University of Pardubice
Faculty of Transport engineering

SYNERGY OF PREFERENTIAL MEASURES IN PUBLIC TRANSPORT

DISSERTATION THESIS

2024 **Ing. Jaroslav Chlumecký**

PhD student

Ing. Jaroslav Chlumecký

Study program

Technology and management in Traffic

Study specialization

P1041D040001 Technology and management in Traffic

Trainer

doc. Ing. Pavel Drdla, Ph.D.

Trainer specialist

—

Training workplace

Department of Transport Technology and Control

Content

Introduction

The global trend of population mobility is an effort to maximize the use of public transport at the expense of individual transport, where for the purpose of the dissertation a passenger car is usually considered as a representative of individual transport. Public transport, in order to fulfil its function correctly and to be competitive vis-à-vis individual transport, requires a number of preferential (support) measures. In the last 20 years, this preference has been realized in public transport in the world, where most of the solutions are implemented only in isolation without any influence on the surroundings. However, in order to increase the efficiency of the application of individual preferential measures, it is necessary that the synergy between the various isolated support solutions for the prioritization of public transport is not neglected. The synergy of preferential measures is an issue that is primarily examined in the dissertation.

1 Current status of the studied issue

From the point of view of the **legal environment**, the issue of public transport preference within the Czech Republic and abroad is dealt with in laws regulating road transport, decrees, government decrees, technical standards and in technical conditions. Public transport preference within the Czech Republic is dealt with in law by selected sections of Act No. 361/2000 Coll., on road traffic, as amended, and in Decree No. 294/2015 Coll., of the Ministry of Transport of the Czech Republic, implementing the rules of road traffic, as amended. In foreign legal regulations relating to the topic of the dissertation, there are provisions on respecting longitudinal and horizontal traffic signs in connection with reserved lanes. These provisions are mentioned, for example, in general road traffic regulations. VwV – StVO (Allegemeine Verwaltungsvorschrift zur Straßenverkehrs – Ordnung) in Germany. The Swedish Traffic Sign Decree (Vägmärkesförordning SFS 2007:90) of 2007 also contains provisions on giving priority to public transport vehicles. In addition, the Decree also contains signals for public transport vehicles, which determine the direction and freedom of a given transport route. (1)(2)(3)

Subsequently, the author proposes a simplified division of preferential measures using the above distribution of preferential measures according to Gardner (4) and Drdla (5). According to the author, the first level of distribution of preferential measures is clearly a division into **direct** and **indirect** preferential measures. The second level of distribution of preferential measures is proposed by the author to be divided into **physical measures of change of transport mode, organizational measures of change of transport mode, modifications of SSZ (light signaling device) signal plans, coordinated and other measures of direct preference**.

The **main physical measures** for changing the transport mode are the BRT (Bus Rapid Transit) and LRT (Light rail) systems, which are mentioned in their studies mainly by Fiorio (6) or Furlan (7). These systems are very effective within the framework of preferential measures, as they completely segregate the ride of a **public transport (PT)** vehicle from **individual car transport (ICT)** and thus provide in essence a guarantee of the adherence to the timetable, fast connection without significant delays at points of intersection with other transport. These are so-called intermediate stages between the classic bus and tram subsystem and the metro subsystem.

Dedicated lanes as a basic kind of organizational measure for changing the traffic regime can be limited in time (i.e. reserved only during peak hours on working days) or permanent. Dedicated lane for buses is according to Viegas and Lu (8) a low-cost option of preference, which is generally the most desired when applying preferential measures.

In addition to the standard dedicated lanes, according to Novotný et all. (9) there are also various modifications, such as the so-called **dedicated shifting lane**, which is realized before the intersection and allows the vehicle to overtake the PT vehicle quickly in case of congestion in the standard lanes. **Exclusive direction in the shift lane** is also used, where the PT vehicle uses the shift lane, which is followed by the standard dedicated lane in the respective direction. At bus stops, where there is a higher intensity of traffic, dedicated lanes are also installed for **exiting the stop with the exclusive preference of PT vehicles**, where other vehicles in the continuous lanes must give priority to the PT vehicle. In some cases, this preference can be supplemented by light signaling equipment. In PT systems, where there are also PT rail subsystems, so-called **combined tram and bus lanes** are also common.

(9) There is also the so-called **Tempo 50**, where the dedicated lane is combined with light signaling equipment.

According to Viegas et all. (8), the solution to not significantly reduce the capacity of the streets by means of permanently reserved lanes may be the **intermittent bus lane (IBL)**, which is an intermittent bus lane. The **intermittent dedicated bus lane** for buses operates as a normal dedicated lane with preference for PT vehicles only when the PT vehicle is actually there or approaching it. At the moment when there is no public transport vehicle, the lane operates as a normal lane for other vehicles as well.

In cities where selected public transport lines are led by one-way streets (usually for spatial reasons), there is also an organizational form of public transport preference through **the possibility of a public transport vehicle travelling on a one-way street in the opposite direction**. In sedated streets, where the entry of ICT vehicles is excluded, it is also possible to **allow a public transport vehicle to travel through a pedestrian zone**. These measures are used precisely for diametric or radial lines serving an urban or historic center, as a rule this exemption is combined with a permit for cyclists to pass through.

The preference for SSZ (light signaling devices) consists of two basic assumptions – **the relationship of the preferred junction to the controlled surrounding junctions and the form of implementation** of the given preference. Gardner (4) gives a division in terms of **the relationship of the preferred junctions to the surrounding controlled junctions** into: isolated systems, systems with a fixed signal plan based on historical data, systems controlled by the movement of the PT vehicle, the MOVA system (a system detecting the movement of vehicles and allowing the timing of the signal depending on the delay, etc.) and coordinated preference systems in the form of SSZ (e.g. green wave).

The integrated/coordinated preference consists of both physical measures and SSZ measures. Its implementation can be a form of queue relocation and so-called **pre-signal** integrated measures using, for example, a dedicated lane and the implementation of SSZ measures. It should be noted that this type and meaning is a completely different type of pre-signal than the one commonly used in rail transport.

The indirect preference tools according to Drdla (1) include mainly monitoring and measuring the quality of public transport, creation of IDS, creation of convenient time fares and intelligent ticketing systems, creation of measures for connecting public and individual transport (e.g. intercept car parks) and many others.

The author focuses primarily on **the issue of reserved lanes** and their more compromised system, i.e. already mentioned intermittent reserved lanes, because on the basis of the analysis of scientific knowledge it is the simplest form of how to prefer the ride of public transport vehicles with minimal implementation costs. Synergistically with this issue the author solves **the interconnection with SSZ measures** taking into account the indirect measures. The author mentions the indirect measures within the design part mainly in the form of comments and also at the end when defining the benefits of the solved proposals.

2 Dissertation goal

With the help of analysis and critical evaluation of scientific knowledge about preferential measures using methods of soft systems analysis and mathematical decision-making methods and approaches, the aim of the dissertation is to compile a methodology for evaluating the synergy of preferential measures in public transport. This methodology sets out a preliminary decision whether the selected synergy measure will be sufficiently effective in solving a particular problematic section.

This methodology for selecting the synergy of preferential measures aims to provide the entity that will implement such a measure with **a preliminary decision** before the implementation starts, **whether the selected synergy measure will be sufficiently effective in addressing a particular problematic section**. **The concept** of sufficiently effective means that the measure will serve to eliminate the resulting undesirable delay of public transport vehicles on the problematic section in question, or to reduce travel time. **The entity** that would use this methodology could be, for example, the implementer of this measure from the position of the local roads technical administration, or the proposer of this measure from the position of the operator or coordinator of public transport within the city (or within the affected public transport lines). **The selection process** itself aims to take into account the lowest possible cost of implementing such a measure with minimal impact on the movement of vehicles (i.e. preferably without increasing the waiting time of these vehicles), which are not the subject of preference and at the same time with the highest possible effect for the vehicles preferred.

3 Processing methods and method of solution

Several methods can be used in the verification to determine **the methodology of synergy of preferential measures.** The main criterion for selecting the appropriate method is the availability of input data needed for the given method and the expectation of the result that the particular method will bring.

In the design part, according to the choice of available possible methods, the author will make the primary use of the mathematical **Petri nets** tool for characterization of the problem solved and then **the methods of force field analysis** and **the Saaty method** will be used for evaluation and verification.

In the introduction of the proposal, the problem solved is identified by a system view. **The term synergy** in this issue for the purposes of the design part means **the connection of two or more measures, which are expected to cooperate with each other**. The evaluation of synergy is then dependent on the effect that each measure brings, especially in terms of time savings, or other aspects and approaches that are addressed in the following paragraphs. **The term preferential measure** means such measure, which serves to improve and streamline the passage of a vehicle by public transport through a given problem spot. **The appropriate synergy of preferential measures** at a given problem spot must meet **several parameters**, namely, such a combination of measures must be as simple as possible to implement with the lowest possible costs. At the same time, the parameters of such synergy must also take into account the minimization of impacts on vehicles in collision directions with the directions of travel of vehicles preferred, eliminate the number of possible collision situations and at the same time maximize the utilization of the capacity of the given local road.

The author of the thesis identifies four types of synergies of preferential measures, which were analysed as the most frequently solved or implemented based on the analysis of both real measures and measures solved in the study materials. These are the following measures: **combination of reserved lane and preference at the intersection with SSZ** (1st synergy); **combination of reserved lane and so-called green wave** (2nd synergy); **combination of bus ride through tram lane with bus stop and pre-signal on SSZ** (3rd synergy); **combination of intermittent reserved lane and preference at the intersection with SSZ** (4th synergy).

Subsequently, the author of the thesis carried out a very detailed **verbal analysis and analysis by a mathematical tool Petri nets** for the above-selected 4 types of synergies between preferential measures. The method used was used to solve individual steps of the given process, which were formed by individual stakeholders. These included in the overall summary the following entities: PT vehicles, ICT vehicles, intersection with SSZ and additional devices (e.g. pre-signal).

These entities and their synergistic behaviour could be characterized on the basis of this method and thus their necessary concurrent behaviour could be displayed. From this mathematical tool applied above, the individual steps result in the behaviour characteristics of the synergy, which can be applied universally (they occur in all 4 cases). These individual steps consist of: approaching the vehicles to the given section, driving the vehicles through the given section/collision directions, entering the vehicles into the next section and the functions of the individual SSZ.

With the help of **force field analysis**, i.e. determining positive forces for the solved cases characterizing their advantages and determining negative forces treating them to their disadvantage, the author evaluated the cases Nos 1 to 4. Within the summary of this evaluation part, recurring statements were determined, which will be used as **evaluation criteria**. These criteria are as follows: **complexity of implementation, utilization of local communication capacity, necessary technical measures, numbers of possible collision situations, numbers of possible concurrent processes** and **waiting times in collision directions**.

For more informative ability of the given comparison of individual solutions, the Saaty method is used, which established three evaluation approaches to the solution by comparing the above mentioned criteria. The resulting approaches are **capacity-security**, **technology-network** and **economical-organizational** approaches. The choice of the approach to the evaluation of the given preferential measure is then up to the choice of the decision-maker, in which way he wants or can approach the given process of selection.

4 Achieved results

Based on the above process of unification of all applied methods (graphic and verbal analysis of synergistic preferential measures, force field analysis, selected criteria and evaluation approaches), 3 steps of calculation are carried out to achieve the appropriate selection of the given synergistic measure. **The first step** is rather a general determination of the number of negative and positive forces, where the difference of the number of positive and negative forces determines the numerical value of the suitability of the given measure, while the measure with the highest value is assumed to be the best. **In the second step**, the selection of the measures is based on the established evaluation criteria and their stated purpose function (trend). Here, the measure with the best result is the one where the given purpose function has been fulfilled for the largest number of criteria. If it happens that the same values of success for more than one measure are fulfilled, it is necessary to move to **the third step** (however, this is not excluded even in the case where only one measure works best). Here, the selection of the measure is made according to Saaty's method of evaluation approaches.

The final selection of the given measure then depends on all partial selections and on the approach of the given decision-maker who plans to implement some of the synergistic preferential measures on a particular problematic section. Based on the research methods used for compiling the evaluation process in the design part of the dissertation, their comparison and evaluation, the author **proposes a methodology for evaluation and selection of synergy between preferential measures**. This methodology consists of a total of 6 consecutive steps.

Step 1 of the given methodology **identifies the problematic section**. This step should include a technical analysis of the given section; determination of the number of junctions affecting traffic intensity and their technical solution; analysis of data from vehicle monitoring information systems; analysis of existing preferential measures, if any, and their existing efficiency and effectiveness; assessment of the necessity to implement a synergy preferential measure.

Step 2 includes an **analysis of the surroundings.** The following actions should be performed here: identification of the significance of collision local roads; determination of traffic intensity of collision directions; identification of the public transport line lines in collision directions and their parameters; identification of measures in previous or subsequent sections.

Step 3 includes **data collection for mathematical assessment**. In this step, the following should be considered: selection of the method for data collection (observation, traffic survey, statistics, CCTV footage, etc.); determination of the traffic intensity of the section (or capacity); identification of the routes of the PT lines; identification of the number of PT lines connections (incl. transport performance); determination of the average time spacing between individual PT connections; determination of the time data.

Step 4 follows the selection of **the approach to the selection of the given preferential synergy measure** and consists of the following steps: quantification of the individual parameters that influence the selection of the given approach; selection of the evaluation approach according to the expected effect from the given synergy of the preferential measure; use of the force field method and the Saaty method for multi-criteria assessment.

In the **5th step** of the given methodology, the selected synergy measure and the chosen approach to its implementation are **verified and validated.** The following actions should be performed here: assessment of whether the proposed synergy measure is in compliance with the applicable legislation; assessment of the following effects in case of the implementation.

In the **6th step**, the final action takes place, namely **the final selection** of the given synergy of preferential measures and thus the whole process of the proposed methodology is completed.

After the proposal of the above-characterized methodology for the selection of the synergy preferential measure, the author further carries out the **verification**. The above-mentioned proposals, including the given methodology, **consider primarily situations** (they are set up as such) **where no preferential measure yet exists.**

However, there may also be a case where the preferential measure has already been implemented. In such a case, the question arises whether the measure sufficiently addresses the given situation. The condition for the most effective analysis of the existing measure is the existence of historical data that were measured before the given implementation, e.g. the change in the average travel time between the two points between which the given measure is located; the calculated BPR function before and after the implementation of the given measure for both PT and ICT vehicles; the average vehicle time spent at a crossroads; the average delay of ICT vehicles in collision directions; or the change in the percentage of PT vehicles travelling on this section on time or with delays together with the value of the change of the given delay.

However, it is also necessary in connection with the above to take into account a broader view of the parallel sections through which ICT transit vehicles can pass after the implementation of the given preferential measure. These vehicles, due to the implementation of the usually restrictive preferential measure for them, previously used this section, for which the users of these transit vehicles are now looking for an alternative. By taking this into account, the absolute values of the data that are used for the calculation of the change of parameters of the section in question can be significantly "damaged" and thus do not provide a sufficiently informative result.

Subsequently, within the verification of the given evaluation draft part of the dissertation, it is possible to approach this issue with consideration **of specific cases**. This is realized using traced data of the development of delays of bus connections within Prague in the time horizon from January to March 2023. With the help of the internet portal mapa.pid.cz. (10) the author identified a total of 166 sections in the territory of the capital city of Prague (out of the total 380 cases monitored), where delays are repeatedly increased within the selected network. The result of this monitoring is a selection of a total of 10 sections, where delays were most frequently increased within the selected monitoring area. The author's proposed methodology is validated on one of these 10 selected sections, namely the interstop section Flora – Orionka. The following is an application of the proposed methodology in the individual steps proposed in this methodology.

In the first step, the problematic section is identified. It is a 420 meters long section in which there are 3 intersections with SSZ. In the whole section, except for the turning lanes, the local road is a single lane, at the first two intersections the buses of the lines in question turn first to the right and then to the left. The section in question has one currently applied preferential measure.

In the second step, the surrounding area is analyzed. The section in question is primarily affected by Vinohradská street. The tram line, which is used by 2 tram lines, runs along this street in a parallel direction with the buses. With the route of the bus lines in question, the tram lines are in collision at the intersection of Vinohradská and Boleslavská streets.

In the third step, the data collection follows for mathematical assessment. The traffic intensity in Jičínská Street in the direction of the section in question is 6 500 vehicles·day^{-1}, in Vinohradská Street it is 6 800 vehicles·day^{-1}, in Boleslavská Street it is 4 100 vehicles·day^{-1}. For the monitored bus lines there are a total of 190 connections·day^{-1}, the average time interval between the connections of the two affected lines is 8.86 minutes. According to the timetable, the travel time of a public transport vehicle in the given section (420 meters) is 3 minutes and the average speed of a public transport vehicle in the given session corresponds to 8.4 km·h^{-1}.

In step 4, the approach to selecting synergy follows. To determine the value of the use of a local road, it is necessary to have data on the capacity of the given local road. To simplify this example of the use of the proposed methodology, values are set where the standard reserved lane reduces capacity by 50% for a two-lane local road, the intermittent reserved lane reduces capacity by 0-50%. In other cases, the capacity utilization of the road is considered at 100%.

In the case of the selection of the 1st and 3rd synergies of preferential measures, it is necessary to implement 2 basic **adaptations** for the given problem spot, in the case of the 2nd synergy, 5 basic adaptations, in the case of the 4th synergy, 4 basic adaptations. In terms of the **number of collision situations** in the case of the 1st, 2nd and 3rd synergies, there is no direct collision situation under the condition of placing directional arrows on the SSZ. In the case of the 4th synergy, there is in this case 1 collision situation, namely the danger to ICT vehicles when turning from a reserved lane into a normal lane, when the signaling starts to prohibit the entry into a reserved lane. In the case of the 1st synergy, 2 **technical measures** are necessary (reserved lane + preference solution on the SSZ), in the case of the 2nd synergy 4 technical measures (reserved lane + preference adjustment on the SSZ at 3 junctions + coordination between them), in the case of the 3rd synergy 2 technical measures (tram strip indication of the possibility of running also for buses + preference solution on the SSZ) and in the case of the 4th synergy 4 technical measures (reserved lane + preference solution on the SSZ + special signal of the reserved lane). In the framework of possible **parallel journeys to maximize the capacity utilization** of the given problematic area, in the case of the 1st, 2nd and 4th synergies there are 3 possible parallel journeys, in the case of the 3rd synergy there are even 4 possible parallel journeys within one phase group at the intersection with the SSZ. The **degree of delay in the collision directions** depends on the maximum length of the signal free in favour of the PT vehicle. The length of the free signal consists of a time span from the detection of a vehicle by public transport with a positive response to it to the passage of the vehicle through the intersection in question.

The 5th step is followed by verification and validation. For the 1st, 2nd and 3rd synergies, both the dedicated lane and the possible guiding of PT vehicles through the tram strip in accordance with Act No. 361/2000 Coll., on road traffic as amended. The intermittent dedicated lane is currently unknown in Czech legislation.

However, a major influence on the surroundings of all 4 possible measures can be assumed on the opposite direction of Vinohradská Street. In this street mentioned in the opposite direction, the daily traffic intensity is the highest within the whole area covered, while the extension of the stop signal in favour of a PT vehicle travelling in the respective preferred direction will take a longer time in this collision direction and will thus have an influence on the length of the queue of waiting vehicles. From the standpoint of the timetable, it can be assumed that there will be at least partial elimination of recurrent delays for vehicles in the preferred direction. On the contrary, it can also be assumed that in certain situations the waiting time of opposite-guided tram vehicles will be extended, for which the delay will increase at that moment. It is therefore necessary to consider from the standpoint of the significance of the participating PT lines whether it is appropriate to give priority to a PT vehicle travelling in the preferred direction as opposed to a preference for a PT vehicle travelling in the opposite direction. Alternatively, it is necessary to consider the sequential sequence of providing signals free on the SSZ for all PT vehicles and to coordinate this sequence appropriately so that the delay of these vehicles occurs in the minimum possible number of cases.

In the last 6th step, the final selection of a specific synergy is made. The best values for the largest number of criteria according to the author's findings or framework-estimated results of individual aspects are achieved by the 3rd synergy measure, i.e. the synergy of guiding buses along the tram strip with corresponding preference at the intersection with the SSZ.

Verification and validation verbally characterized the possibilities of using the defined synergy measures within the real ones with the help of tracking applications of the identified problematic sections. How, the specific synergy measure should be implemented on the given sections, depends on many aspects and approaches. If the given sections and their solutions through synergies of measures are to be approached through a capacity-safety approach, then it is necessary to address the correct horizontal and vertical markings, to analyze which collision directions and whether the wrong understanding of the given measure by all users of the transport area will lead to clashes of individual elements and so on. From the economic-organizational point of view, it is necessary to evaluate what benefits the given measure will provide and what will be its economic return.

If the technological-network aspect is to be taken into account, then it is necessary to address collision directions and impacts on their traffic intensity and increase of travel times, which is a relatively common phenomenon in the case of real problematic sections.

5 Benefits of a dissertation

The author finds the main benefit of the proposals within the given dissertation in the creation of a new methodology for evaluating the synergy effect between preferential measures. The proposed approach should give the prospective decision-maker several questions and answers before the start of the calculation, technical, design and implementation phases. Another substantial benefit for science or practice the author finds in the view of the solution of preferential measures as non-isolated entities, i.e. focusing not only on a specific place on the network, but also taking into account the places involved in the given problem. In many studies it is stated what is the subject of modification or improvement of an existing specific individual problem, but as a rule the impact on the immediate and remote affected surroundings is neglected. In addition to the benefit in terms of the view of the given issue or synergistic reasoning, the author finds the benefit also from the methods used within the design part, which consider ICT vehicles as an “equal partner”. At present, ICT vehicles within the PT network are very often viewed as a disruptive element and a part of the transport space, which is necessary to suppress for the purposes of the preference of PT vehicles. However, the interpretation of the entire design part, including the proposed methodology and evaluation, does not confirm this hypothesis. The direction of work is rather taken away by sufficient analysis of possible impacts on introduced and planned preferential measures and prevention of congestion and related consequences.

In addition to the primary effects of the design part, it is necessary to also determine secondary effects. One of the secondary effects is clearly the saving of time as such. This effect is formed by saving of the time of the PT vehicle, saving of time in this process of the personnel involved, saving of time loss of passengers and at the same time saving of external costs. This above-mentioned saving can be relatively simply quantified in the areas of the cost of the public transport vehicle or the wages of the staff, in the areas of the time loss of the passenger or in the externalities, the calculation of the amount of costs and thus proving the return of investment in a given preferential measure is much more complicated.

Among other possible secondary effects, it is possible to mention in general the improvement of the perception of the quality of public transport from the point of view not only of already existing users/customers, but also from the point of view of potential customers. Thanks to the right and least restrictively implemented preferential measures, this type of customers can monitor the increasing accuracy and reliability of public transport vehicles and, at least in some cases, proceed to the use of public transport instead of the individual one.

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Souhrn/Abstract

Disertační práce na základě podrobné analýzy vědeckého poznání problematiky preferenčních opatření ve veřejné dopravě obsahuje návrh metodiky na správné hodnocení použití synergického preferenčního opatření. Pojmem synergie se rozumí propojení dvou nebo více opatření upřednostnění jízdy vozidla MHD za účelem zvýšení spolehlivosti dodržování jízdního řádu a zvýšení konkurenceschopnosti veřejné dopravy. K návrhu metodiky je použito několik výzkumných metod. Mezi tyto metody patří primárně matematický nástroj Petriho sítě, který je použit pro účel podrobné charakteristiky jednotlivých synergických opatření. Dále jsou použity vybrané metody vícekriteriálního rozhodování a porovnávání sloužící ke stanovení úhlu pohledu na přístup k řešení dané problematiky. Konkrétně je pro tento účel použita metoda analýzy silového pole a Saatyho metoda. Z této metodické části následně vyplývá verifikace a validace návrhu na konkrétní reálné síti a následné celkové vyhodnocení. Hlavním výstupem práce je obecné hodnocení jednotlivých synergií, které má dát rozhodovateli o realizaci daného preferenčního opatření informaci, zda ta konkrétní zamýšlená varianta je adekvátní či ne.

The dissertation, based on a detailed analysis of scientific knowledge of the issue of preferential measures in public transport, contains a proposal for a methodology for the correct evaluation of the use of synergistic preferential measures. The term synergy refers to the connection of two or more measures for prioritizing the travel of public transport vehicles in order to increase the reliability of adherence to the timetable and increase the competitiveness of public transport. Several research methods are used to design the methodology. These methods primarily include the Petri net mathematical tool, which is used for the purpose of detailed characterization of individual synergistic measures. Furthermore, selected methods of multi-criteria decision-making and comparison are used to determine the point of view on the approach to the solution of the given issue. Specifically, the force field analysis method and the Saaty method are used for this purpose. This methodical part subsequently results in the verification and validation of the proposal on a specific real network and subsequent overall evaluation. The main output of the work is a general evaluation of individual synergies, which should give the decision-maker about the implementation of the given preferential measure information whether the specific intended option is adequate or not.