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Model for optimizing parallel services of interurban and long-distance public transport links in Hungary

Abstract

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1. Overview of PhD research

My PhD dissertation is composed of 10 numbered chapters, which discuss the topicality of the research topic, provide a review of the relevant literature and include my novel scientific results.

Chapter 1 justifies the topicality of the research topic and describes its complexity. Chapter 2 elaborates the problem, illustrates how it is realized in practice, defines the scientific terms used in the dissertation and outlines the main fields discussed. Three major fields are identified within public transport: (i) parallel transport links served by buses and trains for long-distance relations; (ii) parallel transport links served by buses and trains at the regional level; (iii) parallel links served by buses in interurban traffic. Chapter 3 is the literature review, which offers a comprehensive overview of the transport effect studies, and also literature on the interurban public transport in general as well as operator and user parameters. Moreover, the literature on demand-responsive public transport is analyzed. Chapter 4 presents the methods applied in the study, including mathematical procedures, methods for data collection and data analysis.

Chapter 5 introduces a model which was created utilizing user and operator parameters in order to delineate the theoretical distance-based boundaries of parallel various long-distance public transport modes. It is illustrated through a practical example how the model is applied, and the results are also presented. The results are analyzed by regression analysis, and the boundaries of parallel transport links are determined.

The optimization strategy is developed in Chapter 6. A generally applicable model is introduced, which is based on the values of quality parameters of the services. The boundaries of intervals are defined for the quality parameter values, which are validated by a logit model. For each interval, measures are suggested, which can enhance the competitiveness of the given public transport mode, and thus regional public transport can become sustainable. The operation of the model is illustrated by a case study.

Chapter 7 presents the results of a survey conducted among passengers to reveal the preferences for changes in parallel public transport links, using *revealed* and stated preference questionnaires. Correlations with the analytical experiment are highlighted, and the results of the survey are presented, arranged according to the length of journeys (km), and the frequency of travelling.

Chapter 8 focuses on the optimization of parallel services using the road infrastructure, applying demand-responsive public transport. A model is presented in which traditional public transport services are replaced by a demand-responsive system of minibuses serving small villages in a given area, with the inclusion of the village warden system. As a result of this model, operational costs are to decrease, while the level of service increases. The operation of the model is illustrated by a case study for an area in Borsod-Abaúj-Zemplén County, Hungary.

Chapter 9. summarizes the novel scientific results in the form of theses. Chapter 10 concludes the dissertation, highlights their theoretical importance and the possibility of using them in practice. Furthermore, the possible further research topics are given in detail, future research directions are set.

2. Topicality of the research topic

Today the environmental impact of traffic and sustainable transportation are gaining importance. For sustainable transportation, demands must be satisfied in a way that minimizes the area used, the necessary energy and the costs (Munkácsy et al., 2018). Fleicher (2005) proposed that research on demands should not be restricted to specific fields.

A basic characteristic of sustainable and efficient interurban transport system is that to some extent its branches complement one another both in space and time. This ensures the economic sustainability of the system. The other characteristic feature is that the transport system should serve travel demands at the highest possible level.

One of the problems of the Hungarian public transport system is that long-distance links are served both by buses and trains, in a parallel manner. There are parallel bus and train services in all regions of the country, and several cross-country parallel links also exist. This situation can result in a competition between the two modes, generating a system that is not sustainable.

In the past decades, steps were taken to terminate parallel transport services, e.g. in the Budapest–Győr link, bus services were stopped. However, these measures did not always result in a sustainable transport system. In the case mentioned above, for example, it turned out that time-sensitive bus users did not switch to trains, but rather changed for individual transport modes (Tánczos et al., 2007; Vörös, 2011). As a result, 30% of passengers were lost. Such a step can actually lead to saving costs of the maintainer of the public transport services and of the bus company. However, the environmental load is increased and the level of public transport services decreases, which may be unfavourable for the whole of the transport system.

Naturally, parallel services are present not only between modes, but also within branches. This is characteristic of road systems connecting hamlets, as in these regions demand-responsive social transport systems have been maintained by local governments for closed communities in the past 20 years, while the state-ordered parallel traditional public transport services have also been operated. This means that both human resource management and vehicle management work suboptimally, i.e. in a wasteful manner. Additionally, the level of transport services is also low. In those parts of the country which are characterized by hamlets, this is an existing problem. Although some projects supported by the European Union have superficially addressed the problem, exact plans have not been created to solve it.

Based on the above facts, it is highlighted in the chapter that in order to optimize interurban transport, innovative models are necessary, which use mathematical analytical tools to handle user and operator parameters in a complex manner.

3. Topic areas and aims of the research

The topic areas of the research have been identified and defined, and the aims have been set.

Three topic areas have been identified.

1. The analytical and user preference-based modelling of long-distance public transportation.
2. The modelling of parallel public transport services at the regional level.
3. The modelling of parallel services concerning interurban bus services.

Long-distance parallel public transport

The aim of examining long-distance parallel public transport systems is to determine which transport mode or modes, or maybe parallel links can secure that public transport would be sustainable and efficient. The factors taken into consideration are user and operator parameters, and distance. In order to achieve this, a mathematical method, regression analysis was applied to analyze the changes of temporal and cost values with respect to distance.

In addition to this analytical approach, this study also aims to explore preferences of passengers for choosing transport modes. In order to achieve this and to be able to reach the highest possible level of services, the correlations between analytical aspects and passenger preferences concerning the quality of services depending on distance have been identified.

In this research topic, my hypothesis was that theoretical distance-based boundaries of a sustainable parallel long-distance public transport system can be delineated by a complex analysis of user and operator parameters and user preferences.

Regional parallel public transport

The aim of examining regional parallel public transport systems is to create a complex and compact service quality index in order to evaluate and optimize regional parallel links. My aim is to identify for each value of the service quality index some traffic organization measures, which result in an increase of the level of transport services, while costs are decreased.

A mathematical method, the logit model is used to explore the correlations between the values of the service quality index and the number of passengers, analyzing the extrema of usefulness functions. European best practices have also been reviewed through implementing a Finnish case study.

My hypothesis is that a complex service quality index relying on several variables and the corresponding traffic organizational measures make it possible to optimize regional parallel

public transport systems. As a result, regional public transport can become sustainable and efficient.

Parallel services in interurban public transport systems

This survey aims to highlight that parallelism is not only present between modes, but also within the road services. Thus this network also needs to be optimized. To illustrate this problem, the serving of areas characterized by hamlets is presented.

In such rarely populated areas, the integration of the already existing traditional and demand-responsive transport systems is suggested in order to create an economically sustainable system with the increasing of the service levels, i.e. ensuring that the hamlets are served at a higher level.

A generally applicable model is created for optimization, which allows for the reorganization of transport performance in a way that operational costs do not rise, but the level of service is increased.

My hypothesis is that it is possible to rationalize the resources and the performance of serving hamlets on public roads in a way that the level of services increases, while the costs remain in the same volume.

Figure 1 shows the relationships between topic areas of the dissertation.

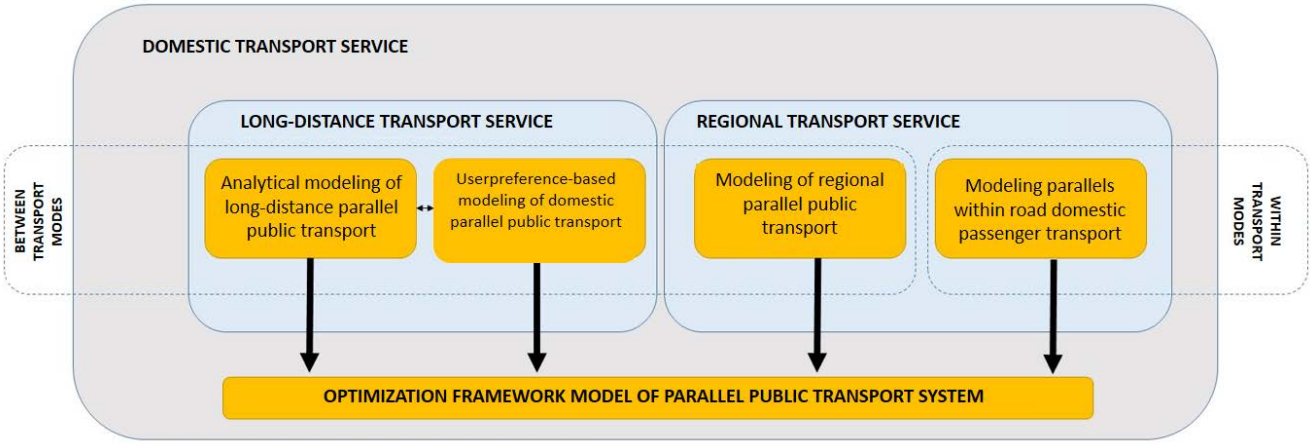

Figure 1. Relationships between topic areas

As the figure above illustrates, the various optimization models are interrelated, and if all of them are applied, the whole system of parallel transport services can be transformed into a sustainable and efficient network.

The basic confines of the study are given below.

- The analysis presented here is based on those versions of the relevant terms and conditions documents and public service contracts that were in force on 1 December 2019.
- The legislation in force on 1 December 2019 was used throughout the dissertation.
- For each topic area, the official Autobus Timetable and the Train Timetable for 2018/2019 was taken into consideration.
- Concerning local public transport services, the timetables valid on 1 December 2019 were considered.
- Temporary timetables introduced owing to major, long-lasting construction activities requiring track closure in the case of train services were disregarded for this study. The basic timetables for the given timetable year was used.

4. Methods

In order to fulfil the research aims in all topic areas, several research methods have been applied.

Regression functions have been used to describe the rules of connections between quantitative characteristics, i.e. user and operator parameters. The strength of relationships are determined by correlation variables. To compare the travel time and travel distance values for each transport mode, regression functions that belong to the Ritz method are applied. Regression functions create a linearly independent system, i.e. none of the functions can be expressed by the linear combination of the other functions. These functions might be trigonometric, exponential or *n*th degree polynomials (where *n* can be an odd or an even number). Polynomials raised to the power of an odd number meet the requirement that they can also describe a phenomenon at the extreme values. Consequently, polynomials raised to the power of 1, 3 and 5, respectively, have been identified that provide the best fit for the examined value pairs. The quality of the application of such polynomials, i.e. how perfectly they fit the data, can be characterized by correlation analysis. A correlation variable is created to describe the correlation between the examined variables.

In the course of optimization, objective functions have been applied, i.e. the minima or the maxima of a real function have been determined (Rardin, 1997). Objective functions have been used to determine the optimal level of the values for user and operator parameters. As the optimization process seeks the best value of the examined function in a given interval, the boundaries of the intervals had to be defined.

The mode choice of public transport can be described by a probability model, based on the space distribution of travels (Kövesné, Debreczeni, Csiszár, 2014). The method of logistic regression, i.e. a logit model has been applied, which is a probability model (Buis, 2016; Hajdu 2004). This statistical method uses a logarithmic function to model a binary dependent variable. The two possible values of a binary variable are represented by an indicator variable (0 or 1).The logarithm of the probability of the occurrence of a given value of a variable in the logistic model is the linear combination of one or more independent variables. Each independent variable might be binary (i.e. two classes encoded by an indicator variable) or a continuous variable (any real value).

The Nested Logit Model belongs to the group of utility-based models. Its basic principle is that the decision maker tends to choose the best, most profitable transport mode, based on parameters (Kosztyó, Török, 2007). The mode of transport is regarded as a binary dependent

variable. Mode choice can be encoded by assigning 0 or 1 to each mode choice, depending on the choice of the passenger.

In order that the properties of the alternatives (in this case, train or bus) can be handled according to their weight, a linearly combined utility function was defined for each alternative based on travel time and travel cost weight factors. Utility functions are widely applied in several fields of economy, especially in macroeconomic consumption theory. The aim of their application is to model the preferences over a given set of goods or services of a market player – or in other cases – of the whole society. The number of the variables in the function equals the number of goods considered (i.e. modes of transport, in this case) (Debreu, 1954; Fishburn, 1970).

In public transport planning, it is of utmost importance to take travel demands into consideration. Only a transport system that meets the travel demands can function efficiently and offer attractive alternatives to individual transportation.

Data collection was the basis for my detailed survey, which was conducted in two ways:

- direct data collection, carried out with a device with a unique identifier;
- application of questionnaires, administered during a personal interview (e.g. *revealed preference* and *stated preference* types).

Data on personal preferences can be collected by using questionnaires, having focus-group discussions or conducting interviews (Földes, 2019). The latter two methods are applicable if the sample size is relatively small, and deep correlations are to be revealed. Questionnaires are used if the sample size is big, and general tendencies are to be discovered. In order to reach the largest possible sample size, I used questionnaires.

Two types of questionnaires were used:

- *revealed preference* type;
- *stated preference* type.

In surveying public transportation, data on travel patterns is often collected from passengers by *revealed preference*-based questionnaires. This method reveals the individual mobility patterns for the operator of the transport services.

Revealed preference questionnaires are used to inquire about the present travel patterns of users. My questionnaire was compiled based on similar surveys, respecting the main rules of editing. It is important to choose the correct questionnaire type (Scipione, 1994), to follow the

main steps of questionnaire edition, and to create a process-like build-up, which is easily understood. In order to avoid misunderstanding on behalf of the respondents, questions were formulated in a simple way, without redundancies (Hosseininasab, 2015). The following question types were included in the questionnaire:

- multiple choice questions (Csapó et al., 2008);
- scaling questions (Földes, Csiszár, 2018);
- open questions (Kiss, Tátrai, 2012).

In the multiple choice type, the respondent can choose between pre-defined answers. This type is applicable for yes-or-no questions and to elicit demographic data. As for scaling questions, the respondent associates a value on a pre-defined scale to a parameter, which can reveal how important the parameter is for the user. Open questions were applied in justified cases only, as the processing of such answers is difficult, data cleaning is time-consuming, and answers might be misunderstood.

Stated preference questionnaires can be applied to explore decision-making processes and latent user demands. The respondent is put into a model situation created on the basis of real data, and the decision made allows for exploring the real values of goods and services and the user mode choices. It must be noted that *stated preference* questionnaires can be used to support decisions according to Krajnyik (2008) if the goods or services are hypothetical (e.g. during a development process, hypothetical goods can be created by modifying the parameters of existing goods, and consumers can state their preferences).

The *stated preference* method is not widely used in Hungary. Evaluation can be divided into three groups.

- *CV (contingent valuation)* reveals how much a respondent would be willing to pay for a given service or certain goods in a given situation.
- *CA (conjoint analysis)* allows the respondents to rank the presented goods and services according to their preferences.
- *DCE (discrete choice experiment)* allows the respondents to choose the most valuable one out of a list of goods or services (Kroes, Sheldon, 1988).

Stated preference methods are widely applied in fields where the role of the market is restricted, i.e. the consumers' habits, choices and willingness to pay cannot be explored by examining the real market (e.g. if public services are monopolized). This is why in this study *DCE analysis* is applied to explore user preferences, as interurban traffic is ordered by the state or local government from monopolists. Cards with real parameters for each transport mode

were prepared for the questionnaire. Respondents were asked to choose the more beneficial one.

Questions were formulated carefully, and the contents of the cards were clearly organized.

Answers given to the questionnaires were copied into a database to ease processing.

By comparing the results of the different types of questionnaires, correlations between the current and preference-based mode choices have been examined, together with the results of the analytical survey.

5. Novel scientific results

Thesis 1

I have set up a model based on user and operator parameters to evaluate parallel long-distance public transportation services, which relies on regression analysis to model the competitiveness of different modes of transport. I have defined the theoretical distance-based boundaries for the values of travel time and unit costs per place in a vehicle using regression polynomials, with respect to distance.

My publications connected to this thesis are: (Lakatos, Mándoki, 2017a), (Lakatos, Mándoki, 2017b), (Lakatos, Mándoki, 2018b), (Lakatos, Mándoki, 2018c), (Lakatos, Mándoki, 2019b), (Lakatos 2019c).

This thesis is discussed in detail in Chapter 5 of the dissertation.

The existing and recurring problem of parallel bus and train links in long-distance public transport in Hungary has been addressed here. Sustainable transport means that different means of transportation should complement each other. Thus, it is indispensable to optimize parallel links.

I have created a 5-step model to solve this problem, which evaluates the operator and user parameters of public transport depending on distance.

- Step 1. Definition of travel chains, selection of parallel public transport links.
- Step 2. Calculation of user parameters (travel time, distance) and operator parameters (unit cost per place in the vehicle).
- Step 3. Modelling of correlations between parameter values with a mathematical method, namely regression analysis.
- Step 4. Determination of theoretical distance-based boundaries both from user and operator perspectives.
- Step 5. Analysis of the possibilities of developing the model.

Using the above model, travel chains between Budapest and 15 county seats or towns with county rights have been determined. These chains all have parallel links *(Figure 2)*.

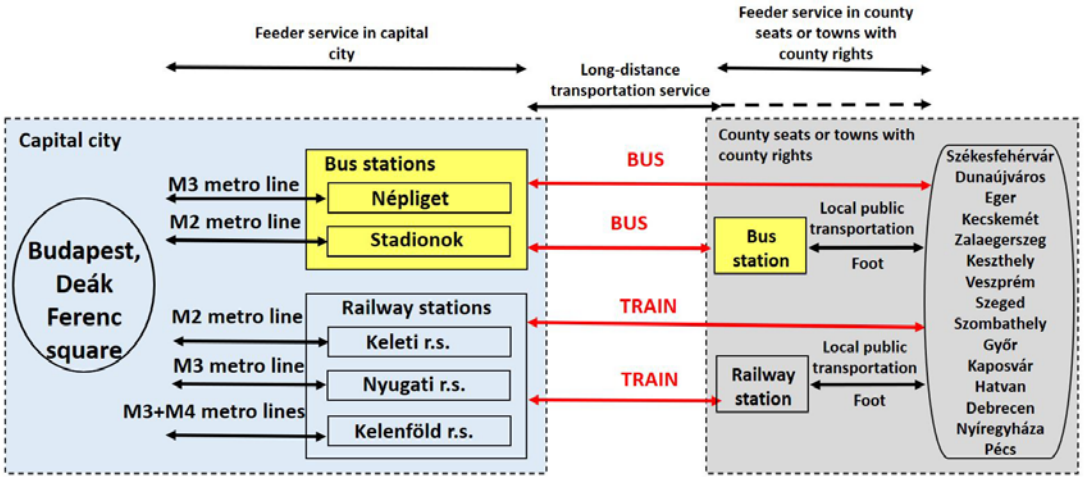

Figure 2. The examined travel chains

During the evaluation, polynomial regression has been fit to the value pairs, i.e. travel time, as user parameter and travel distance; and unit cost per place in the vehicle, as operator parameter and distance. The optimization possibilities of long-distance public transport modes have been divided into sections according to the relative position of the functions and deviation values. *Figure 3* shows the major findings.

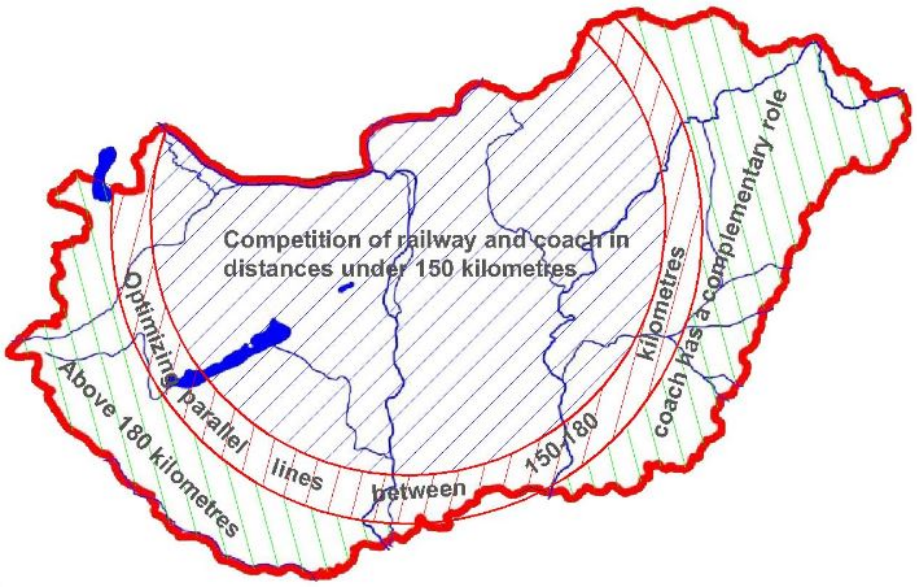

Figure 3. Theoretical boundaries in Hungary, determined by regression functions

I have proven that the competitiveness of buses even for long distances can be enhanced if Tempo100 quality buses are applied.

It has been demonstrated that the deviation of unit costs per place in the vehicle is inversely proportional to distance *(Figure 4)*.

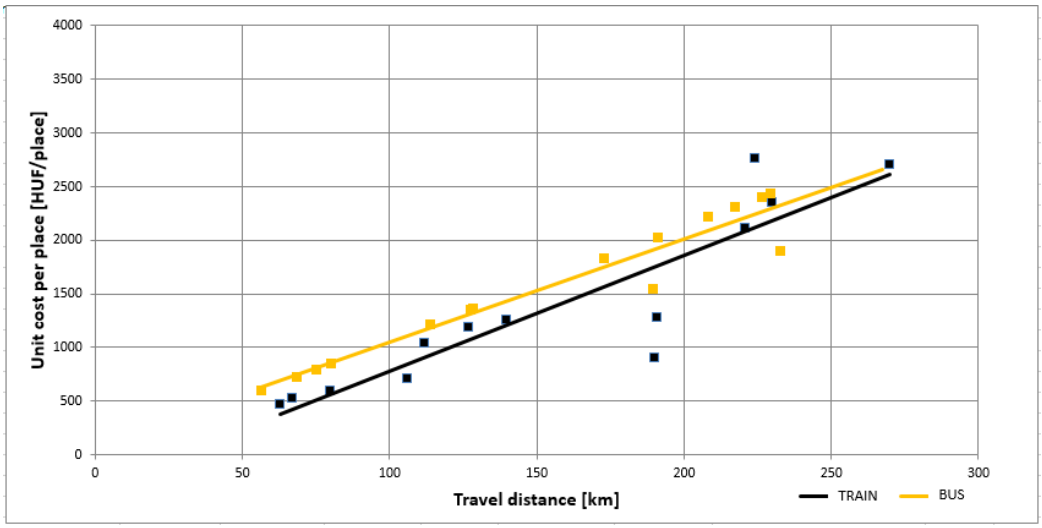

Figure 4. Unit cost per place in the vehicle for trains and buses with respect to travel distance (without Kaposvár and Zalaegerszeg)

Thesis 2

I have created a generally applicable, innovative model in order to optimize the parallel links in regional public transport. The model is based on an objective index, which is calculated from complex parameters. The intervals of the values of quality indices selected by objective functions determine the type of traffic organization measures. The boundaries of intervals, and thus the whole model have been validated by a logit model.

My publications connected to this thesis are: (Lakatos, Mándoki, 2018a), (Lakatos, Mándoki, 2018b), (Lakatos, Mándoki, 2018c), (Lakatos, Mándoki, 2019a), (Lakatos, Mándoki, 2020c), (Lakatos, Mándoki, 2020d).

This thesis is discussed in detail in Chapter 6 of the dissertation.

The existing and recurring problem of parallel bus and train links in regional and long-distance public transport in Hungary has been addressed here. Sustainable transport means that different means of transportation should complement each other. Thus, it is indispensable to optimize parallel links.

In order to solve this problem, a generally applicable complex model has been created *(Figure 5)*. The value of a quality index *(M)* has been calculated (1) based on some major parameters (travel time, available services, number of inhabitants) *(Table 1)*.

$$M = \sum_{j=1}^{n} \left(\frac{1}{n_{daily\ i,j,b}} \cdot t_{travel\ i,j,b} \cdot p_j - \frac{1}{n_{daily\ i,j,v}} \cdot t_{travel\ i,j,v} \cdot p_j \right) \quad (1)$$

Table 1. Legend for *Equation (1)*

Variable	Description	Dimension
i	departure (settlement)	–
j	arrival (settlement)	–
k	transport mode (b – bus, v – train)	–
$t_{travel\ i,j,k}$	total time required for covering the distance between the centres of i and j settlements, by k mode of transport	[min]
$n_{daily\ i,j,k}$	number of vehicles per day running between i and j settlements, by k mode of transport	[piece]
p_j	the proportion of the number of inhabitants of the given settlement and the total number of inhabitants of the settlements served by the given service	[-]

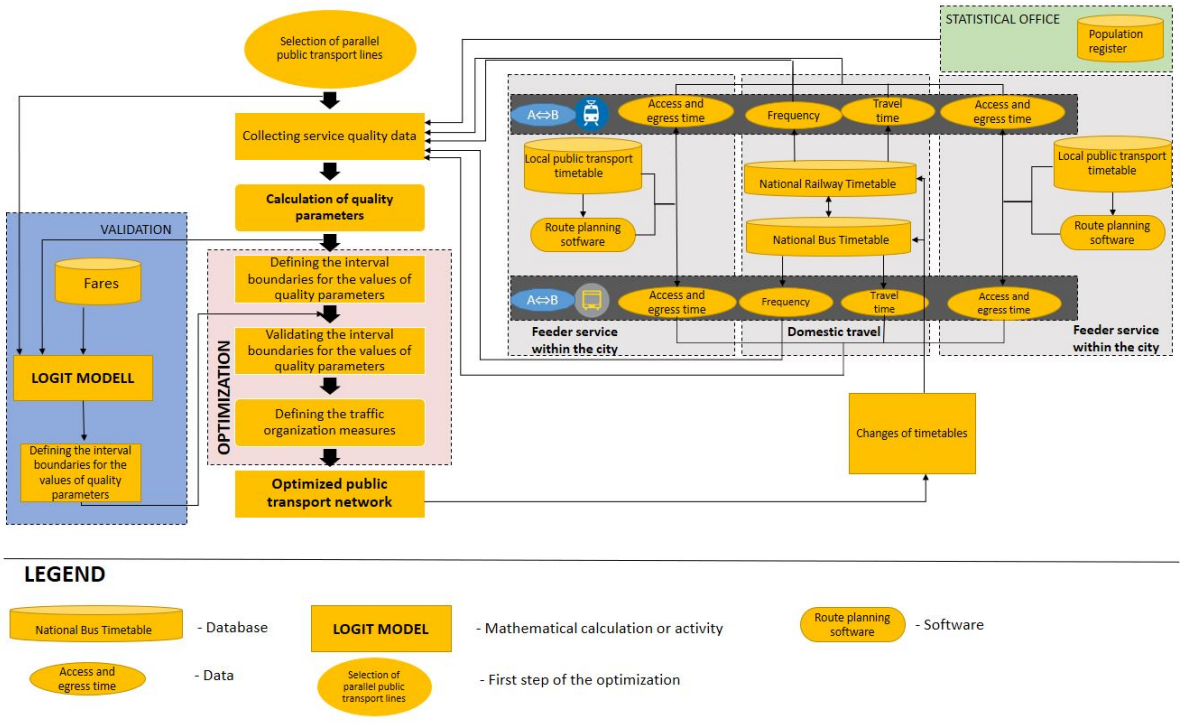

Figure 5. The optimization model for regional parallel public transport links

Based on objective functions (2, 3), interval boundaries for the values of quality parameters have been defined. These were validated by the logit model-based evaluation of the following values: number of passengers using parallel bus and train links, offered travel times, offered travel costs.

$$M \rightarrow max. \tag{2}$$

$$K_{invest.\ i,j,k} \rightarrow min. \tag{3}$$

Traffic organization measures *(Figure 6)* to maximize the *M* value have been defined for each interval, while minimizing investment costs ($K_{invest.\ i,j,k}$).

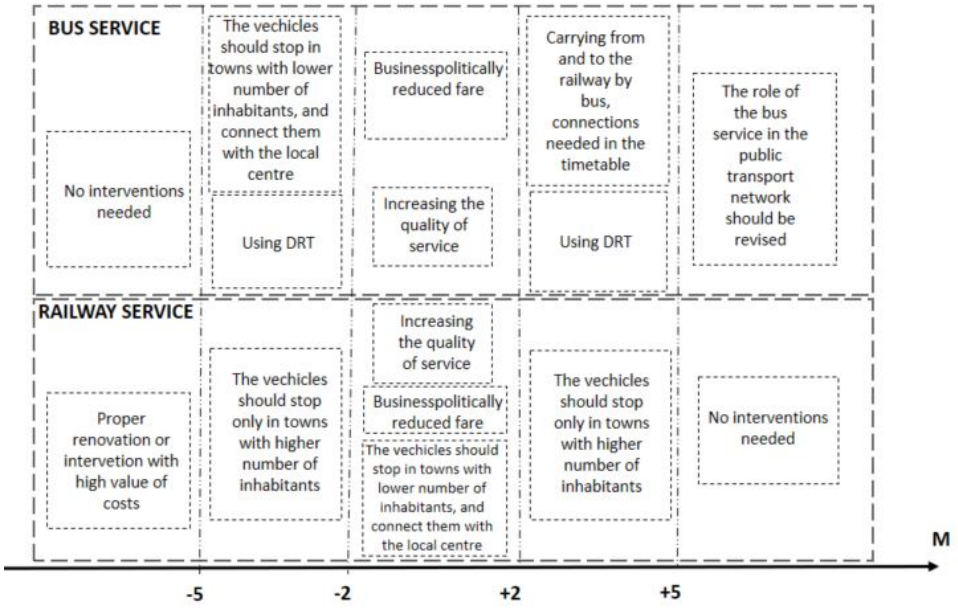

Figure 6. Suggested measures, depending on the precise values of the quality index

The applicability of the model has been proven through a case study, which includes the optimization for all of the 7 regions of Hungary, handling all the parallel bus and train links of the country.

It has been declared that with the help of the quality index values that are based on the number of inhabitants, travel time and available services, the regional parallel links can be optimized. The level of service can be increased solely by traffic organization measures, without the need for considerable investments.

Thesis 3

I have created an analytic model based on various types of questionnaires in order to determine the user preferences with respect to travel distance and passenger motivation in the case of parallel public transport links. I have determined the major correlations between analytical optimization and user preferences.

My publications connected to this thesis are: (Lakatos, Mándoki, 2017a), (Lakatos, Mándoki, 2017b), (Lakatos, Mándoki, 2017c), (Lakatos, Mándoki, 2017d), (Lakatos, Mándoki, 2019b), (Lakatos, Mándoki, 2019d), (Lakatos, Mándoki, 2020e).

This thesis is discussed in detail in Chapter 7 of the dissertation.

I have explored the problem of user preferences for mode choice in the case of parallel long-distance public transport services. Passengers take into consideration several parameters when deciding on the mode of transport. The complex correlations behind their mode choice have been explored and a model for user behaviour has been set up *(Figure 7).*

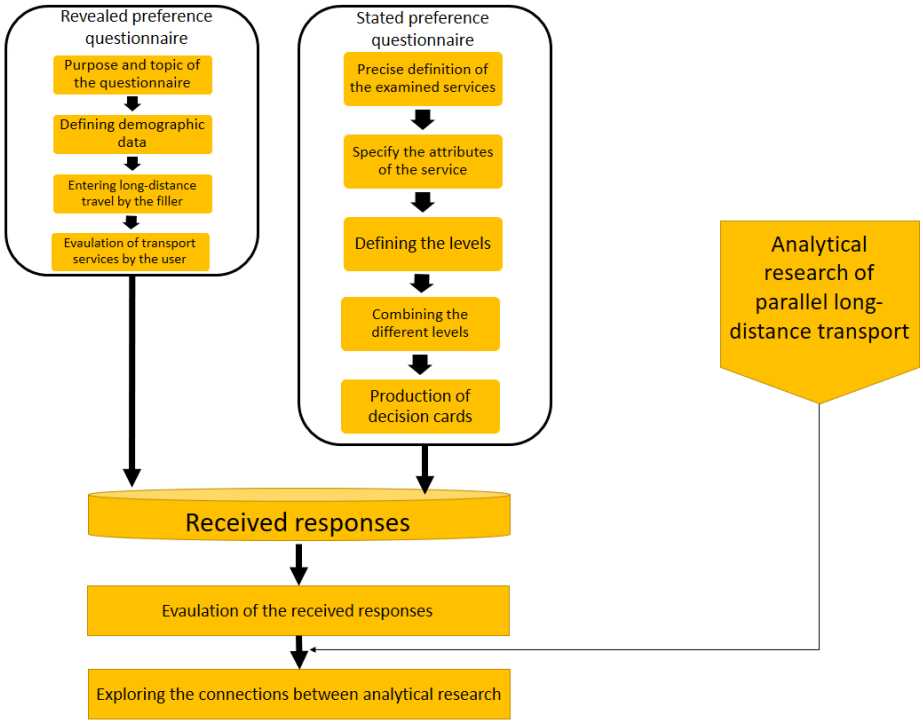

Figure 7. The model for user preferences

Revealed and stated preference questionnaires have been applied to get to know passenger preferences. The importance of each parameter in the decision-making process of users has been determined based on the answers to the questionnaires.

I have revealed that user preferences change depending on travel distance. Three distance intervals have been defined, according to which user expectations concerning travel time, comfort and costs change. It has been proven that the distance intervals corresponding to mode choice are in harmony with the suggestions for traffic organization measures defined analytically.

It has been proven that bus services are preferred owing to reliability and travel time, while train is chosen for comfort. Users also connect several extra services to trains.

I have stated that the motivation for travel plays a crucial role in mode choice. This question is very important, because there is a high proportion of people commuting to work on a daily basis among the passengers.

Thesis 4

I have created a 7-step innovative model to create an effective and sustainable interurban public transport model to serve regions with hamlets. The model is based on the optimization of traditional and demand responsive public transport systems. Complex parameters (performance, cost, resources) determine the extent of the enhancement of public transport service levels, which is achieved by reducing or maintaining the present volume of costs.

My publications connected to this thesis are: (Lakatos, Mándoki, 2018b), (Lakatos, Mándoki, 2018c), (Lakatos et al., 2020a), (Lakatos et al., 2020b).

This thesis is discussed in detail in Chapter 8 of the dissertation.

To serve areas with hamlets with public transport networks is a challenging task in the whole of Europe. Traditional public transport networks are hardly sustainable in areas with a low number of inhabitants and low population density, and services have low availability.

I have created a 7-step complex and compact model to serve settlements with a low number of inhabitants with a demand responsive traffic system *(Figure 8).* I used this model to optimize parallel services within a transport mode, based on user and operator parameters.

The model allows for replacing the traditional public transport network with a flexible system. I have increased the level of service *($Z_{(x, \alpha)}$)*, while costs for the given period of the day *(C_{day}, C_{op})* and also parallelism *($P_{running}$)* have been minimized, based on the following objective functions (4, 5, 6, 7).

$$Z_{(x,a)} \text{ -> max} \quad (4)$$

$$C_{day} \text{ -> min} \quad (5)$$

$$C_{op} \text{ -> min} \quad (6)$$

$$P_{running} \text{ -> min} \quad (7)$$

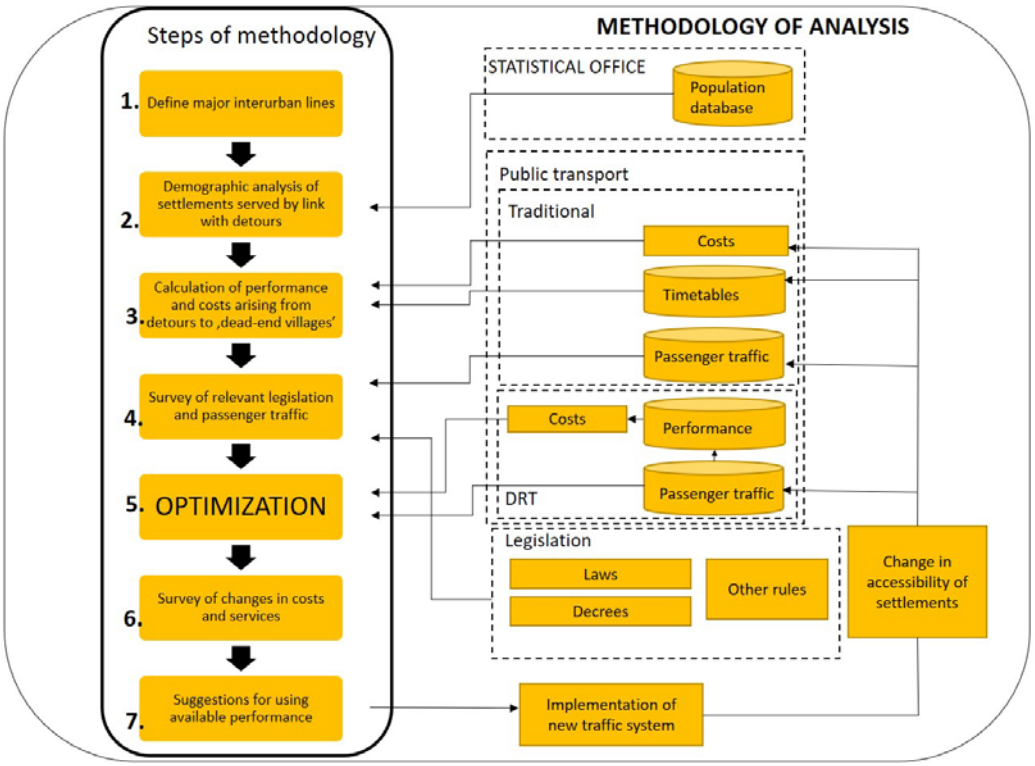

Figure 8. Survey model

I have conducted a case study for an area in Borsod-Abaúj-Zemplén County, Hungary, based on the above model.

I have proven that the public transport service for 'dead-end' villages with a diminishing population can be improved by the introduction of demand responsive transport and the effective distribution of the present resources, without extra costs, which is beneficial both for users and operators. I have also proven that by maintaining the present volume of costs, it is possible to provide extra services (e.g. ensuring an hourly schedule for access and egress services from 'dead-end' villages harmonized with the main route services, instead of the present occasional services).

I have stated that parallel transport networks can be optimized by the application of this innovative model in order to make the public transport services for rarely populated areas sustainable.

6. Practical applications

Today the preference of public transport services over individual transportation is a hot topic in the field of transportation. This can not only be achieved by regulating individual transport modes, but also by offering a higher level of public transport services that match the needs of passengers. Furthermore, the volume of costs has a significant effect on the quality and quantity parameters of services.

I have demonstrated the applicability of the models proposed in my theses in case studies that cover the whole area of Hungary, which proves that these models can be implemented into existing systems. Additionally, I have analyzed European best practices in order to ensure the highest possible level of applicability.

The fact that I have revealed passenger preferences concerning mode choice in public transport enhances the applicability of my research, as I have taken into consideration the most important factors of users to set up the models. In sum, the quality expectations of the passengers for transport services have been explored.

The optimization possibilities described here can set the path for transport organization in the future. While the level of service is enhanced, the financial costs of the operator or the client of the operator are also optimized. As a result, while the user is offered an attractive mobility service, the costs of the operator are minimized.

The suggested optimized interurban public transport system can offer an attractive alternative to individual transport, while maintaining the present level of financial costs.

7. Directions for further research

Based on my present results, I wish to continue my research with the same perspective, intensity and attitude.

I continuously follow the relevant literature and explore research gaps. Several new research topics have raised my interest, while I also wish to develop my own models.

New research directions include:

- regarding Chapter 3.1. in the dissertation, the evaluation of the factors examined in the model developed for the optimization of parallel services between modes of transport and within road public transport, the external effects (environmental and accident costs) can be quantifieds with a CBA based on guide documents;
- the replacement of traditional public transport services with demand responsive transport systems at the local level within cities, focusing on the outskirts and off-peak hours;
- application of innovative systems in local public transport networks (e.g. including taxi or car-sharing services);
- exploration of flexible pricing schemes in long-distance public transport systems, based on my model;
- further surveys to explore user needs, with a special focus on the correlations between demands and perceived quality, to facilitate modelling;
- Applicability of autonomous vehicles – both from the point of view of users and operators – in the field of ‘dead-end villages’;
- examination of the regularity of different public transport modes – as well as its effects – in the case of interurban, long-distance, parallel public transport;
- user preference and parameter-based analysis of parallel international public transport in order to optimize the division of labor in transport;
- assessing public transport needs using innovative methods (on-board Wi-Fi based traffic counting).

The examination of these problems can enhance the complexity of the analysis and evaluation of the research topic.

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