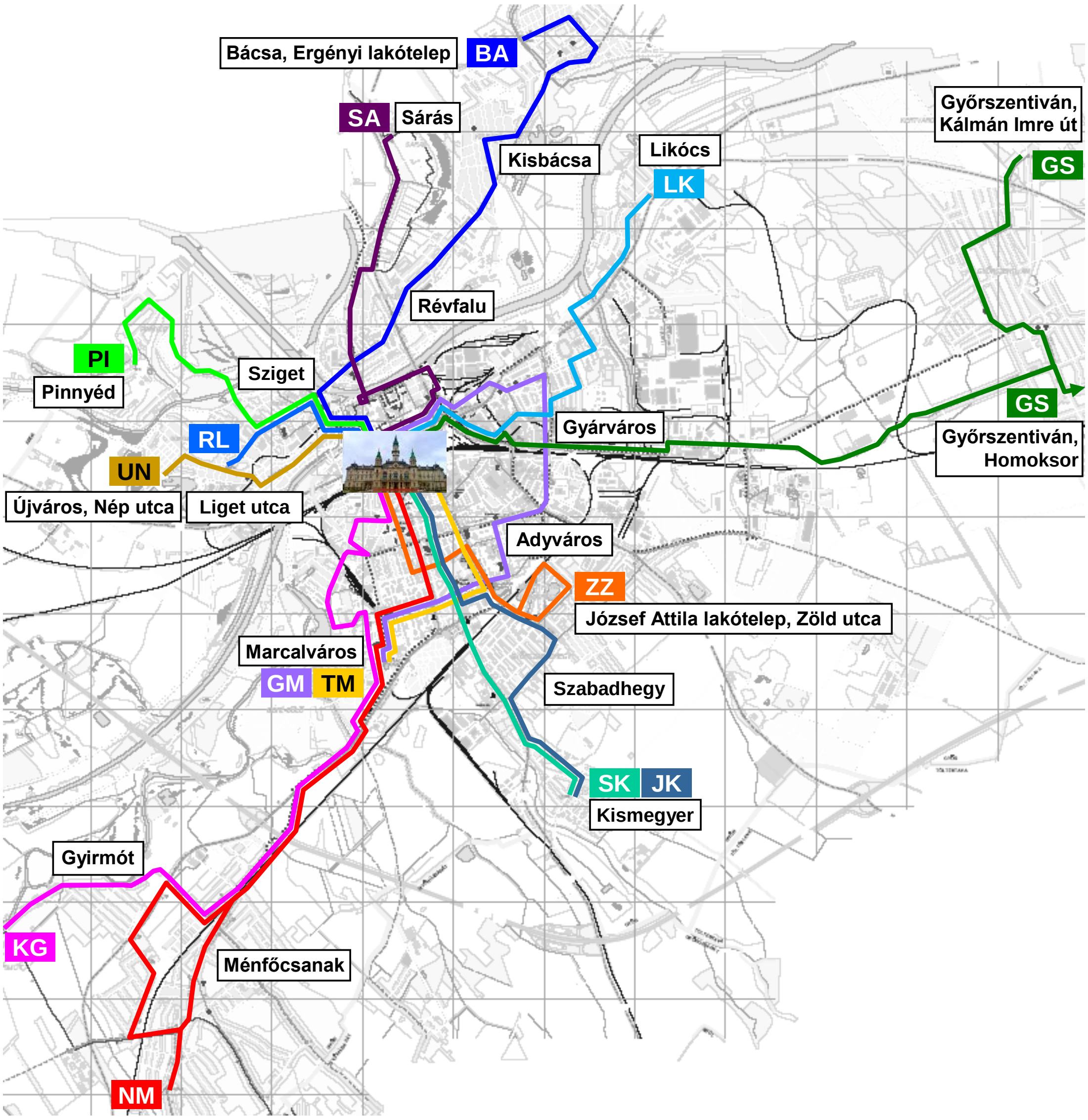

Figure 1. Map of the possible line-ends in Győr

The circular and regional lines shown in Table 2 were defined as fixed lines.

Table 2. Properties of the fixed lines in Győr

Sign	Route	General vehicle type	Average service frequency
7	Révai Miklós utca – Szabadhegy – Adyváros – Virágpiac	solo	25 minutes
9	Egyetem – Belváros – Adyváros – Révai Miklós utca	solo	26 minutes
10	Autóbusz-állomás – Víziváros – Bácsa	solo	100 minutes
17-17B	Virágpiac – Adyváros – Szabadhegy – Révai Miklós utca	solo	25 minutes
19	Révai Miklós utca – Adyváros – Belváros – Egyetem	solo	26 minutes
32	Autóbusz-állomás – Ménfőcsanak, Hegyalja utca	solo	64 minutes
34-36	Autóbusz-állomás – Ménfőcsanak, Győri út [– …]	solo	54 minutes
CITY	Egyetem – Városrét – Belváros – Városrét – Egyetem	solo	15 minutes

It should be noted that although the present study is based on a regular school and work day, with a different timetable (frequency) for most lines at different times of the day, since the available destination matrix is all-day, for simplicity, average service frequencies are defined and used throughout the day. Using the directional filtering mentioned above, the nearly 2.4 million network variants identified by (2) could be narrowed down to 301,918 variants, so this filtering method proved to be very effective. The results of the evaluation program, which was run on about 300 thousand network variants, are shown in Table 3, which shows the indicators for some special network variants.

Table 3. Indicators for some special network variants

Position (by mean cost)	Specialty of the network	Vehicle km	Capacity km	Sum of gener. journey times	Trans-fers	Rel. capacity km	Rel. sum of gener. journey times	Mean of rel. costs
1	Best ranking	10,477	945,736	2,468,291	9,960	72.114	91.007	81.561
12	Best with no radial line	10,561	967,201	2,435,504	9,068	73.750	89.799	81.775
2,707	Least capacity km	10,277	914,227	2,617,100	11,388	69.711	96.494	83.103
41,530	Least vehicle km	9,552	932,965	2,651,669	9,224	71.140	97.769	84.454
57,553	Most similar to the current network	10,219	964,177	2,600,551	10,091	73.520	95.884	84.702
146,286	Least transfers	11,320	1,091,887	2,396,176	8,096	83.258	88.349	85.803
190,013	All lines are radial	10,041	955,996	2,712,186	13,121	72.896	100.000	86.448
297,164	Least generalized journey times	15,237	1,311,451	2,148,229	10,242	100.000	79.207	89.603
300,635	Worst with no radial line	14,000	1,273,442	2,259,471	8,828	97.102	83.308	90.205
301,918	Worst ranking	13,912	1,250,141	2,370,907	11,903	95.325	87.417	91.371

In this context, it is important to note that the suitableness of network variants (and thus the ranking of all versions) was determined using the sum of the capacity km in terms of operating costs and the so-called generalized journey times which are good indicators of passenger preferences. The generalized journey time is based on the physical journey time, however a weighting is also used (waiting time: 1.6 multiplier, walking time: 1.7 multiplier), and the 11.7 minute "penalty" for transfers also expresses the inconvenience to passengers, thus reflecting their satisfaction with the service more accurately than the raw journey time (Winkler, 2013). As the dimension and magnitude of the operator and passenger metrics differ, relative values of both were determined and averaged over 50-50% to arrive at a mean indicator reflecting the perspective of both parties.

On the other hand, Figure 2 shows the main operator and passenger-side indicators for all the 301,918 network variants in the form of value pairs. From the point set, a linear relationship between the number of capacity kilometers issued and the generalized journey time of passengers can be clearly seen: to reduce generalized journey times, meaning to increase passenger satisfaction, it is generally necessary to increase the volume of service. It may be possible to achieve the same level of satisfaction with a smaller or a larger volume (i.e., less "smartly" designed) network (hence the "thickness" of the shape in Figure 2) but the general trend is the (logical) relationship above.

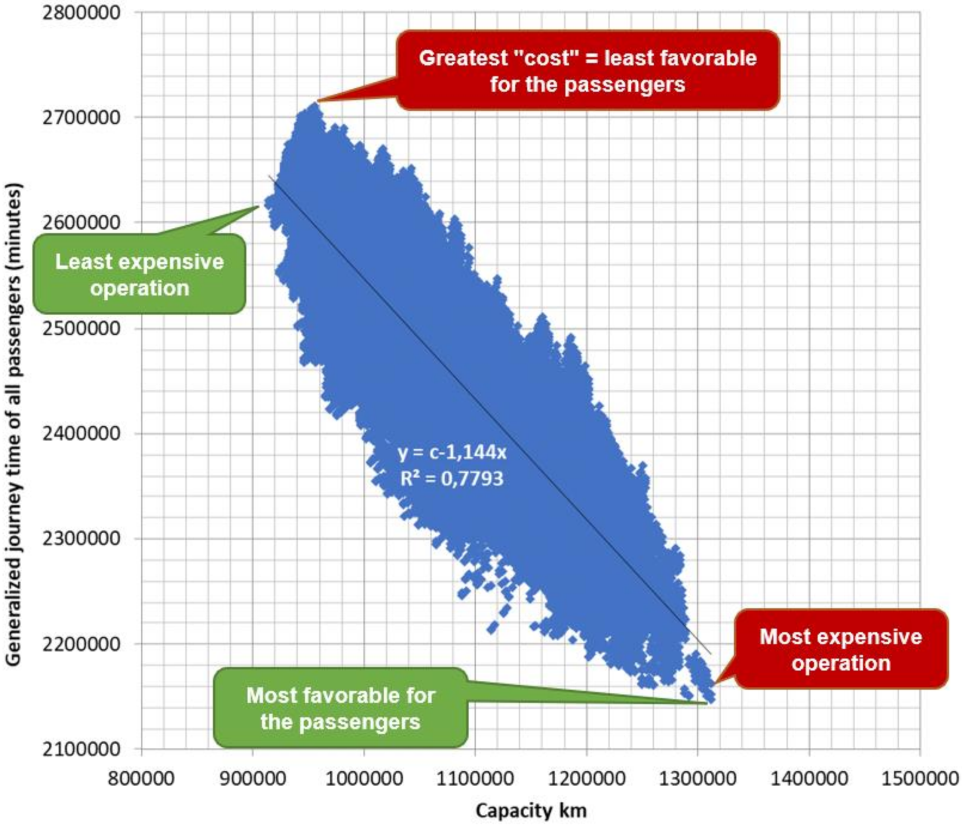

Figure 2. Map of the possible line-ends in Győr

A few important observations from the results:

- the most favorable network variant consists of 6 diameter lines and 2 radial lines, while the network operating in reality contained the same line-ends in the form of 5 diameter lines and 4 radial lines
- the best of the all-diameter networks ranked 12th in the order of suitableness of all variants (true, the worst ranking of this type of network is 300,635, so you can design a very bad network with all-diameter lines, too!)
- in contrast, the network variant with only radial lines is ranked 190,013, well in the bottom half of the field
- the network variant operating in reality is ranked 57,553, thus in the top 20%.

Based on the observations above, it can be concluded that in the case of Győr, the structure of travel demands does indeed justify a high ratio of diameter lines, even more than what is available today, if the necessary infrastructure improvements could be implemented.

Table 4 shows the lines of the network version that came first in the suitableness contest. As mentioned above, the majority of the lines are diameter, with only Győrszentiván and Gyirmót having a terminus in the city center. It should be noted, however, that this network would not be operational at present (or only with significant overheads), as there are no social facilities for bus drivers at the terminals of several suggested lines. The latter development would be appropriate for Kismegyer (new lines 1 and 3), Liget utca (new line 2) and Likócs (new line 6). (Of course, network variants that could not be operated with the current infrastructure could have been excluded in the pre-screening, but they were deliberately not filtered out, as the analysis method could also be used to identify the necessary location for such infrastructure improvements.)

Table 4. Lines of the network with the best ranking

Line (line-ends)	Route	General vehicle type	Average service frequency
1 **UN**-**SK**	Újváros, Nép utca – Kossuth Lajos utca – *City center* – Szabadhegy, vasútállomás – Kismegyer	solo	30 minutes
2 **RL**-**NM**	Liget utca, Nyár utca – Radnóti Miklós utca – *City center* – Nagy Imre út – Marcalváros – Ménfőcsanak, Győri út	articulated	15 minutes
3 **PI**-**JK**	Pinnyéd – *City center* – Jereváni út – Kismegyer	solo	60 minutes
4 **SA**-**GM**	Sárás – Városrét – *City center* – Gyárváros – Adyváros – Marcalváros	solo	30 minutes
5 **BA**-**TM**	Bácsa, Ergényi lakótelep – *City center* – Adyváros – Marcalváros	articulated	30 minutes
6 **LK**-**ZZ**	Likócs – *City center* – Zrínyi utca – Zöld utca, Szőnyi Márton utca	solo	30 minutes
7 **GS**	*City center* – Győrszentiván	articulated	40 minutes
8 **KG**	*City center* – Kálvária utca – Marcalváros – Gyirmót	solo	60 minutes

It is interesting to note that the new line 5 is practically identical to the current line 11, which has evolved in several stages to reach its current form, which is well established in practice and confirmed by this study. Another point in common with today's actual network is the radial (or more precisely Y-ended) nature of the Győrszentiván line group.

Possible Improvements

As already mentioned in previous sections of this paper, the research and development of the "LiMa" software is still in its early phase, so there are many opportunities for further development. The model is not yet able to deal with common line segments very well, e.g., where one line-end could be connected to several others (currently only one is possible). Of course, if this is achieved, work also needs to be done on the synchronization of the frequency of the lines containing the common segment.

In its current form, the algorithm is only usable in small or certain medium-sized single-center cities. For wider use, the model should also allow the possibility to compose lines of not just two, but more sections. In the Győr example, it would also have been possible to split the "NM" and "KG" line-ends in Marcalváros, thus allowing more combinations to be tested, but this would understandably have increased the running time of the program.

Additional solutions should also be considered when setting up frequency, as currently the aim is only to prevent passengers not being able to get on the buses, so frequencies are only increasing, but unused lines are not being decreased in frequency, so there could be significant unnecessary excess capacity. Of course, in designing the solution, attention should be paid in order to avoid creating an endless cycle of repeated decreasing and increasing in the algorithm. As another way to reduce unnecessary excess capacity, it would be important to manage shortened services. The first two improvements mentioned above, the management of common sections and the composing of more than two sections, would automatically enable this.

The assignment could be implemented by using stop-level journey planning, as well as a "multi-way" and/or "multi-step" assignment technique. Of course, the options mentioned above should be treated with caution, since even a small extension (e.g., 16 line-ends instead of 14) increases the number of possible networks by a factor of 20, and consequently the running time of the program.

However, a minor improvement in the assignment process is not expected to cause any major problems, since a slight increase in runtime would still mean a system that is practically usable, especially in light of the fact that the evaluation of network variants can be perfectly distributed and parallelized, i.e., the operation can be performed on several processors, possibly on several computers at the same time, and the results can easily be collected.

Conclusion

The paper presented the concept and theoretical background of an IT solution for the planning of radial-diameter local public transport networks, the applicable algorithms, and the experiences of the first implementation on the example of local bus transport in the city of Győr. It is important to note that the presented results (network lines and frequencies) at this stage of the research, should not be regarded as solutions to be implemented immediately in practice in an unchanged form, since, as explained in the previous section, the model and software can still be further developed and improved in a number of areas. The presented network illustrates how the method works in a specific city, but if the method is further developed, the results will of course vary to a greater or lesser extent. However, the initial experiments are encouraging, as the program developed gives acceptable solutions to real-world problems, in a reasonable runtime, by exploring all reasonable possibilities.

Scientific Ethics Declaration

The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Notes

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