Design and Evaluation of Transportation Systems

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Abstract. The paper presents the state-of-the-art in the fields of designing and evaluating complex transportation systems. Both components (design and evaluation) are presented as separate phases of a combined methodology and its major concepts and rules are described. Three alternative approaches to design/redesign of the transportation systems are presented, including: heuristic (intuitive - oriented) design supported by simulation, optimization (mathematical programming) - based design and hybrid approach based on the application of several combined procedures, including the 4-stage model. In the evaluation phase two major concepts are described, such as: Cost Benefit Analysis (CBA) and its variations and Multiple Criteria Analysis (MCA). The real life case study, focused on the heuristic redesign of the section of the transportation system, construction of alternative transportation solutions and their multiple criteria evaluation, is demonstrated.

Keywords: Transportation system · Methodology of design/redesign and evaluation

1 Introduction

Each transportation system is a set of components, such as: transportation infrastructure (roads, railways, passengers' terminals, stops, transfer points, airports, piers, hubs and depots, distribution centers, parking lots, garages) fleet of vehicles (cars and buses, trains and trams, boats and airplanes), human resources and governing rules (traffic regulations, service standards, management rules) that ensure a coordinated and efficient transfer/movement of people (passengers) and/or goods from their origins to destinations in a certain area [1].

Transportation systems are designed to provide a certain level of transportation service at rational (competitive) costs. This is achieved by/in each transportation system through proper coordination of the movement of people and/or goods with the corresponding movement of vehicles and appropriate utilization of the transportation infrastructure. Transportation systems are intended to offer reliable and timeless delivery of passengers and goods in a cost-effective manner through efficient utilization of transportation assets (vehicles and infrastructure).

Transportation systems can be single-mode or multi-modal transportation solutions [1]. In the first case they operate in one environment (air, rail, road, water) and use one type/mode of vehicles, while in the second case they operate in different environments

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and utilize various types/modes of vehicles. In all transportation systems the transportation infrastructure is usually arranged in the form of a network with link (linear) components such as: roads, railways, airways, waterways and canals as well as node (point-oriented) components (terminals), such as: airports, railway stations, bus stations, warehouses, trucking terminals, refueling depots (docks, stations) and seaports. The vehicles used in transportation systems are [1]: automobiles (private, passenger-cars), bicycles, buses, trains, trams, trucks, boats, ships, barges, airplanes and helicopters. As far as the transported medium is concerned transportation systems can be principally divided into: passengers'-oriented facilities and freight transportation solutions. The former may be public (based on scheduled services) or private. Freight transportation systems are usually private and focused either on Full Truck Loads (FTL) or Less Than Truck Loads (LTL).

Planning and designing of a transportation system is a complex process of conceptualizing, developing and implementing the idea of moving people and/or goods in a certain area between their origins and destinations [1, 2]. It is focused on matching (satisfying) transportation demand by the provision of an appropriate transportation supply in the form of transportation infrastructure and fleet, properly managed by professional crews (people) and coordinated by certain operating rules. Design of a transportation system is a collaborative and team-oriented activity that requires the application of interdisciplinary knowledge and skills, common sense, scientific principles and information technology tools to provide for the safe, efficient, comfortable, and environmentally compatible movement of people and goods. Planning and designing of a transportation system is associated with defining transportation goals and policies for a certain area/region, analyzing and predicting transportation needs, development of various concepts of transportation solutions that satisfy these needs, elaboration of an investment plan and implementation of the proposed concepts/ideas.

Planning and designing of a transportation system has a strategic character [1–3]. Depending on the size and scope of the transportation system its design can be performed at a continental, national, regional and local levels. It is an activity of transportation policy makers, transportation and traffic planners and engineers, designers and developers of transportation infrastructure and/or transportation – logistics consultants. These groups of experts support governmental and private institutions, authorities at different levels (national, regional and local) and transportation systems operators to construct the most rational and desired set of components (described above) that constitute the transportation system. The design of a transportation system usually involves the following stages, described in Sect. 2 [1–3]:

– Analysis of transportation demand.
– Design of a transportation network.
– Traffic assignment.
– Definition of transportation modes (types of vehicles).
– Allocation of crews.

Planning and designing of a transportation system involves five basic categories of measures [1, 2, 4, 5] characterized in Sect. 2:

– Land use design.
– Infrastructure development.
– Implementation of management rules.
– Information provision.
– Design of pricing strategies.

All of them must be integrated and properly coordinated to create an efficient, safe, reliable, sustainable, accessible, affordable and user-friendly transportation system. In many cases the transportation system is not designed from scratch. Its certain components exist in a considered area but their further coordination, development and reshape is required. In such a case instead of designing the whole concept of a transportation system transportation planners focus their efforts on redesign, enhancement and improvement of certain segments or areas of the transportation system. The redesign of the transportation system consists in introducing substantial changes in several of its critical components [6]. It may involve: route changes (extensions, eliminations, reconstructions), relocation of stops/crossdocking points, construction of integrated multi-modal transfer terminals, fleet replacement and reassignment, better coordination of schedules, and many others. As a result different variants – transportation solutions of the transportation system can be constructed/developed. These variants of/alternative solutions for a transportation system are to enhance the standard of transportation service, improve overall efficiency of the transportation system and ensure the improvement of its major performance characteristics. In case of the transportation system redesign, the above mentioned measures (or their selected categories) and the above described stages of transportation system planning are applied to adjust the existing transportation system or its sections to new requirements, expectations and desires. The system is adapted to the new changing environment and both technological, organizational and social – oriented changes are introduced to improve its standard and performance. Both design and redesign of the transportation system requires substantial financial, environmental and social expenditures [1, 7, 8].

2 Design and Redesign of the Transportation System

As presented in Sect. 1 design and/or redesign of a transportation system involves 5 major stages. Their definition, content/scope and major characteristics are shortly presented below [1–3].

Analysis of transportation demand (either for passengers' movements and/or freight movements) in a certain area consists in recognizing current (existing) and future transportation needs [1, 2]. This analysis is based on survey research and personal interviews with prospect users of the transportation system. It results in a definition of the Origin – Destination (O-D) Matrix which is an overall representation of prospect (or existing) traffic flows in a considered area, between certain traffic zones and their central points, being the approximated representation of traffic origins and destinations.

Design of a transportation network is focused on [1–3]: definition of nodes, such as: road and railway crossroads, terminals, depots and hubs, warehouses/distribution centers, harbors, border crossings, transfer points and design of arcs corresponding to specific segments or legs of transportation connections/routes. In this phase single-mode and/or multiple modes transportation routes are designed. In this phase certain analytical tools and computer-based procedures (algorithms) usually support transportation planners in route/network design.

Traffic assignment consists in allocating traffic flows (passengers and freight) to the pre-defined transportation network. In this phase, based on the application of different network assignment algorithms [2] concrete traffic flows are allocated to specific segments/arcs of the transportation network. As a consequence the capacity utilization of specific segments of the network can be computed and visualized, and certain adjustments can be introduced. In the traffic assignment phase transportation planners search for a network equilibrium in an iterative procedure.

Definition of transportation modes (types of vehicles) refers to the analysis of different modal options of moving people and/or freight in a transportation system [1, 2]. Single mode or multi-modal solutions can be considered in this phase. Transportation planners recognize and assess different transportation modes/types of vehicles that are to serve the considered transportation network. After having been selected the transportation modes/types of vehicles are assigned to service the traffic flows and carry out concrete transportation jobs. In this phase different compositions of heterogeneous, multi-modal fleet can be considered, including: private passenger vehicles, commercial vehicles, trains, trams, vessels and/or planes. In public transportation systems this phase results in the definition of operating frequencies and headways on specific transportation routes and allows for generating the corresponding timetables. Different mode evaluation and fleet composition computational methods can be applied in this phase.

Allocation of crews (drivers, stewards, etc.) **to vehicles**; definition and scheduling of their tasks [1, 2]. This phase refers to commercial and public vehicles and is usually defined as rostering. It is not performed in case of individual, passengers' vehicles owned by private persons. In this phase various crew scheduling algorithms can be applied.

As presented by Garrett [1], Hansher and Button [2], Anderson et al. [4] and Hills et al. [5], five basic categories of measures must be used and coordinated to design an efficient, comfortable and convenient transportation system (see Sect. 1). These measures, often called necessary components of the transportation system development are characterized below. They must be integrated and properly coordinated to create an efficient, safe, reliable, sustainable, accessible, affordable and user-friendly transportation system.

First of them is **Land Use Design**, i.e.: an activity, process or professional branch encompassing various disciplines which seek to order and regulate land use in an efficient, sustainable and ethical way, thus preventing land-use conflicts. Based on the United Nations definition [9] Land Use Design means the scientific, aesthetic, and orderly disposition of land, resources, facilities and services with a view to securing the physical, economic and social efficiency, health and well-being of local (urban and rural) communities. The goal of Land Use Design is the welfare of people and their communities by creating convenient, equitable, healthful, efficient, and attractive environments for present and future generations. The land use design is required to properly integrate the transportation infrastructure with its surrounding environment and define its desired location. A good land use plan allows for provision of a transportation system with high accessibility, good connectivity and operating efficiency, environmental sustainability and high level of life comfort for local community. There is a growing interest in research focused on land use and transport planning integration. Many researchers prove [1, 2] that a strong interaction between land use and transport planning exist. They develop new, modern, advanced paradigms of combined land use and transport design [1, 2].

The next, critical measure of transportation system design is **Infrastructure Development** [1]. This phase is investment intensive and requires high level of expenditures and organizational effort. Transportation infrastructure is usually arranged in the form of a network with link (linear) components such as: roads, railways, airways, waterways and canals as well as node (point-oriented) components (terminals), such as: airports, railway stations, bus stations, warehouses, trucking terminals, refueling depots (docks, stations) and seaports. The transportation infrastructure development can be financed by both private and public institutions, which in some instances may establish a public-private partnership. The development of a transportation infrastructure is in many cases organized in the form of transportation projects, such as: extension of the metro line in the public transportation system; development of the segment of the national highway/motorway; construction of the regional distribution center; development of a roundabout or flyover in an urban transportation system; building a new sea terminal. Many computer based methods [1, 10] have been developed to support the transportation infrastructure development.

Another important component of transportation system design is **Implementation of Management Rules** [1, 3]. These rules control the flow of people (passengers) and goods in the transportation system. They are implemented in a hierarchical manner, from the top to the bottom and refer to strategic (e.g.: setting the location of the transportation depots, defining transportation modes), tactical (e.g.: elaborating a fleet replacement policy; designing fixed routes) and operational issues (daily dispatching of vehicles; rerouting crews and vehicles in case of unexpected events). In each transportation system, regardless the transportation mode, they cover such areas as: traffic regulation and control, marketing issues - customer service rules and standards (definition of service portfolio, establishing the quality standards), safety and security issues, information and communication principles (information flow associated with the traffic flow), technological standards, fixed assets management rules (including: fleet management policies and infrastructure management policies), human resource management rules (including selection of crew members, assignment and scheduling of employees to transportation tasks), environmental policies, financial policies (e.g. profitability; costs and incomes; payment policies; cash flows).

Information Provision is a stage focused on implementing proper communication standards and tools that provide information for customers in the transportation system [1, 3]. The current level of technological development allows for providing information in different ways, including: regular printed promotional materials (leaflets, brochures, posters), electronic boards with a variable informational content, web pages and portals, mobile applications and others. In general, information provision in transportation systems facilitates customers to use the transportation system, access the transportation service and find the most desired transportation solution corresponding to the customer's objectives. Information provision systems can be associated with the transportation infrastructure (fixed location), including information boards located at the terminals (airports, railway stations, bus terminals) and/or placed along the roads and highways. They can also have a mobile character as on-board tools the vehicles are equipped in. In the passengers' transportation systems the current standard of information provision are technologically advanced navigation systems and electronic passengers' trip planners [1, 3]. In the freight transportation systems the most common solutions are web portals [1]. The typical content of information provided in transportation systems includes: transportation connections (corridors) between pre-defined origins and destinations, operating dates and hours, including: departure and arrival times (frequencies), space/seats/capacity availability, transferring points/terminals, travel distance and time, prices/tariffs for transportation services, extra/additional services (e.g. insurance, cargo handling, transfer of additional equipment), travel conditions (e.g. weather, road works and/or accidents, traffic congestion), travel delays and/or diversions.

Design of pricing strategies is a final stage of transportation system development [1, 3]. It consists in defining prices for transportation and supplementary services offered by transportation systems and fees for using transportation infrastructure (terminals, roads, parking lots, etc.). In passenger public transportation prices are usually publicly announced and they usually depend on the distance to travel and the time advancement the travel is planned with. It also depends on the standard of traveling (1st, 2nd class) and the speed of movement (regular movements vs. express movements). In freight transportation the most commonly used tariffs are based on vehicle – kilometer prices or tone – kilometer prices. The first pricing strategy refers primarily to Full-Truck-Loads (FTL), while the second one is usually applied for Less-Than-Truckloads (LTL). In many transportation systems the following components of pricing strategies are implemented [1, 3]: congestion pricing (different fees for travelling in peak hours or peak seasons); parking/terminal charges; road tolls (depending on the standard); emissions fees; fuel taxation.

Design and redesign of a transportation system or its components can be performed in different manners [1, 3]. Based on the works of various authors [1–3, 11–15] three major approaches to design/redesign of the transportation system, can be distinguished. These include:

- heuristic (intuitive - oriented) design supported by simulation,
- optimization (mathematical programming) - based design,
- hybrid approach based on the application of several combined procedures, including the 4-stage model.

The first approach is based on the application of intuition, common sense and expert knowledge of designers (traffic engineers, experts – analysts, consultants, transportation managers, researchers) who use their experience and expertise to develop specific transportation solutions. This creative phase of transportation system (re-) design is combined with computational testing of the proposed concepts in the simulation software. The experts usually design several alternative options and compare them based on the results of simulation. The behavior of traffic flows is examined and the impact of concrete transportation solutions on the operations of the whole transportation system is investigated. In many cases this phase is not an individual work but requires a common, group effort. In this approach different methods of generating solutions can be applied, including: brainstorming, concurrent design of transportation solutions, step-wise design based on discussions and exchange of ideas between experts/designers. Usually, the analysis starts with a comprehensive diagnosis and evaluation of the existing transportation system and its corresponding transportation solutions. The status quo (current condition of the transportation system) is the benchmark for the design of new options. In many cases **SWOT ANALYSIS** of the current transportation system is developed and its strengths and weaknesses, opportunities and threats are defined.

The heuristic design/redesign of the transportation system may include such elements as: reconfiguration of the transportation network with elimination of certain routes/connections and extension of others, changes in the distribution of hubs/depots, terminals and stops, redefinition of the modal split and fleet composition (introduction of new transportation modes and reduction of others), infrastructural investments (road and tramway construction, introduction of parking lots – Park & Ride system, closing and opening new depots), changes based on legal regulations (e.g. speed limits), changes in pricing policies, changes in frequencies/headways of transportation means resulting in the redesign of the timetables. The overall objective of introducing the above mentioned changes is to enhance the overall efficiency and quality of the transportation systems.

As described above **in the testing/computational phase** the heuristically developed solutions **are simulated**. Simulation is a popular and effective operations research technique used to analyse a wide range of dynamically changing systems [16]. Researchers define the simulation as a controlled statistical sampling technique [17]. The essence of simulation is to carry out a series of computational experiments, using various input data introduced into a simulation model, that describes the operations of the real system and to generate a set of output data that characterizes and assess the considered system. Simulation allows us to check, monitor and evaluate the behaviour of the real system under different realistic conditions, in an artificial computer – based lab environment. There are many generic/universal simulation approaches, including [17]: Monte Carlo techniques, Markov Chains models or queuing theory - based methods. Several software packages, including: Arena, Extend Sim, Aris, Flexim and many others have been developed to carry out the above described analysis. The current state of the art simulation packages have graphical, object-oriented character and allow for simulating both continuous and discrete events.

As far as transportation systems are concerned a specialized simulation technique, called traffic simulation, can be applied. Based on the Highway Capacity Manual 2000 [18], traffic simulation is “a computer program that uses mathematical models to conduct experiments with traffic events on a transportation facility or system over extended periods of time”. It can describe the entire transportation system (e.g. urban, regional or national) or its selected part or component, such as: several intersections, a motorway segment and/or a roundabout. The simulation model consists of two mutually interrelated components, i.e.: information on demand that characterizes the needs for movement (passengers, freight) and information on supply that describes transportation network, traffic zones (e.g. residential and business areas) and vehicles (public and private). Depending on their accuracy and scope the simulation models can be divided into [19]:

- Micro-simulation models that describe traffic at high level of detail and distinguish single, separate units in the traffic flow (different types of vehicles, pedestrians) and mutual interactions between them. They are usually applied for the detailed analysis of limited segments of transportations systems. The most popular micro-simulation tools are Vissim, Aimsun, Corsim.
- Meso-simulation models that describe traffic at an intermediate level of detail and distinguished particular units in the traffic flow but do not take into account interactions between them. They are less precise and usually applied for the components of transportation systems covering larger areas. The most popular meso-simulation tools are Netflo, Dynasmart, Transims.
- Macro-simulation models that describe traffic at a high level of aggregation, as a uniform traffic flow. They are based on deterministic relationships between the quantities characterizing the traffic flow such as: volume, speed and density. Macroscopic simulation has been developed to model an entire transportation network and/or system. The most popular programs that simulate the movement in the macro scale are Visum, Emme, Transcad.

The second design method, called **optimization (mathematical programming)-based design** consists in formulating the transportation system design problem in terms of mathematical programming. This approach is focused on constructing the original mathematical model of the decision situation and then solving the considered decision problem with the appropriate computer-based tools (commercial solvers, self-developed academic software) being the computer-implementation of certain quantitative, optimization methods, originating from the field of Operations Research (OR). In Operations Research - OR [17] **optimization** (alternatively: **mathematical optimization** or **mathematical programming**) is a quantitatively – oriented process focused on selecting the best (most desirable) solution/variant/action from a set of available/feasible solutions/variants/actions with regard to (a) certain measure(s) of merit (criterion/criteria). In general, optimization leads to solving an optimization (mathematical programming) problem that can be stated as follows [17]:

Given: a function f: $A \to \mathbf{R}$ from a set A to the real numbers
Sought: an element x_0 in A such that $f(x_0) \leq f(x)$ for all x in A ("minimization") or such that $f(x_0) \geq f(x)$ for all x in A ("maximization").

Typically, A is a subset of the Euclidean space $\mathbf{R}^n$, usually defined by a set of constraints, i.e.: equalities or inequalities that the elements of A have to satisfy. The domain A of f is called the *search space* or the *choice set*, while the elements of A are called candidate solutions or *feasible solutions*. The function f is denominated by different terms, including: an **objective function**, a **utility function** or a **fitness function** [3]. The optimization process leads to the selection of an optimal solution, that is such a value of x in A that minimizes (or maximizes) the objective function f. As described above the optimal solution is generated with the application of different computational procedures (algorithms) [17].

In this approach a transportation system design problem can be also formulated as a **multiple criteria (objective) optimization problem**. In such a case the designers also formulate the objective function $\boldsymbol{F(x)} = \boldsymbol{f_j}(\mathbf{x})$, composed of $\boldsymbol{j = 1, 2, \ldots, J}$ criteria and a set of constraints that define the space of feasible solutions $\boldsymbol{x} - \boldsymbol{A}$. The designers are searching for such a solution $\boldsymbol{x}$ in the decision space $\boldsymbol{A}$ which image in the objective (criteria) space z^{x} generates the most desired values of the objective function $\boldsymbol{F(x)} = \boldsymbol{f_j}(\mathbf{x})$ [20, 21]. The image of a solution $\boldsymbol{x}$ in the objective space is a point $\mathbf{z}^{\mathbf{x}} = \left[z_1^{\mathbf{x}}, \ldots, z_J^{\mathbf{x}}\right] = \mathbf{f}(\mathbf{x})$, such that $z_j^{\mathbf{x}} = \boldsymbol{f_j}(\mathbf{x})$, for j = 1, .., J. Important notions in this context are: dominance relation and Pareto-optimal (efficient) solution that refer to optimality in a multiple objective sense. Point $\mathbf{z}^1$ *dominates* $\mathbf{z}^2$, $\mathbf{z}^1 \succ \mathbf{z}^2$, if $\forall j\, z_j^1 \geq z_j^2$ and $z_j^1 > z_j^2$ for at least one j. Solution $\mathbf{x}^1$ dominates $\mathbf{x}^2$ if the image of $\mathbf{x}^1$ dominates the image of $\mathbf{x}^2$ in the objective space. A solution $\mathbf{x} \in A$ is Pareto-optimal (efficient) if there is no $\mathbf{x}' \in A$ that dominates $\mathbf{x}$. Point being an image of a Pareto-optimal solution in the objective space is called non-dominated. The set *PO* of all Pareto-optimal solutions is called the Pareto-optimal set. The image *ND* of the Pareto-optimal set in the objective space is called the non-dominated set or Pareto front [20, 21].

In the optimization based design the designers must have advanced analytical skills and experience in mathematical modeling and OR-oriented approach to solving complex decision situations. They usually search for an optimal structure of the transportation network (nodes, links), the most efficient assignment of the traffic flows (vehicles, freight, passengers) to the network, the best vehicle routes (in terms of costs, travel times, safety), the most desired vehicles and crew schedules (timetables) and/or the optimal solution for a concrete transportation project (location, design structure- and/or material-wise).

The third design method, denominated by **hybrid approach** is a combination of the two previously described ideas. It encompasses both heuristic design, application of simulation techniques and optimization methods. This approach has an interactive and iterative character in which conceptual phases alternate with the computational phases. This approach is well rooted in the transportation research through the concept of a so called, **Four-Stage Model** [2]. The Four-Stage Model (FSM) is a primary tool for the transportation system analysis, assessment of its performance and prediction of its future behavior. It is assumed in the FSM that transportation system $\boldsymbol{T}$ and activity system $\boldsymbol{A}$ serve as exogenous inputs to performance procedures $\boldsymbol{P}$ and demand procedures $\boldsymbol{D}$, respectively. Transportation system T is defined as all elements of transportation infrastructure and services, while activity system $\boldsymbol{A}$ corresponds to spatial distribution of land uses and the demographic and economic activities associated with them. The overall objective of the FSM is the equilibration of the transportation system, i.e. the determination of the equilibrium flows in the considered transportation network. In some cases location procedures $\boldsymbol{L}$ and supply analysis methods $\boldsymbol{S}$ are required to support the efficient application of the FSM. Usually, they are combined with FSM but not formally integrated with the basic equilibration algorithm.

As its name indicates the FSM is composed of the following four phases [2]:

- Trip generation.
- Trip distribution.

- Modal split.
- Traffic assignment.

In each of these phases different analytical tools and computational procedures are applied to find a proper and most desired solution. The objective of the **first stage** is to define the magnitude of total daily movement (passengers and/or freight) in the model transportation system at the elementary unit (household, business) and zonal levels (Traffic Analysis Zones – TAZ-s) for various trip purposes. In this phase different, multiple factors regression models [2] are applied. Separate generation paradigms are applied for trip production and attraction. In the **second stage** the trip/movement ends (from trip generation) are recombined into trips either as production – attraction pairs or origin – destination pairs. In this phase various destination choice models and algorithms are applied. The most commonly used technique is the gravity model, equivalent to the Law of Gravitation. As a result a movement/trip matrix or O-D matrix is generated. The **third stage** consists in defining the **modal split**, i.e. the share of each transportation mode in all movements/trips. In this phase various assignment algorithms based on complex objective functions that include many human characteristics and behavioral factors are applied. These assignment or choice – based methods take into consideration choice probabilities of individual trip/movement – makers. The **last stage** concerns the **traffic assignment** and is strictly associated with the **route choice** by concrete trip/movement makers. In this phase modal O-D movement/trip matrices are loaded on the modal networks. As a result the paths chosen by trip/movement makers from their origins to the destinations are specified and the level of traffic flows (vehicles, passengers, freight) assigned to concrete sections of the transportation network (streets, public transportation routes) are determined. The Traffic Assignment is carried out with the application of advanced: Non-Deterministic Shortest Paths Search Algorithms, Multiple-Paths Assignment Procedures (Exponential Probability Function), Static and Dynamic Assignment Procedures [2].

3 Evaluation of Transportation Systems

Evaluation of transportation systems has been a widely discussed topic for many years [11, 12, 14, 22, 23]. Many authors have developed different methodologies of evaluating transportation systems, processes and projects, including: cost-benefit analysis (CBA) [24], cost-effectiveness analysis (CEA), regional economic impact study (REIS), environmental impact assessment (EIA) and Multiple Criteria Analysis (MCA) [11, 23].

The author of this chapter would risk a statement that two of the above mentioned methodologies are most popular for transportation applications and most frequently used for the evaluation of transportation systems. These are: Cost – Benefit Analysis and Multiple Criteria Analysis, often called Multiple Criteria Decision Making/Aiding.

3.1 The Methodology of Cost – Benefit Analysis

Cost – Benefit Analysis (CBA) [24] is a universal methodology of assessing socio – economic benefits of a certain solution, project and/or undertaking. It is commonly used in transportation systems to investigate whether a certain transportation concept generates overall benefits and balances the costs associated with its implementation. The major principle of CBA is the maximization of the global social welfare of the society. It is based on a core concept of a traditional economy, pointing out that a "rational consumer/customer" always behaves and acts to increase his/her overall welfare. It is assumed that he/she knows what are his/her individual needs and expectations and how concrete solutions/concepts and projects can contribute to their satisfaction, resulting in the increase of his/her individual welfare. It is further indicated that individual welfares can be added and in such a way aggregated to the overall welfare of the society.

The CBA measures if a concrete (transportation) project changes and enhances the above described welfare, i.e. increases the overall socio-economic benefits generated by a concrete (transportation) implementation. CBA recognizes and computes all positive (benefit-oriented) and negative (cost-oriented) effects of a considered concept/project/solution. It expresses all benefits and costs in financial terms and transforms all its outputs (positive and negative) into monetary units and compares them. Thus, in CBA the interests of different stakeholders, their preferences and benefits as well as shortcomings/weaknesses and costs of a certain project or investment are combined (aggregated) and expressed in monetary units. In the CBA three measures are usually computed to assess the overall profitability/utility of the considered project (investment). These include: Economic Net Present Value (ENPV), Economic Internal Rate of Return (EIRR) and Benefit-Cost Ratio (BCR) [24]. In all the above mentioned characteristics the discounted cash flows of benefits (positive flows) and costs (negative flows) are combined and compared. Through the discount mechanism the time value of money is taken into account.

The **Economic Net Present Value (ENPV)** [24] is a measurement expressed in monetary units of the profitability of a(an) project (undertaking) that is calculated by subtracting the present values (PVs) of discounted cash outflows (total costs, including initial investment cost) from the present values (PVs) of discounted cash inflows (benefits) over a period of time. A positive ENPV results in a profit, while a negative NPV results in a loss of a certain (transportation) solution/project. The ENPV measures the excess/surplus or shortfall/shortage of cash flows, in present value terms, above the cost of funds. In practical terms transportation investments/projects with the highest positive ENPVs are selected by the decision makers (DMs) for pursuing and real world implementation.

The Economic Internal Rate of Return (EIRR) [24], also called the discounted cash flow rate of return (DCFROR), on an investment or project is the "annualized effective compounded return rate" or simply rate of return that sets the Economic Net Present Value (ENPV) of all discounted cash flows (both positive and negative) from the investment/project equal to zero. Thus, it is the discount rate at which the total Economic Net Present Value of future positive cash flows (benefits) is equal to all negative cash flows (costs), including the initial investment. EIRR, expressed percentage-wise [%] is an indicator of the profitability, efficiency, quality, or yield of an investment. Based on the CBA principles DMs compare EIRRs of various financial activities/capital projects or investments, including the transportation ones, in terms of their rates of return and select those that generate the highest (maximum) values of EIRRs. The term *internal* refers to the fact that its calculation does not involve external factors, such as inflation or the cost of capital.

The Benefit-Cost Ratio (BCR) [24], sometimes called Profitability Index Rate (PIR) is an indicator that attempts to summarize the overall value for money of a (transportation) project or proposal. As its name indicates the BCR is the ratio of the discounted benefits (positive cash flows) of a project/undertaking, investment or proposal, expressed in monetary terms, relative to its discounted costs (negative cash flows), also expressed in monetary terms. Thus, the **benefit cost ratio (BCR)** is a dimensionless measure that takes into account the amount of monetary gain realized by performing a (transportation) project versus the amount it costs to execute it. General rule of thumb is that if the benefit is higher than the cost the project is a good investment. The higher the BCR the better. The BCRs are used extensively in transportation to carry out the cost-benefit appraisals of transportation projects over their service lives. In practical terms, when the DM copes with the budgetary constraints of a certain (transportation) project, the net BCR is computed as a ratio of ENPV (future net benefits) to total expenditure falling within the constraint, including initial investment and regular operating costs.

3.2 The Methodology of Multiple Criteria Analysis

Multiple Criteria Analysis (MCA), often called Multiple Criteria Decision Making/Aiding (MCDM/A) [20, 21, 25] is a field of study and a coherent methodology, originating from Operations Research (OR) [17] which aims at giving the Decision Maker (DM) some tools/methods in order to enable him/her to advance in solving complex decision problems in which several – often contradictory – points of view must be taken into account [21, 25]. MCA can help the Decision Makers (DMs) in analyzing and assessing transportation systems, solving complex transportation decision problems that arise in those systems, in evaluating innovative transportation projects, concepts and solutions intended to up-grade and enhance transportation systems, in analyzing trade-offs and balancing conflicting interests associated with the operations of certain transportation processes and systems, in searching for the most desired, compromise decisions for the users and stakeholders of transportation systems.

MCA/MCDM/A focuses its efforts on assisting the DM in solving multiple criteria decision problems, i.e. situations in which, having defined a set of actions/variants/solutions $\boldsymbol{A}$ and a consistent family of criteria $\boldsymbol{F}$ the DM tends to [21, 25]:

- determine the best subset of actions/variants/solutions in $\boldsymbol{A}$ according to $\boldsymbol{F}$;
- divide $\boldsymbol{A}$ into subsets representing specific classes of actions/variants/solutions, according to concrete classification rules;
- rank actions/variants/solutions in $\boldsymbol{A}$ from the best to the worst, according to $\boldsymbol{F}$.

As presented above there are two major components of each multiple criteria decision problem, i.e.: a set of actions/variants/solutions ***A*** and a consistent family of criteria ***F***. The set of ***A*** can be defined directly in the form of a complete list or indirectly in the form of certain rules and formulas that determine feasible actions/variants/solutions, e.g. in the form of constraints [20, 21, 25]. The consistent family of criteria ***F*** should be characterized by the following features [21, 25]:

- it should provide a comprehensive and complete evaluation of ***A***,
- each criterion in ***F*** should have a specific direction of preferences (minimized – min or maximized – max) to adequately indicate the global preferences and expectations of the DM,
- each criterion in ***F*** should not be redundant with other criteria in ***F***; the domain of each criterion in ***F*** should be disjoint with the domains of other criteria.

There is a variety of computerized, MCDM/A methods that help the DMs to solve the above described multiple criteria decision problems. These methods can be classified according to several criteria, including [21, 25]:

I. the overall objective of the decision method correlated with the category of the decision problem,
II. the moment of the definition of the DM's preferences,
III. the manner of the preference aggregation.

Based on the above mentioned classification criteria one can distinguish the following categories of MCDM/A methods, respectively [21, 25]:

- **I Criterion**
  - multiple criteria choice (optimization) methods (e.g. LBS, Steuer Procedure, Topsis),
  - multiple criteria sorting (classification) methods (e.g. Electre Tri, 4eMka),
  - multiple criteria ranking methods (e.g. Electre III/IV, AHP).
- **II Criterion**
  - methods with an a'priori defined preferences (e.g. Electre methods, Promethee I and II, UTA, Mappac, Oreste),
  - methods with an a'posteriori defined preferences (e.g. PSA method),
  - interactive methods (e.g. GDF, SWT, Steuer Procedure, STEM, VIG, LBS).
- **III Criterion**
  - the methods of American inspiration, based on the utility function [8] (e.g. AHP, UTA),
  - the methods of the European/French origin, based on the outranking relation [26] (e.g. Electre methods, Promethee I and II).

The MCA/MCDM/A methodology [21, 25] clearly identifies major participants of the decision making/aiding process, such as: the decision maker (DM), the analyst and the interveners (stakeholders) and describes their roles in this process. As opposed to classical OR techniques MCA/MCDM/A methods do not yield optimal solutions, because in reality the solutions that would simultaneously optimize several, contradictory criteria do not exist. Instead of that the methodology of MCA/MCDM/A searches for the compromise solution that satisfies the interests of the above mentioned parties, analyzes the trade-offs between the considered criteria and takes into account specific preferences and expectations of the DMs and stakeholders. In the MCA/MCDM/A methodology different criteria can be used to evaluate transportation systems or solutions, including: investment costs/profitability, safety and security, environmental friendliness, reliability (timeliness; schedule fulfillment), travel/delivery time, accessibility and others. As opposed to CBA in MCA these criteria do not have to be transformed to the monetary units and aggregated.

3.3 Basic Features of Selected MCDM/A Methods

In the presented analysis two most popular MCDM/A methods, i.e. ELECTRE III/IV and AHP, have been applied. The first one, based on the binary outranking relation [26] belongs to a European (French) school of MCDM/A, while the second one, based on the multi-attribute utility theory [27] is an important representative of an American school of MCDM/A. Both methods are classified as multiple criteria ranking methods; thus they rank the variants form the best to the worst.

ELECTRE III/IV method belongs to a family of ELECTRE methods, proposed by B. Roy [26]. In this method, the basic set of data is composed of the following elements: a finite set of variants, a family of criteria, and the preferential information submitted by the DM. The preferential information is defined in the form of criteria weights – w_j and the indifference – q_j, preference – p_j and veto – v_j thresholds [21, 25, 26].

The outranking relation in the Electre III/IV method [26] is built on the basis of the so called concordance and discordance tests. In the concordance test a concordance matrix, composed of the global concordance indicators $C(a, b)$, is constructed. The matrix presents the pairwise relationship between alternatives and indicator $C(a, b)$ expresses the extent to which the scores of a and b on all criteria are in concordance with the proposition a outranks b. The values of $C(a, b)$ depend on the values of concordance indexes for each criterion $C_j(a, b)$ and weights of criteria w_j. The concordance index $C_j(a, b)$ indicates to what extent the statement "a is at least as good as b" on criterion j is satisfied. The value of this index is between 0 and 1 and it is calculated on the basis of thresholds $q_j[f_j(a)]$ and $p_j[f_j(a)]$ for each criterion function $f_j(a)$. Afterwards, taking into account the relative importance (weights) w_j of each criterion index $C(a, b)$ is computed. In the next stage – called the discordance test, a discordance index $D_j(a, b)$ for each criterion j is calculated. The notion of discordance brings into play the veto threshold $v_j[f_j(a)]$ on specific criteria. The underlying idea of the veto threshold is as follows: even if the statement "a outranks b" is born out by all criteria except one, it is possible that the difference $f_j(b) - f_j(a)$ on the discordant criterion is so great that it becomes impossible not to take it into account.

When the global concordance indicator and the discordance indexes on specific criteria have been established, the Electre III/IV method constructs an outranking relation S for each pair of alternatives (a, b). The outranking relation indicates the extent to which "a outranks b" overall. This relation is expressed by the degree of credibility $d(a, b)$, which is equivalent to the global concordance indicator $C(a, b)$ weakened by the discordance indexes $D_j(a, b)$. The values of $d(a, b)$ are from the interval [0, 1]. Credibility $d(a, b) = 1$ if and only if the assertion aSb ("a outranks b") is well founded, ***d(a, b)*** = 0 if there is no argument in favor of ***a S b*** (not ***a S b*** – "***a*** does not outranks ***b***"). The definition of ***d(a, b)*** results in the construction of the credibility matrix based on which the method establishes two preliminary rankings (complete pre-orders) using a classification algorithm (distillation procedure). During this procedure one can obtain a descending and an ascending pre-order. In the descending distillation the ranking process starts from the selection of the best variant, which is placed at the top of the ranking. In the next steps, subsequent best variants are being selected from the set of the remaining variants and placed on the subsequent highest positions of the ranking, until all variants are ranked. In the ascending distillation the variants are ranked in the inverse order. The process starts from the selection of the worst variant and placing it at the bottom of the ranking. In the next steps, subsequent worst variants are being selected from the set of the remaining variants and placed on the subsequent lowest positions of the ranking, until all variants are ranked The final results can be presented either in the form of the ranking matrix or in the form of the outranking graph. They are the results of the intersection of the above mentioned complete pre-orders. The ranking matrix and the outranking graph define the pairwise relationships between variants. The following situations can be distinguished there: indifference (I), preference (P), lack of preference (P$\sim$) and incomparability (R).

The AHP (Analytic Hierarchy Process) method is a multiple objective ranking procedure, proposed by [28], focused on the hierarchical analysis of the decision problem. Through the definition of the overall objective, evaluation criteria, sub-criteria and variants the method constructs the hierarchy of the decision problem. On each level of the hierarchy, based on the pair-wise comparisons of criteria, sub-criteria and variants, the DM's preferential information is defined in the form of relative weights $\boldsymbol{w_r}$ [28]. Each weight represents relative strength of the compared element against another and it is expressed as a number from 1 to 9. All weights have a compensatory character, i.e.: the value characterizing the less important element (1/2, 1/5, 1/9) is the inverse of the value characterizing the more important element in the compared pair (2, 5, 9).

The algorithm of the AHP method focuses on finding a solution for a, so called, **eigenvalue problem** [28] on each level of the hierarchy. As a result a set of vectors containing normalized, absolute values of weights $\boldsymbol{w_a}$ for criteria, sub-criteria and variants is generated. The sum of the elements of the vector is 1 (100%). The absolute weights $\boldsymbol{w_a}$ are aggregated by an additive utility function. The utility of each variant $\boldsymbol{i}$ – $\boldsymbol{U_i}$ is calculated as a sum of products of absolute weights $\boldsymbol{w_a}$ on the path in the hierarchy tree (from the overall goal, through criteria and sub-criteria) the variant is associated with. The utility $\boldsymbol{U_i}$ represents the contribution of variant $\boldsymbol{i}$ in reaching an overall goal and constitutes its aggregated evaluation that defines its position in the final ranking.

The important element of the AHP algorithm is the investigation of the consistency level of matrices of relative weights $\boldsymbol{w_r}$ on each level of hierarchy. Through the calculation of a, so called, consistency index ***CI*** one can measure how consistent is the preferential information given by the DM. If the value of ***CI*** is close to 0 the preferential information given by the DM is considered to be almost perfect. The acceptable level of ***CI*** is below 0.1.

4 Real World Case Study. Design and Multiple Criteria Evaluation of a Section of a Transportation System

4.1 Major Features of the Considered Situation/Problem

The considered situation refers to the redesign of a major traffic artery in the medium-sized urban transportation system in Poznań, Poland. The considered street, called Grunwaldzka is 6.6 km long and connects the city center with the south-western boundaries of the Poznań metropolitan area. It runs from the Poznań major central roundabout Kaponiera in the south-western direction towards the suburbian residential area, called Kwiatowe (Flower) District. Grunwaldzka Street is the main access road to the Poznań City Football Stadium (Grunwald District) and the Local Municipal Cemetery (Junikowo). Both road and tramway traffic goes along this street.

The street redesign is carried out within the Poznań Transportation Infrastructure Development Plan associated with the Poznań city preparation for the European Football Championships – EURO 2012. Poznań as the EURO 2012 host city was expected to improve traffic connection between the football stadium and both suburbs and city center. The major objective of the considered redesign is the street capacity extension, resulting in the improvement of the comfort of travel for passengers and the reduction of the travel time. The major effort of the redesign is focused on the redevelopment of the road and tramway railroad at Grunwaldzka street on its specific segment between Smoluchowskiego and Malwowa streets (1.7 km long) and intensive reconstruction of the existing intersection Grunwaldzka – Smoluchowskiego, which is located in the area adjacent to the football stadium (see Fig. 1).

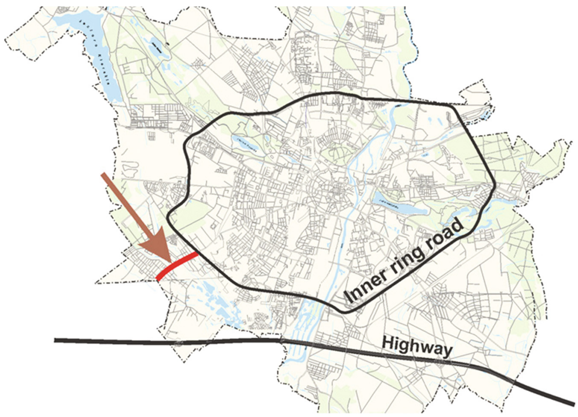

Fig. 1. The location of the considered redesign project (red color – segment of Grunwaldzka street) in the Poznań urban transportation system

As presented in Fig. 1 the considered segment of Grunwaldzka street connects the suburbs with the city inner ring road. The construction of this ring road is not complete. Its certain sections are already in operations, while others are still under development.

In the considered area the ring road goes along Smoluchowskiego street and crosses Grunwaldzka street at the critical intersection for the considered project, i.e. Grunwaldzka – Smoluchowskiego intersection. As presented in Fig. 1 the segment of Grunwaldzka street under consideration as located quite close to the National Highway A2 going in the East–West direction. Thus, the street redesign has also an impact on improving the highway accessibility for the local traffic.

The problem at stake consists in designing/developing and implementing the most desirable transportation solution for the considered segment of Grunwaldzka street. The project has been launched by municipal authorities acting together with the representatives of the UEFA (Union of European Football Associations). In the considered case the decision maker (DM) is the City Board that makes final decision concerning the selection and implementation of the concrete transportation solution at Grunwaldzka street. The DM wants to receive and assess several alternative concepts and evaluate them from different perspectives, including: economic, safety-oriented, technical, environmental and social. In the undertaken analysis the DM wants to take into consideration their own preferences as well as the interests of various stakeholders, including: local residents/travelling passengers, public transportation system operator, representatives of UEFA. The City Board (DM) wants to review several alternative transportation solutions and find the one that best fits theirs and stakeholders' expectations. To receive an independent, expert opinion they hire the analyst (author of the paper) to carry out the intended analysis. His task is to design and experimentally/computationally test the considered transportation solutions, evaluate them and finally select and recommend the most desired option.

4.2 Design and Testing of the Considered Variants

Five variants, denominated Variant 0 - V0, Variant 1 - V1, …, to Variant 4 - V4 have been considered as alternative transportation solutions for Grunwaldzka street redesign. They have been designed heuristically and tested with the application of the traffic simulation tool (Visum). Since Visum Software – the product of the German company PTV is a traffic simulator based on the 4-stage model framework one may conclude that the performed design phase has had a hybrid character.

Variant 0 - V0 corresponds to the existing transportation solution at Grunwaldzka street; thus it reflects the status quo and constitutes the benchmark for the considered analysis. Variants: V1, V2, V3, and V4 represent various, specific concepts of the redesign and are featured by different transportation solutions for the considered segment of Grunwaldzka street and its critical intersections. All transportation solutions have been designed heuristically and tested in the traffic simulation package Visum/Vissim. The variants are presented graphically in Fig. 2.

Variant 0 - V0 is a single level transportation solution along the whole street and at a critical intersection of Grunwaldzka and Smulochowskiego streets. The variant represents the current solution, which is a single road with one lane in each direction that extends to two roads with two lanes in each direction at the considered intersection. A separate tramway railroad runs parallel to the road along Grunwaldzka street on the considered length of the segment (1,7 km long). On the single road segment the

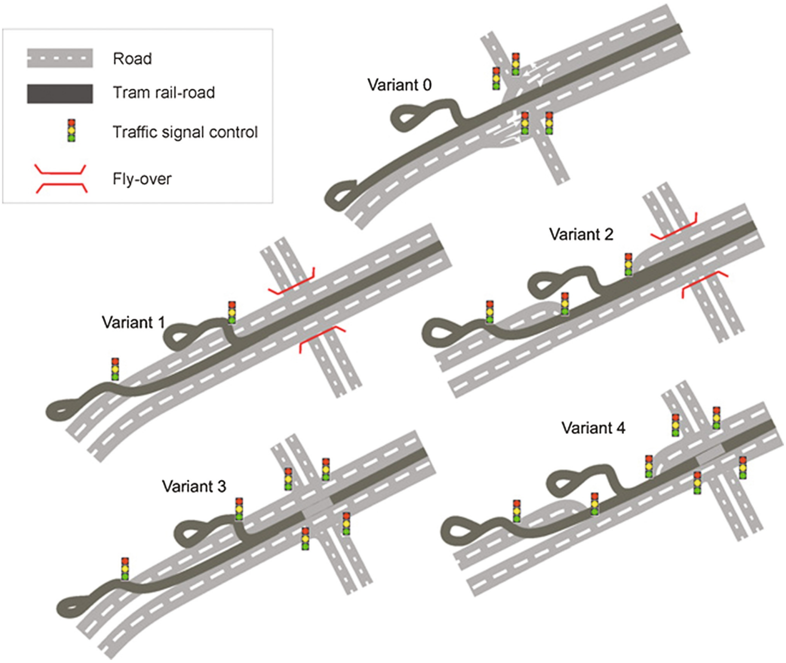

Fig. 2. Graphical representation of variants V0, V1, …, V4, i.e. transportation solutions/concepts developed for the redesign of the main artery in Poznań (Grunwaldzka street)

tramway corridor is located at the northern side of the street. At the intersection, where a single road extends to two roads it crosses the road traffic and goes in the middle of the artery, between roads moving traffic in the opposite directions (see Fig. 2). In this variant the prospect inner ring road that crosses Grunwaldzka street is in its present, underdeveloped form. It is a simple single collector/distributor road with one lane in each direction. It collects traffic from local roads and distributes it to arterials. This solution creates a serious bottleneck at the considered intersection. It is featured by the existence of two tram loops for various tram lines and four traffic signal controls at the intersection. **V0** is a zero - level investment solution, relatively safe but not very comfortable (travel time - wise).

Variant 1 - V1 is a two level transportation solution at a critical intersection of Grunwaldzka and Smulochowskiego streets with a fly-over above the proposed inner ring road (see Fig. 2). It is featured by two roads with two-lanes in each direction (arterial road) and a separate tramway railroad that runs along the whole segment of Grunwaldzka street. The tramway corridor is located in the middle of the artery, between roads. It crosses the northern road next to the integrated bus – tramway loop to provide access form trams there. In this variant the inner-ring road that crosses Grunwaldzka street is well developed, as a collector/distributor road with two separate roads, two lane each. This variant is featured by the existence of one tram loop for selected tram lines and another integrated bus – tramway loop for the majority of tram lines and all bus lines operating in this area. Two traffic lights are proposed in this variant to ensure smooth integration of the tramway traffic with the road traffic. **V1** is the most expensive and at the same time the most comfortable transportation solution.

Variant 2 - V2 is a two level transportation solution at an intersection of Grunwaldzka and Smulochowskiego streets with the flyover above the inner ring-road. This variant is a combination of two, two-lane roads (1.2 km) in the external sections of the considered street segment and a single two-lane road (0.5 km) in the central part of the segment (near the tramway loop). Thus, the two two-lane roads merge into single two-lane road in a certain segment of the street and then split again into two, two-lane roads (see Fig. 2). Similarly to variant V1, the tramway corridor in variant V2 is located between the roads and crosses the northern road to provide access to the tram loops. V2 is featured by the well developed the inner ring-road as in variant V1. The loop solutions are organized in the same way as in variant V1 (one tram loop and one integrated bus – tramway loop). Three traffic lights are required in this variant to properly integrate the tram and road traffics. Variant V2 can be considered as a median transportation solution in terms of investment costs and comfort of travel (travel time). Due to existence of three collision points of the road and tramway traffic in this variant it is featured by a relatively low safety.

Variant 3 - V3 is a single level transportation concept. It is featured by the same solutions as in variant V1 (see Fig. 2), except the fly-over that is replaced in variant V3 by a standard intersection. Again, it is featured by two roads with two-lanes in each direction and a tramway corridor located in the middle of the artery, between roads. The inner-ring road is well developed in this variant (as it is in variant V1). The loop solutions are identical to their equivalents in variant V1. There are six traffic lights in this variant, including four in the Grunwaldzka - Smoluchowskiego intersection and two to integrate tramway traffic with the road traffic. **V3** is a comfortable and expensive transportation solution.

Variant 4 - V4 is a single level transportation concept at an intersection of Grunwaldzka and Smulochowskiego streets. It is featured by the same solutions as in variant V2 (see Fig. 2), except the fly-over that is replaced in variant V4 by a standard intersection. Thus, it is a variant being a combination of two, two-lane roads (1.2 km) and a single two-lane road (0.5 km). Variant V4 is featured by a well-developed the inner ring-road as in variants V1 and V2. The loop solutions are identical to their equivalents in variant V2. There are seven traffic lights in this variant, including four in the Grunwaldzka - Smoluchowskiego intersection and three to integrate tramway traffic with the road traffic. **V4** is a uncomfortable (travel time - wise) and relatively inexpensive (investment cost – wise) transportation solution. Safety-wise it is not the recommended concept due to three collision points of the road and tramway traffic.

As mentioned above, all the variants: V0, V1, …., V4 have been simulated in the macro-simulation tool Visum. The macro approach has been selected due to the following arguments: 1. The considered area is relatively large and the traffic in this neighbourhood has a strong impact on the movements in the whole city. The area covers the connection between the city center and the suburbs. 2. For the considered event (European Football Championship – EURO 2012) it was essential to test the movements of passengers between the Football Stadium, city center, sightseeing attractions and Football Fun Zone. These locations are quite dispersed all over the city. 3. The DM's wish was to test the influence of the proposed transportation solutions for the global movements/traffic in the whole metropolitan area, especially along major transportation corridors: Grunwaldzka, św. Marcin and Królowej Jadwigi streets; Głogowska and Pulaskiego streets; and around the Inner Ring.

For the traffic simulation experiments the traffic model of the Poznań Metropolitan area, developed by traffic engineers at the Poznań City Hall, has been applied. This model has been customized and properly adapted to the proposed changes – transportation solutions at Grunwaldzka street. These have involved: adaptation of the transportation network and slight adjustment of the traffic zones according to the variants assumptions, generation of a new modal split for the whole metropolitan area and re-calculation of the traffic assignment in the overall transportation network. To determine the new modal split the authors have applied the well-known nested logit model [1, 2] and have generated the realistic shares of travellers/passengers using public (M_{PuT}) and private (M_{PrT}) means of transport. The modal split has been computed for all considered variants. For the considered situation the proportion M_{PuT}/M_{PrT} has ranged as follows: 44%/56% for V3, through 45%/55% for V0 (current solution) to 46%/54% for V4. Using advanced traffic assignment algorithms the transportation network has been loaded by traffic and the volumes of passengers' and vehicles' flows on particular links of the network have been computed. Finally, certain parameters characterizing particular variants have been produced. These included in particular variants: ridership for all transportation modes, average travel and riding times, average waiting and transfer times at the stops, average passenger speed, aggregated traffic safety ratio, noise and pollution parameters. Based on these parameters the evaluation criteria have been defined and their values have been computed.

4.3 Multiple Criteria Evaluation of the Designed Transportation Solutions

The designed variants – transportation solutions have been assessed with the application of one of the most commonly used transport evaluation methodologies, i.e. the MCA (see Sect. 3). The parameters generated in the testing phase have served as the input for the construction – definition of the evaluation criteria of all designed variants. Based on the expectations of the DM and major stakeholders (mentioned in Sect. 3) different evaluation aspects have been considered in the formulation of specific characteristics.

The evaluation of the considered variants have been formulated as a multiple criteria ranking problem. Thus, the variants have been assessed by a family of criteria and ranked from the best to the worst. The following criteria have been defined:

***Average Travel Time* (C1) [Minutes, Seconds] – Minimized (MIN).** This criterion represents an important component of the passengers' comfort of travel, thus it expresses the major interest of local residents - passenger (travellers). It is associated with both social and technical aspects of evaluation. The criterion is defined as an arithmetic average of individual travel/riding times required to cover a distance of the analysed road section by each passenger (in the considered traffic flow) travelling either by a private (individual) and/or a public mean of transport.

Traffic Safety **(C2) [-]** – is a criterion that evaluates road safety level of each considered variant (investment plan), measured by the predicted annual number of accidents on the considered section of the road. It represents, again, the socio-technical aspect of evaluation. The criterion is formulated as a function of the accident index corresponding to the risk associated with the accident occurrence on the above mentioned infrastructural solutions, and the vehicles traffic volume. This criterion is **minimized (MIN).** It is important for both local residents – passengers, public transportation system operator and UEFA.

Investment Costs **(C3) [mln PLN] – Minimized (MIN).** This criterion has an economic character and it is very important for local municipal authorities – the City Board (DM) - investor and UEFA (as a co-investor). Expressed in monetary units, it is defined as a total amount of money (overall costs) required to carry out a particular variant (transportation solution). In the criterion definition the following components are included: labor costs, material costs, costs of equipment and machinery.

Investment Profitability **(C4) [%] – Maximized (MAX).** This criterion is defined, again as a financial – economic parameter that evaluates financial performance (efficiency) of each variant. It is defined as an Internal Rate of Return (IRR) or in other words the interest rate at which the discounted investment costs and incomes generated by the considered section of the urban transportation system balance in a certain time horizon (25 years). This criterion is important for the City Board (DM), UEFA and public transportation system operator.

Environmental Friendliness **(C5) [pts] – Maximized (MAX).** This criterion characterizes the level of environmental friendliness of the considered variants. It is defined as a number of points (0–10), assigned by experts, that corresponds to the evaluation of the negative impact of particular investments on environment in the neighbourhood of the considered road section. The definition of this criterion is based on the assessment of noise and air pollution levels. The criterion has an environmental character and it is strictly correlated with the quality of life. Thus, it is important for local residents.

Based on the input data from the Visum Macro Simulation Software and additional external information the criteria values for all the considered variants have been computed. As a result the Evaluation Matrix have been constructed – see Table 1.

After having constructed the Evaluation Matrix computational experiments have been initiated. To increase the reliability of the generated results all computational experiments have been performed with the application of two most popular and representative multiple criteria ranking methods, i.e. ELECTRE III/IV and AHP (see description in Sect. 3). Computational experiments required the definition of preferences of the DM and major stakeholders.

All these groups (DM and stakeholders), composed of several individuals each, have been interviewed and surveyed. For each person an individual preference profile has been defined. It has included two elements: his/her perception on the importance of each criterion and his/her sensitivity on the changes of the criteria values. The individual preferences have been aggregated into a common group preference model for: City Board (DM), public transportation system operator, residents (passengers) and

Table 1. Evaluation matrix for the analysed variants.

Criteria		Unit	Direction of preference	V0	V1	V2	V3	V4
C1	Average travel time	[min, s]	Min	5 min 31 s	2 min 39 s	3 min 41 s	3 min 13 s	4 min 0 s
C2	Traffic safety	[accidents]	Min	1.36	1.74	3.12	2.29	4.10
C3	Investment costs	[PLN][a]	Min	0	55.72	44.12	47.77	36.17
C4	Investment rofitability-IRR	[%]	Max	2.58	3.28	2.62	2.86	2.21
C5	Environmental friendliness	[pts]	Max	2.00	8.32	7.01	8.04	7.97

[a]1 Euro = 4 PLN (roughly)

representatives of UEFA. Afterwards all four group models have been averaged and integrated into an overall, final model of preferences.

Different modeling techniques have been applied to construct the preference models characteristic for the Electre III/IV and AHP methods. As presented in Sect. 3 the Electre III/IV method preference model has been constructed with the application of weights w_j, defined for each criterion (the aspect of criteria importance) and indifference q_j, preference p_j and veto v_j thresholds, describing the interval-oriented sensitivity of the DM and stakeholders for each criterion. The AHP method preference model has been constructed based on the pair-wise comparisons of criteria and variants – transportation solutions. As presented in Sect. 3 this model of preferences is expressed in the form of relative weights w_r on the 1 to 9 point scale and has a compensatory character. The comparisons between criteria result in the definition of their importance, while the comparisons of variants for each criterion correspond to the definition of the DM and stakeholders sensitivity.

The following steps of the computational procedure have been performed:

- With the application of **ELECTRE III/IV method**:
  - Computing the concordance indicators $C(a, b)$, presented as a concordance matrix.
  - Computing discordance indexes $D_j (a, b)$.
  - Generating the values of the outranking relation S expressed by the degree of credibility $d(a, b)$ and presented in the form of credibility matrix.
  - Performing descending and ascending distillations, resulting in producing complete pre-orders.
  - Obtaining the final outranking graph and the corresponding ranking metrix.
- With the application of **AHP method:**
  - Computing consistency indexes CI for each matrix of relative weights w_r at each level of the hierarchy (criteria and variants).
  - Generating a set of vectors containing normalized, absolute values of weights w_a for criteria and variants.
  - Computing utility of each variant i – U_i.
  - Generating the final ranking of variants based on the values of their utilities U_i.

Due to space limitation the above mentioned (space demanding) steps of the computational procedures of ELECTRE III/IV and AHP methods have been omitted and only final results have been demonstrated. For an interesting reader all these computational phases can be found in other publications of the author, e.g.: [14]. The final output (after all of the above mentioned steps of the computational procedures of both methods) is presented in Fig. 3.

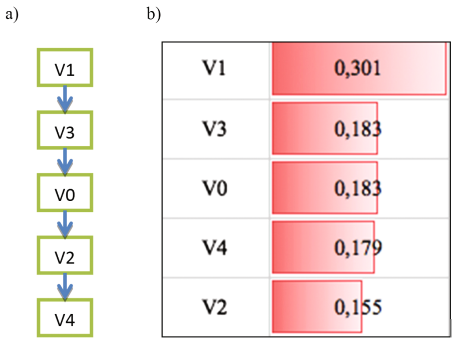

Fig. 3. Final results of computational experiments generated with the application of: (a) Electre III/IV method and (b) AHP method

As one can see the rankings generated by both methods, ELECTRE III/IV and AHP, have a similar but not identical form. The ranking produced by the application of ELECTRE III/IV method has a graphical character (outranking graph) and demonstrates the positions of all variants – transportation solutions in the ranking without showing the distance between them. The ranking generated by the application of the AHP methods gives both pieces of information, the positions of variants in the ranking and their distance between each other, measured by the difference of their utilities $\boldsymbol{U_i}$.

The leader of both rankings is variant V1 – two-level transportation solution with a fly-over above the inner ring road. As presented in Fig. 3(b) the utility of variant V1 is substantially higher than utilities of its counterpart variants V3 and V0, being placed at the next positions. In the ELECTRE III/IV method – based ranking variant V3 is preferred to variant V0, while in the AHP method – based ranking they are considered indifferent (equal value of utilities $\boldsymbol{U_i}$ = 0,183). As indicated by both rankings variants V2 and V4 are considered the weakest transportation solutions, although their positions are inversed in both rankings.

Based on the generated results variant V1 is the most desired transportation solution and it is recommended for implementation. Although it is the most expensive transportation solution (investment-wise) it guarantees excellent comfort of travel for passengers (travel time), very good traffic safety and outstanding environmental friendliness. It is also very promising profitability-wise. While comparing two leading variants V1 and V3 it is worth noticing that an 8 mln PLN (roughly 2 mln Euro) investment difference between these variants results in substantial travel time savings of 34 s. per passenger (18%), 24% improvement in terms of traffic safety, 15% higher investment profitability and 3% enhancement of environmental friendliness. The above mentioned unit travel time savings between variants V1 and V3 generate roughly (for the analyzed traffic) the overall annual travel time savings of 1200 h.

Variant V1 compared with the existing transportation solution – variant V0 generates enormous difference in terms of the following aspects: travel time – almost 3 minutes per passenger (roughly 50% improvement) and environmental friendliness (300% improvement). For the analyzed traffic the overall annual travel time savings (variants V3 vs. V0) amount to 6300 h. It is worth mentioning that the overall position of variant V0 is relatively high in the ranking due to 0 investment level and very good performance safety-wise. Variant V0 outperforms variant V3 in terms of traffic safety by 28%.

5 Conclusions

The chapter presents the basic and most popular concepts and methodologies of designing and evaluating complex transportation systems. The presented considerations have universal character and refer to different types of transportation systems, including both: single mode and multimodal systems as well as freight and passenger transportation systems. Universal rules concerning design and redesign as well as evaluation of transportation systems are presented. The paper contains both the theoretical background of the considered topics and the practical application of the presented concepts and methodologies.

As far as design/redesign of the transportation system is concerned, major stages of the design/redesign process are described. These include:

- Analysis of transportation demand.
- Design of a transportation network.
- Traffic assignment.
- Definition of transportation modes (types of vehicles).
- Allocation of crews.

The author demonstrates five basic categories of measures associated with planning and designing of a transportation system, such as:

- Land use design.
- Infrastructure development.
- Implementation of management rules.
- Information provision.
- Design of pricing strategies.

In addition, three major approaches to design/redesign of the transportation system are characterized:

- Heuristic (intuitive - oriented) design supported by simulation.
- Optimization (mathematical programming) - based design.
- Hybrid approach based on the application of several combined procedures, including the 4-stage model.

As far as the evaluation of a transportation system is concerned, two major methodological schools of assessing transportation systems are presented and confronted. These are: Cost Benefit Analysis (CBA) and Multiple Criteria Analysis (MCA), also denominated by Multiple Criteria Decision Making/Aiding (MCDM/A). Major terms, features and methodological principles associated with both fields are presented. Three basic measures used in CBA to assess the overall profitability/utility of the considered transportation solutions are characterized, including: Economic Net Present Value (ENPV), Economic Internal Rate of Return (EIRR) and Benefit-Cost Ratio (BCR). Basic terms of MCA or MCDM/A are also presented, including: the definition and classification of a multiple criteria decision problem, the description of a consistent family of criteria and the categorization of the MCDM/A methods. Basic features of two, most representative MCDM/A ranking methods, including: ELECTRE III/IV and AHP are demonstrated.

Practical applicability of the presented paradigms is presented in the case study (Sect. 4) that refers to the redesign of a critical section of a medium-sized urban transportation system. The redesign has a hybrid character. It is based on a heuristic construction of alternative transportation solutions supported by simulation and optimization (application of a Four Stage Model – FSM). The proposed solutions reshape the major artery that connects the city center with the suburbs of the metropolitan area. Four generated variants are compared with the existing transportation solution. In the assessment phase a multiple criteria evaluation of variants is performed. A series of computational experiments is carried out. The proposed solutions are ranked from the best to the worst.

From a theoretical/methodological point of view the presented research has generated the following original output:

– Presentation of the methodological principles of design and evaluation of transportation systems in a condensed, abridged form.
– Comparison of two alternative approaches of transportation systems' evaluation, i.e.: CBA and MCA.
– Testing two alternative MCDM/A methods and confirming their suitability for the evaluation and ranking of alternative transportation solutions.

From a practical point of view the critical findings of the presented research are as follows:

– Presentation of the real world redesign of a section of a transportation system. Development of several transportation solutions based on hybrid approach, including: heuristic construction of variants supported by simulation and optimization techniques.
– Multiple criteria evaluation of the proposed solutions – variants, including: definition of the consistent family of criteria, modeling DM's and stakeholders preferences, carrying out computational experiments resulting in the ranking of variants and final recommendation of a selected variant for implementation.
– Generating substantial improvements thanks to the real life application of the selected variant – V1 – two level transportation concept with a fly-over above the

inner ring road. The most radical changes refer to environmental friendliness (300% improvement) and comfort of travel (50% improvement).

In the author's opinion the following conclusions may be drawn from the presented research:

- The combination of heuristic design and different analytical tools generates a set of realistic transportation solutions. The intuitive construction of variants based on imaginative thinking, creativity and expert knowledge proves to be a reasonable approach. At the same time the author claims that a ridged, systematic verification of the generated concepts is required. Thus, their testing and improvement is strongly recommended through simulation and optimization techniques.
- When several variants have been generated their comparative analysis and evaluation is required. The MCDM/A methodology is a universal tool that allows for a comprehensive and complete evaluation of alternative transportation concepts/solutions. As presented in this chapter, in the multiple criteria oriented evaluation of transportation solutions different multiple criteria ranking methods can be applied. In the author's opinion, both AHP and Electre III/IV methods have generated satisfactory computational results and can used as generic tools of the transportation systems' evaluation.

In the author's opinion further research can be conducted in the following directions:

- Comparison of alternative design approaches, i.e. purely heuristic method with optimization – oriented design and hybrid approach. Analysis of generated transportation solutions for the considered case.
- Application of other MCDM/A methods (e.g.: Oreste, Promethee, ANP) in order to rank various redesign variants of a the considered section of a transportation system. Thorough analysis and comparison of the generated results.
- Application and comparison of MCA and CBA methodologies for the evaluation of the considered variants – transportation solutions.

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