CONSISTENCY BETWEEN STATE ROAD NETWORK PLANNING AND RENEWED FEDERAL GUIDELINES OF ACCESSIBILITY

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ABSTRACT

This paper reports on recent methodological developments to address mutual requirements and to solve possible conflicts of objectives between spatial planning and road network investment at federal state level in Germany.

On the one hand, the renewed "Federal Guidelines of Accessibility for an Integrated Network Design" (RIN) suggest an assessment of air-line speeds in given central-place grids, consequently developing standards and priorities to overcome service level deficits. On the other hand, the state-run road construction administration pursues an agenda of infrastructural and organizational measures to enhance the network. The focus here is on adapting physical capacities to the occurring load pattern, seeking a minimum of the running costs while complying with transport safety and environmental regulations.

The theoretical part of the paper proposes a unified, constraint-based planning model, whose formal description is given. The study region chosen for the practical application is the German federal state of Thuringia, in conjunction with an existing integrated transport supply-demand model. After undertaking a policy analysis for the period 2005 – 2025 we will demonstrate our modelling approach, aimed at accomplishing a consistent improvement strategy and thus giving an adequate decision support for the state authorities.

Key Words: Road Network Planning, Spatial Planning, Central Place Theory, Accessibility, Consistency, Search Algorithm, Transport Modelling

1 INTRODUCTION

1.1 Consistency of Public Policies

Consistency, as defined by dictionaries, stands for "agreement or harmony of parts or features to one another or a whole: correspondence; specifically: ability to be asserted together without contradiction". [1] For example, an uncompromised, masterly architecture or the soundness requirements in formal sciences materialize the above notion of consistency.

In contrast, a number of public (economic) policies – at least in decentralized, non-authoritarian societies – exhibit a certain degree of contrariness or inconsistency. Grether (1965) describes this characteristic as an inherent limitation and directs his investigation on decision-making towards "a reasonable, attainable level of consistency" of policies with respect to private, unregulated industries [2].

Being a side effect of a culture of consensus in connection with complex budget redistribution mechanisms, a public policy's lack of consistency may delimitate its effectiveness. Moreover, inconsistencies can make it contestable by affinity groups or public bodies competing for state funds. Objections by the parties involved regarding the adequacy of the budget spending may lead to ad-hoc decisions entailing new inconsistencies later on.

1.2 Road Network Planning vs. Spatial Planning

In Germany, the long-term spatial planning constitutes a cornerstone of public policies, influencing development perspectives in general by intervening in land-use, infrastructure and the local provision of public facilities in particular. All spatially relevant plans are directed by the legal regulations and also coordinated, ensuring that conflicts with strategies and underlying goals are avoided or at least minimized. In the federal structure, the 16 German federal states define their models of spatial development and designate so-called "central places" (see 2.1) as well as axes of communications between them. [3]

Transport networks grant public access to services of regional importance. In addition, a well-functioning integration within state-of-the-art transport networks is regarded as one of the key factors for economic prosperity and further development potential of a region. The concept of regional accessibility, which has asserted successfully in theory (e.g. Vickermann 1999), establishes itself in the planning practice (see Straatemeier, 2008). [4] [5]

For the foreseeable future, road vehicles remain the principal mode of transportation. Thus, road infrastructure investments and regional accessibility development plans are closely related economic policy instruments. Furthermore, transport system improvement generally occurs on individual projects of different sizes, anticipating the vehicle flows of a certain order of magnitude.

The relevance of road investment in the context of accessibility raises the issue of how to align a multiyear agenda of individual improvement projects, typically ordered by their benefit cost ratios, with the long-range spatial plans. Although there is a call for consistency of public policies regarding transport infrastructure and regional development, this objective is not easily achieved in practice. At least three types of inherent conceptual and organizational impediments to a better concertation may be ascertained:

(i) Transport flows are bridging gaps between supply and demand of goods, but also between - slowly-changing - regional structures. Historically, road networks emerged and adjusted to the needs of a volatile transport demand as well as the underlying infrastructure cost structures. Therefore, incongruencies with communication axes of temporary master plans, aiming a balanced regional development, are inevitable.

(ii) Although there is an exchange of data, the planning processes are not sufficiently unified in detail. Taking the practice of respective administration, the decision authorities for spatial planning and road infrastructure planning are faced by separate entities. Even the vocabularies of concepts, software tools, and the planning cycles are hardly synchronized. In effect, the decisions are being made next to each other. Under these circumstances, the social optimum of the lowest-possible resource consumption is hardly achieved.

(iii) The preference structure of the planning authorities in charge is non-uniform, and the benefit cost ratio is not necessarily the ultimate decision criterion. This observation suggests itself also with reference to studies such as Fridstrom and Elvik, 1997, aiming to explain the distribution of state funds by the road investment project characteristics.[6] The rank order multinomial logit model reveals further preferences besides a strict welfare maximization to influence the ranking and later budget approval of road investment opportunities.

1.3 Problems of Integrated Planning Support

Planning decisions are generally discrete. A goal-oriented approach seeking to determine the most appropriate set of measures therefore leads to a combinatorial optimization problem, subject to technical feasibility and further boundary restrictions. The pursuit of regional accessibility improvements and the road network operator's remodelling goals – as listed in Table I - constitute two bundles of requirements concerning the future network performance.

Table I: Target system of spatial planning and road planning goals (Source: Own representation)

Spatial Structure	Road Network
desirable distribution of people & activities:	*project benefit cost ratio, influenced by*
-participation and competitiveness	*-reduction in user costs*
(accessibility commitment to/by local politicians/ investors)	(cut travel times, upgrade & capacity adjustment to traffic volume, increased comfort level for drivers)
-balanced development	*-reduction in social costs*
(backlogs on continental, national and regional level, urban sprawl)	(road safety, environmental impacts)
-environmental aspects	*-operator's cost reduction*
(mitigation of pollutions, land and resource consumption)	(bundling degree of transport flows, utilization of any subsidies supplied)

Given a scarcity of budgets, the establishment of priorities between remodelling project opportunities somehow needs to align these goals (Table I). The literature references on coordinated spatial / network planning are numerous, however, to be grouped into two major streams of development:

(i) Algorithms to solve the road planning task with respect to an overall accessibility maximization with suitable search heuristics, such as Antunes et al., 2003 [7]

(ii) Incremental, visual support tools for manual planners, helping to overlook the complexity, e.g. Kammeier, 1999. [8]

Particularly in the first case, the attempt to unify the two planning approaches bears on the size of the decision space. The intractable complexity of practice-oriented case studies puts the modeller to the necessity to reduce the massive search efforts by downsizing the networks and the origin-destination matrices to a very minimum.

1.4 Paper Outline

This piece of work seeks to overcome some weaknesses of the current appraisal practice by contributing a mechanism that reconciles the aforementioned goals of spatial planning and road network planning. More specifically, the integration task is to detect, address and solve possible conflicts of objectives between the renewed federal guidelines of accessibility and road network remodelling at federal state level in Germany.

Based on practical project experiences, this contribution demonstrates an enhanced investment policy development through the combined use of the following elements of a new approach:

- The measurement of the road level of service at given edges of a central place grid,
- The integration of the central place connections within a transport network model,
- The conversion of the joint spatial and road network planning problem into a scheduling task of predefined network remodelling activities
- The use of consistency methods to detect and solve upcoming conflicts of goals.

The remaining paper is organized as follows: Section 2 provides the conceptual foundations for the approach to be presented, i.e. central place grids mapped onto road infrastructure networks, road level of service measurement, and “consistency-assuring” technologies from computer sciences. In Section 3, the problem dimensions and decision support needs are summarized, motivating a unified, constraint-based planning approach whose formalized description and implementation are presented thereafter. Section 4 refers to a case study recently conducted for the federal state of Thuringia. We will demonstrate the steps during the practical application and investigate attainable levels of consistency for a real-world planning context, followed by a discussion and conclusions in the final section 5.

2 CONCEPTUAL FRAMEWORK

2.1 Central Place Grids Mapped onto Road Networks

The Christallerian central place theory (CPT) was established to explain the reasons behind spatial distribution patterns. It proposes geometrically arranged hierarchies or grids of settlements (cities, towns, market town, villages) - depending on their functionality for the surrounding settlements. Generally speaking: The larger a settlement is, the more comprehensive it is in its services portfolio and the corresponding “catchment area”. Despite of criticism regarding ill-suited, static assumptions and questionable applications in the past century, the underlying ideas remain a core part of planning paradigms, and were further developed to cover spatial phenomena of a globalized world. [9]

Central places are interlinked with neighbouring peers as well as the assigned centre perching above within the hierarchy. The resulting grid structure at the identical functionality level is obtained by Delaunay triangulation, a common geoscientific method, applied to a spatial arrangement of nodes symbolizing central places (later abbreviated as: CP).

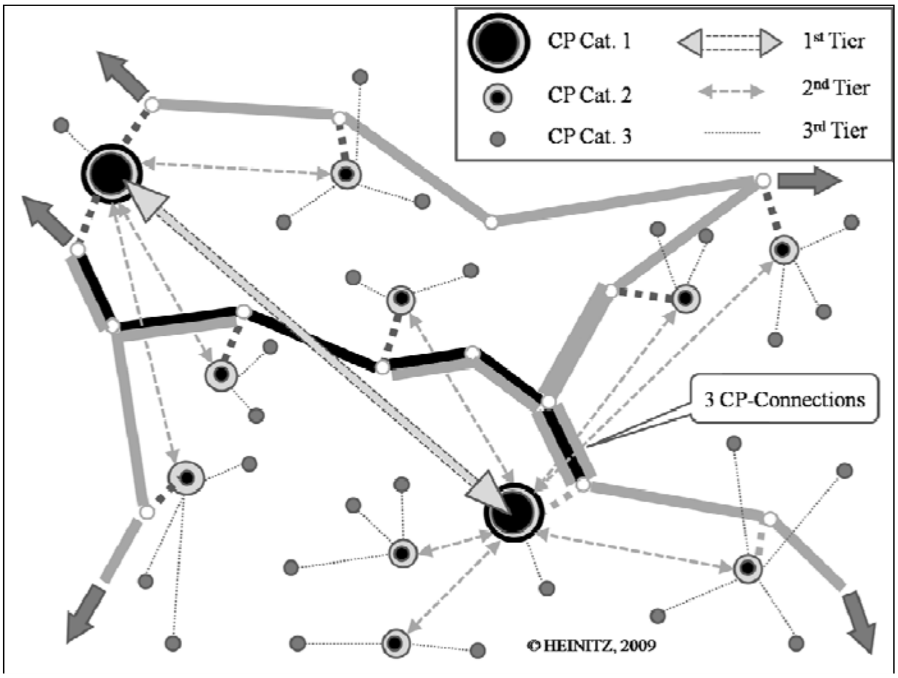

Figure 1 – Applying a central place concept to a road network model (Source: Own representation)

For a given multi-tier network of triangular air-lines connecting central places (CP) of different categories, these CP connections may be mapped to the physical infrastructure. Figure 1 illustrates this exemplarily for a real-world setting of 25 central places of three categories. The network assignment step can be performed either manually (e.g. according to a regulatory presetting) or by automated optimum-path algorithms. Note that any network edge may bundle several CP connections.

2.2 Road Level of Service Measurement

Rating systems such as the U.S. Highway Capacity Manual (HCM) or the German handbooks RAS-N and HBS are considered as key pieces of advice to road planners worldwide. The underlying idea of such guidelines is to standardize road level of service assessments on link, intersection or/and route level in order to pinpoint infrastructural remodelling measures. Differences between these manuals arise of the choice of performance indicators deployed as well as the predefined (national) standards. In principal, the following three variants of measurement may be observed:

(i) The extent or disposition of a link / intersection to (observable) congestion
(ii) The ratio between the traffic volume per hour versus the appropriate capacity of the link type
(ii) The average travel speed achieved when driving the entire route from the trip makers' origin to the destination.

While the first two - interconnected - measures mainly indicate capacity deficiencies in relation to the traffic volumes, the third is an accessibility measure, abstracting from the infrastructure provision. The German federal guideline for an integrated transport network design (RIN), issued in late 2008 is such an instance to standardize forthcoming project appraisals for roads and public transport, [10]. The outcome of this measurement is parameterized externally by a central place grid as described in 2.1.

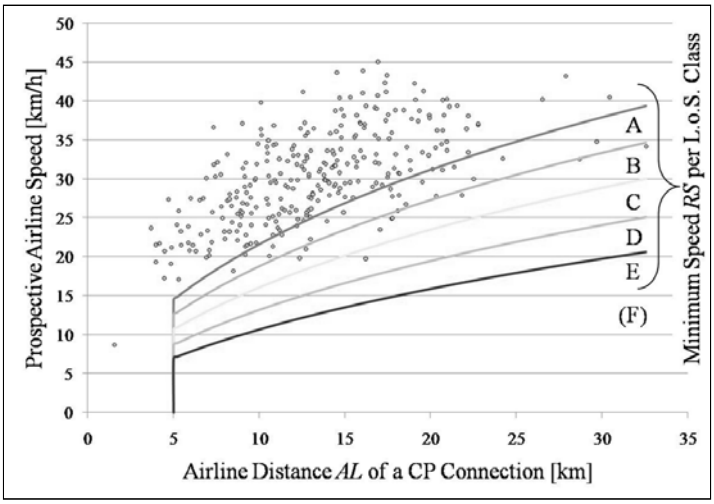

Figure 2: Exemplary accessibility assessment according to the RIN 2008 guidelines, *n*=294 (Source: Own representation)

In the case of the road supply, the air-line speeds achieved along the predefined edges of the triangular reference network are categorized similarly to the HCM into levels "F" to "A" according to given nonlinear functions of the air-line distance between the central places: The minimum air-line speed RS required by the RIN guidelines for a level of service classification l monotonously depends on the air-line distance AL to be covered as follows:

$$RS_l \geq \frac{1}{\beta_{1,l} \cdot AL^{(\gamma_l)} + \beta_{0,l}} \qquad \text{(Eq.1)}$$

Note that $\beta_{1,l}$, $\beta_{0,l}$ and γ_l are functional coefficients, predefined by the guideline.

Such minimum air-line speeds may be computed for all CP connections, given a past, current or prospective network status. Taking a sufficient service level "C" as an example, the predetermined functional parameters β_1, γ and β_0 are .25, -.676 and .0096 respectively. Inserting these parameters in Eq.1 yields to a minimum air-line speed of ~ 23 km/h for any 15 kilometre leg. Even for a mountainous region, assuming that the air-line distance corresponds to a real network distance of some 25 kilometres, the required speed of 38 km/h is still moderate.

Consequently, the exemplary scatter plot of Tier-III-Connections in Thuringia (Figure 3) reveals that – given a future network status – the CP links mostly qualify for the RIN standards set for the highest class "A". Note that a RIN draft version of 2007 published a deviating parameter set, whose road level of service criteria are far more strictly. Due to this scope of interpretation, the two versions will be used concurrently for the onward research.

2.3 Constraint-Consistent Planning

Constraints are restrictions, employed to represent incomplete information in order to describe relationships between partially undetermined objects (cf. Frühwirth & Abdennadher, 1997). [11]

Constraint programming allows for a declarative problem formulation by establishing a network of restrictions. It uses a generalization of the traditional computer storage model, where a variable can either be "assigned" or "unassigned". A constraint store administers partial information about a variable - expressed as a constraint on the variable - and checks the consistency of added constraints with its current contents. A variable is assigned if no further non-redundant constraints can be imposed without causing an inconsistency [12].

The explicit use of boundary conditions to infer a solution is not only a different, programming paradigm:

(i) Constraints serve to keep the search space manageable by eliminating inconsistent valuations of the problem variables from the search space. For several NP-hard problems, the additional computational effort to perform consistency checks the additional effort to perform repeated consistency tests is still a very good trade-off in terms of shortcutting the search procedures. E.g., the handling of disjunctive constraints choices which can be withdrawn, for instance in a job-shop scheduling problem, is generally more elegant and more successful in terms of computation times than it is in integer programming.

(ii) Constraint-consistent activity-based models (CCAB), a new type of transport models were proposed by Heinitz and Liedtke, 2009, as a generalization and combination of activity-based models and the traditional multi-stage transport modelling framework. [13] Ensuring maximum consistency between the micro, "meso" and macro levels, providing compatibility to multi-agent modelling techniques and using solution strategies similar to human decision-making behaviour, the new model type bridges the gap between "econometrics-oriented" and "simulation-oriented" research in transport modelling. Furthermore, "back cast" computations can be performed, searching inversely for feasible transition paths towards an a-priori stated search goal.

3 A UNIFIED PLANNING APPROACH

At this point, a new methodology is proposed that allows for a unified approach of spatial planning and road network planning, to be later applied at the federal state level. The first subsection (3.1) underlines and specifies the need for a consistent decision support from a German viewpoint. Subsection 3.2 provides the formal description of the unified scheduling model, whereas subsection 3.3 demonstrates how the model may be encoded and solved through a constraint network.

3.1 Decision Support Needs

Given the decennial national infrastructure master plans, a coarse framework of federal-funded road projects and the default path of the realization are set. However, the federal state authorities pursue further infrastructural projects at a smaller scale. Due to the volatility of budget appropriations in connection with industrial location strategies and regional dynamics, e.g. caused by the demographic change, there is a need to make periodic adjustments.

The modelling approach therefore assumes an initial set of state road remodelling projects of a given time frame and cost, embedded by decreasing benefit cost ratio within a given infrastructure framework programme (national / Trans-European) and Federal state's spatial planning parameters. The underlying central-place grid is assumed to be fixed at short-run, but functionalities and corresponding axes may be updated every +/- five years. Estimates of prospective load pattern are obtained for five year intervals from the underlying transport model.

On behalf of the state authority, the task is to perform a consistent (re-)scheduling of its network remodelling projects, unifying the priorities of spatial planning and network operating cost savings while facing budget constraints for project expenditures and variable costs of operation. Besides the scheduling of the entirety of remodelling measures, a flexible proof-of-concept for selected CP connections is another practical requirement of the state road administration.

3.2 Definitions and Basic Dependencies

The model dimensions, the model's endogenous and exogenous variables, parameters and constants are declared and explained in the Annex Tables IV to VI. Most of the model variables are annualised. The time-reference is then marked by an index y.

Let i subscript every geographical place / vertex, given by its surface coordinates (GL, GW). The central place concept is formalized by a 4-tuple, made up of the set O, the assigned functionalities CP, the set of interconnections $\mathrm{R} = \mathrm{O} \cdot \mathrm{O}$, and the set of assigned connection significance tiers CS.

$$\left(\{i\}, \{CP_i(y)\}, \{r(i,j)\}, \{CS_r(y)\}\right) \;;\; i, j \in \mathrm{O}, i \neq j, CP \in \mathrm{Z}, r \in \mathrm{R}, CS \in \mathrm{S}, y \in \mathrm{Y} \qquad \text{(Eq.2)}$$

A level of service $L_r(y)$ – between "F" and "A", corresponding to the metrics 0 to 5 – is assigned to every central-place connection r and year y, based on a distance-related minimum air-line speed RS:

$$L_r(y) = L_r(\theta_r(y), AL_r, RS(AL_r, l)) \; ; \; , r \in \mathrm{R}, y \in \mathrm{Y}, l \in \mathrm{L}$$
$$L_r = l \Leftarrow \begin{cases} RS(AL_r, l+1,) > AL_r / \theta_r(y) \geq RS(AL_r, l); \; l \neq \text{"A"}, \\ AL_r / \theta_r(y) \geq RS(AL_r, l) \qquad ; \; l = \text{"A"}. \end{cases} \qquad \text{(Eq.3)}$$

The travel times θ_r can be obtained by summing up the travel times on all edges $e \in \mathrm{CD}_r(y)$ of the designated road corridor. This road corridor is obtained from the underlying graph network model. These road corridors are given by the framework planning, typically using shortest, i.e. time-minimizing path as of year y's network status. Since every path is represented by an ordered set of edges, on can state:

$$\theta_r(y) = \sum_{e'} \theta_{e'}(y) \; ; \; r \in \mathrm{R}, y \in \mathrm{Y}, e' \in \mathrm{CD}_r(y) \qquad \text{(Eq.4)}$$

Every edge e of the road network graph is subject to changes every year and characterized by the following 9-tuple:

$$\begin{aligned} &(k_e(y), C_e(y), Q_e(y), U_e(y), t_e(y), V_e(y), \theta_e(y), S_e{*}(y), N(y)) \\ &\text{with } k_e \in \mathrm{K}, t \in \mathrm{T}, y \in \mathrm{Y}, e \in \mathrm{E}. \end{aligned} \qquad \text{(Eq.5)}$$

Within this tuple, k_e denotes the classification of edge number e of year y, $C_e(y)$ the infrastructure costs of year y. As a result of network assignments of past or forecasted vehicle matrices, $Q_e(y)$ denotes edge e's average annual daily traffic volume (AADT) as of year y, $U_e(y)$ the link capacity utilization as of year y in per cent, $t_e(y)$ the Stolz-Maecke cross-section type as of year y, $V_e(y)$ and $\theta_e(y)$ the average speed and resulting travel time. The expression $S_e{*}(y)$ represents the highest connection significance as of year y, whereas $N(y)$ stands for the number of CP connections using this infrastructure during this time slice.

The resulting link travel time depends on the constant edge length EL and the CR speed-flow function appropriate for the edge type t, whose arguments are given by further state variables.

$$\theta_{e'}(y) = EL_{e'} / CR(t_{e'}(y), Q_{e'}(y), K_{e'}(y)) \qquad \text{(Eq.6)}$$

The state variables mentioned above may vary over time inasmuch as the relevant links are tackled by the individual development measures set (IM_p) of a network remodelling project $p \in \mathrm{P}$. Let the complete projects P_p constitute the portfolio Π.

A remodelling project shall be characterized by its start year G_p - still to be scheduled, a project duration PD_p its benefit cost ratio class BC_p, and set of a set IM_p of 5-tuples, representing the individual remodelling measures. Thus IM_p again refers to a – possibly small - subset of edges – now indexed by h:

$$\begin{aligned}&\Pi := \{\mathrm{P}_p\} \text{ with } \mathrm{P}_p := (G_p, PD_p, BC_p, \mathrm{IM}_p)\\&\text{whereas } \mathrm{IM}_p = \{(e,t,t',k,k')_h\}\end{aligned} \qquad \text{(Eq.7)}$$

As defined by the 5-tuple above, an individual measure encodes a state transition. It may lead to an alteration of the links' cross-section type t and/or the current road classification k. Its completion after a project duration PD yields to a new link travel time θ, depending on the ratio of edge length EL and the speed – indicated by the speed-flow function CR.

$$\theta_e(y') = EL_e / V_e(y') \qquad \begin{aligned}&\text{with } y' = y + PD\\&V_e(y') := CR(t'_e(y'), Q_e(y'), K'_e(y'))\end{aligned} \quad . \qquad \text{(Eq.8)}$$

As a consequence of this, link travel times will influence certain several service levels $L_r(y')$ of the central place grid - as stated in Eq. 3 and 4.

Taking the economic perspective of the road network operation costs, we distinguish between the annual infrastructure costs $C(y)$ and the annual project-related expenses $M(y)$. The total network costs $C(y)$ sum up the link-specific annuity amounts, given by the unit costs of ownership $UC_e(y)$ as well as the annual social infrastructure costs $SC_e(y)$ - both per kilometre and depending on the traffic volume Q - times the edge length.

This yields to the following expression for the total network costs as of year y:

$$\begin{aligned}&C(y) = \sum_e C_e(y) = \sum_e EL_e \cdot (UC_e(y) + SC_e(y))\\&\text{with } UC_e(y) = UC(t_e(y), Q_e(y), k_e(y)) \quad , \; SC_e(y) = SC(t_e(y), Q_e(y), e, y)\end{aligned} \qquad \text{(Eq.9)}$$

The project-related expenses $M(y)$ are a conditional sum over project-specific annuity amounts – as far as year y lies within the assigned project period G_p ... G_p+PD_p. In the following, let the project expenses be evenly applied by assumption to every affected year cut-off date, e.g. four terms for a three-year measure.

As expressed in Eq.10, the total investment costs IC_p are further broken down to a fixed amount FI_p, and the investment cost for a cross-section transition $t \rightarrow t'$ (per network kilometre), $EI(t, t')$ – times the edge length EL_e.

$$M(y) = \sum_p \frac{\delta_{py}(G_p) \cdot IC_p}{PD_p + 1}$$
$$\text{with } \delta_{py}(G_p) = \begin{cases} 1 \leftarrow G_p \le y \le G_p + PD_p \\ 0 \text{ else} \end{cases} \quad \text{(Eq.10)}$$
$$IC_p = FI_p + \sum_{e \in \mathrm{IM}_p} EL_e \cdot EI\left(t_e(GP_P), t'_e(G_p + PD_p)\right)$$

The problem at hand is to schedule the projects of the portfolio Π such that the central place network is enhanced in terms of accessibility improvements and operating cost savings, subject to a constrained budget per time interval: The sum of the estimated costs of ownership $C(y)$ and the annual project expenses $M(y)$ must not exceed an annual budget appropriation $TB(y)$.

$$C(y) + M(y) \le TB(y) \quad \text{(Eq.11)}$$

For this purpose, the accessibility (or service) level L per central place connection r may be defined by aggregation at CP significance tier level, as well as in total. The accessibility objective function is set up as

$$\sum_{s' \in S} \sum_{r | s(r)=s'} L_r(y) = \sum_{s' \in S} L_{s'}(y) = L(y) \to \max . \quad \text{(Eq.12)}$$

In an alternative formulation, the accessibility levels may be weighted by the significance tier:

$$\sum_{s' \in S} \left(s' \cdot \sum_{r | s(r)=s'} L_{\mathrm{r}}(y) \right) = \sum_{s' \in S} s' \cdot L_{s'}(y) = \tilde{L}(y) \to \max . \quad \text{(Eq.13)}$$

Note that the set of edges constituting the central place grid varies over the course of the five-year framework planning periods. Its overall length $EL(y)$ and costs $C(y)$ are given by:

$$C(y) = \sum_{e \in \overline{\mathrm{E}}(y)} C_e(y), \quad EL(y) = \sum_{e \in \overline{\mathrm{E}}(y)} EL_e \text{ with } \overline{\mathrm{E}}(y) := \{ e | S_e * (y) > 0 \} \quad \text{(Eq.14)}$$

A focusing on the central place network $\overline{\mathrm{E}}(y)$ along with a downgrade or abandonment of parts of the residual network $\mathrm{E} \setminus \overline{\mathrm{E}}(y)$ may result in considerable cost savings without a deterioration of the accessibility levels within the defined central place grid.

3.3 Constraint Network Representation

A constraint reasoning technology allows for an implementation of the unified planning model. The formulae of 3.2 define a cohesive representation as a network consisting of a set of inter-related variables and constraints.

The nodes represent the problem variables, whose domains are dynamically restricted sets of possible values, and constants. The network edges are formed by constraints, i.e. predicates that assure the boundary conditions by narrowing down the adjacent variable domains to valid combinations of valuations.

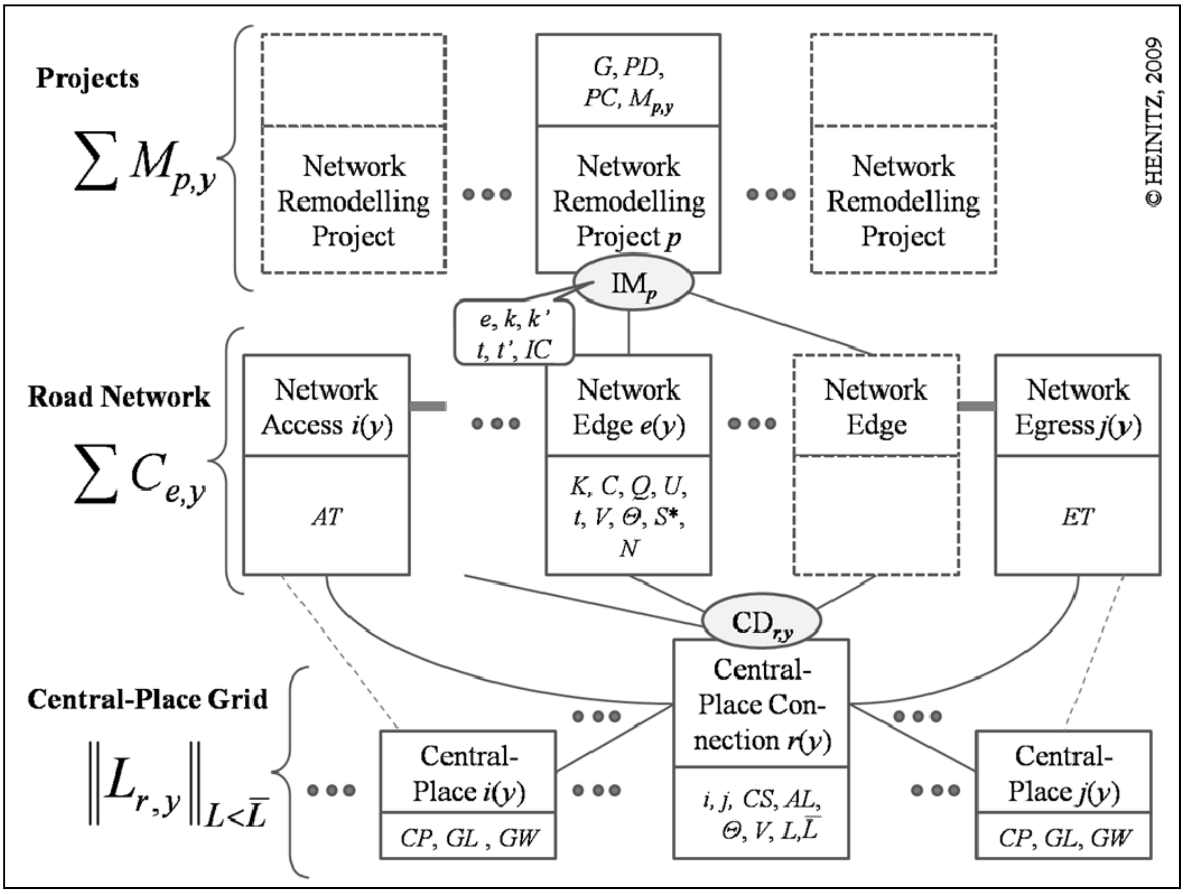

Figure 3: Outline of constraint network to implement the unified approach (Source: Own representation)

An outline of the principal network structure is given by Figure 3. For the sake of clarity, the problem variables are encapsulated in a object-oriented structure. There are three main object classes - projects, road network edges and CP connections – matched by 1:N relations as depicted. Both a remodelling project and a CP connection comprise certain set of network edges. The variables used are systematized as in subsection 3.2. All domains are discrete – implemented either as integer intervals or enumerated sets. Accordingly, constraint relations containing equations and/or inequalities link the variables, with a stepwise linearization of the nonlinear dependencies if necessary.

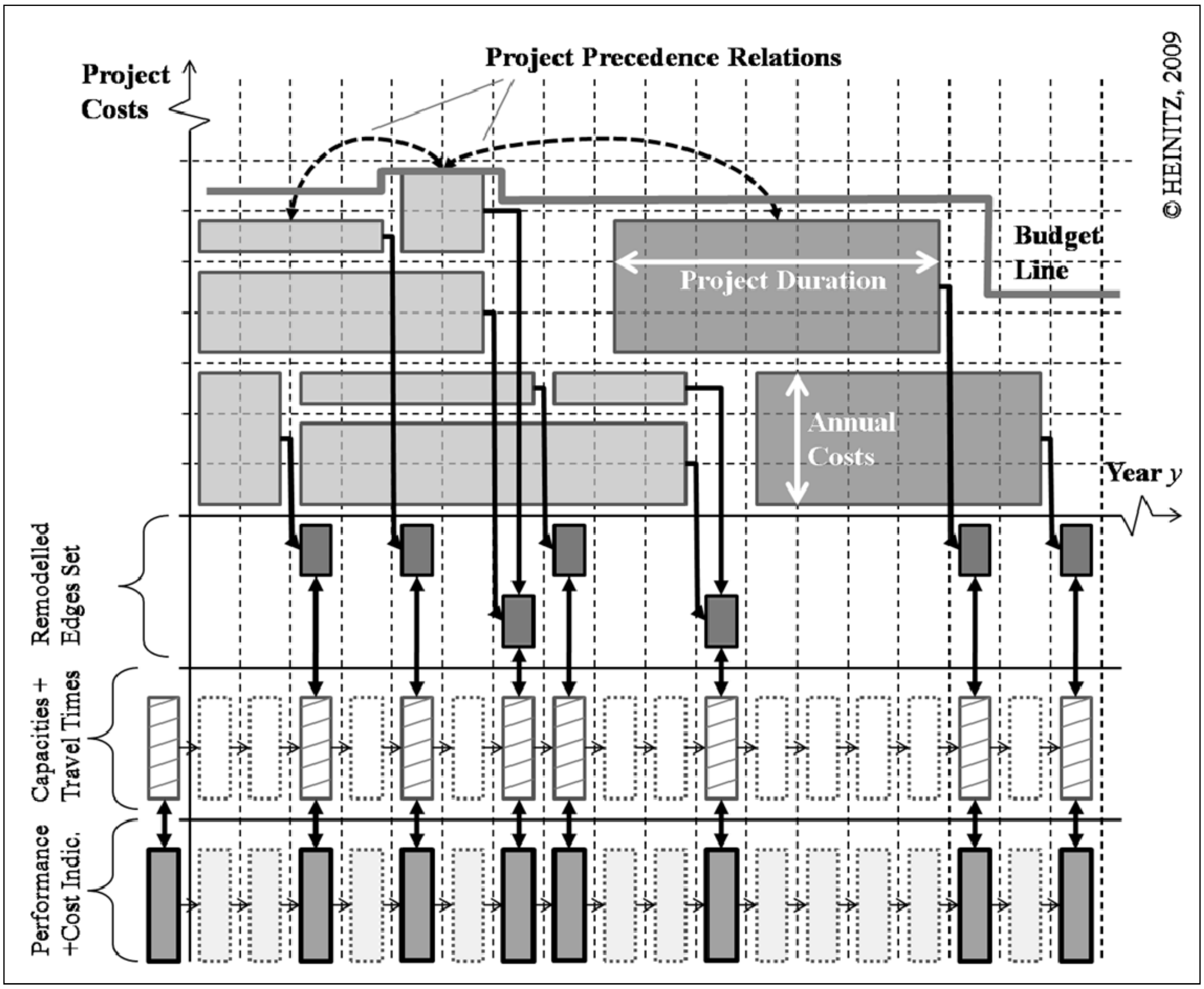

Figure 4: Interval scheduling problem of road remodelling projects (Source: Own representation)

The extended Gantt chart in Figure 4 illustrates the constraint relations over the time axis. The diachronic network consists of constraints imposed within a distinct network status for one calendar year as well as the “transition constraints” to express the relaying of edge characteristics such as capacities or travel times to the succeeding time interval. It also depicts further details of the diachronic constraint network, such as precedence relations and budget restrictions.

Having qualified and quantified the constraint network with real data, the aim of the computation is to verify the consistency and obtain recommendations for the interval scheduling of individual projects. Therefore, a simple “looking ahead” and a complete algorithmic scheduling, given a full relaxation of the constraint network, are distinguished.

4 APPLICATION

The German federal state of Thuringia was chosen as a reference to apply the unified modelling approach. At first, subsection 4.1 introduces the study area and the corresponding central place grid. An overview of road remodelling projects for the period 2005 - 2025 and their modelling is given in subsection 4.2. In the following, preliminary results of the joined consideration of accessibility and network design are given. Subsection 4.3 deals with the consistency at the level of the overall remodelling programme, presupposing an implementation as planned. It also contributes findings to date to the inverse problem: Putting the remaining project schedule into question, we identify those remodelling activities which are immediately tackling CP connections with accessibility deficits.

4.1 Study Area

The investigation of accessibilities in connection with road infrastructure projects was applied to the state of Thuringia, using the integrated transport model. Its study area is located halfway between Berlin and Frankfurt, currently inhabited by 2.3mn people, and covers an area of 16,172 km^2. The display window of Figure 5 shows the current central place grid. The structure of the investigation area exhibits a number of settlement classified as county (GZ), district (MZ), regional (OZ), as well as metropolitan (ME) centres.

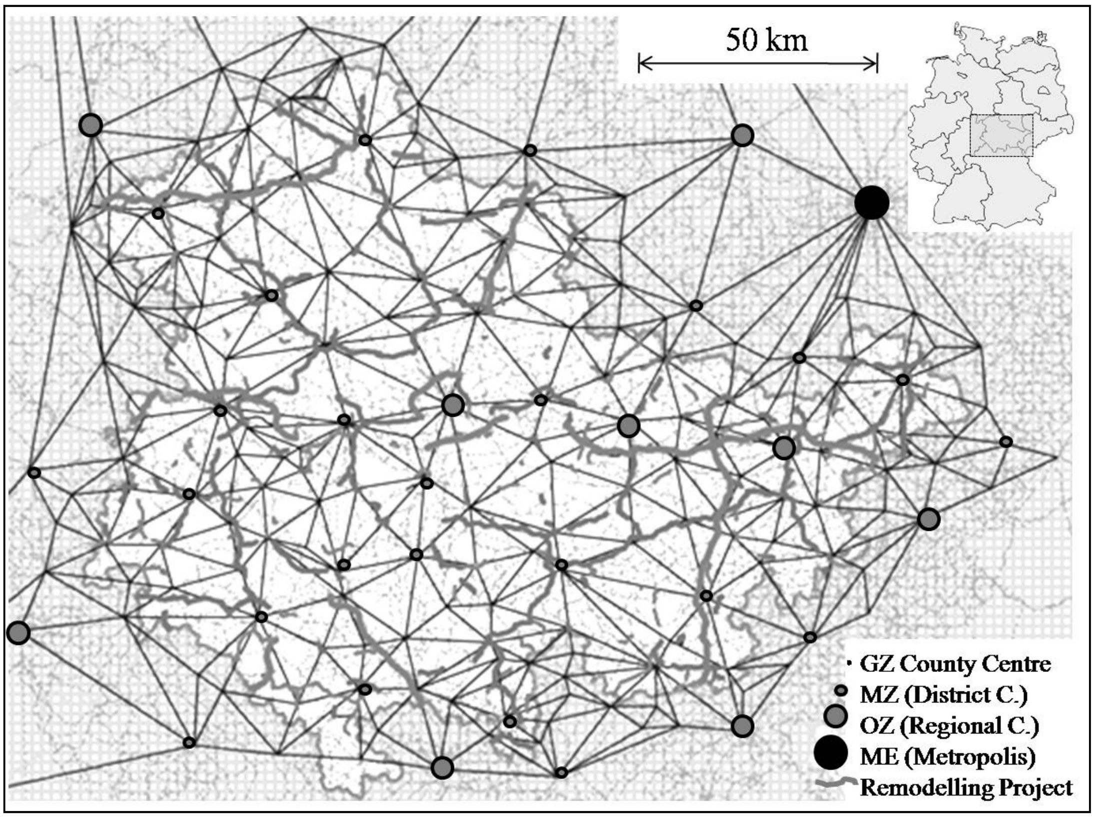

Figure 5 –Study area with Tier III CP grid and road remodelling projects (Source: Own representation)

Figure 5 also depicts the lowermost central place grid, providing the basic connection between adjacent county centres. Covering the study area of Thuringia and neighbouring regions, one obtains a framework of 1032 bidirectional edges in total. In our model, the triangulated CP connection network of the three distinct tiers

- Tier 0/I: ME↔OZ and OZ↔OZ, 33 CP relations
- Tier II: MZ↔MZ and MZ↔OZ, 185 CP relations,
- Tier III: GZ↔MZ and GZ↔GZ, 814 CP relations

links 205 nodes – with 119 are located within Thuringia and 86 in the surrounding federal states. These central place nodes, from metropolises down to county centres, are being mapped to centroids of existing traffic cells, thus making the CP connections routable through the transport network model. As specified in the unified model (see 3.2 et seq.), all road projects on the state territory, dated year 2005 to 2025 and beyond, are depicted the background.

4.2 Infrastructural Projects

By the beginning of 2009, the State Road Construction Authority of Thuringia (TLBV) has managed a dense road network of 10,004 km total length – thereof 24% federal motorways on behalf of the federal government, 47% state roads and 29% county roads.
Two decades after the German reunification, the construction activities are still numerous. Counting from the year 2005 onward, the ongoing remodelling process may be itemized by a total of 476 measures, affecting up to 1983 network kilometres. Implementing these measures until 2025 and beyond within the Thuringia road network model, at least every 12th edge of the directed network graph changes is properties. The projects are pointing to the respective edges of the underlying road network model of some 50,000 edges.

Table II: Affected edges of the road network model – by measure and road class (Source: Own analysis)

Road Class / Measure	Ø (inactive road)	A (motorway)	B (federal)	L (state road)	K (county road)	G (comuunity r.)	Σ
Abandonment	60		2			2	64
Newly Constructed	12	84	776	426	22	32	1352
Upgrade/Redesign	4	206	638	344	16	30	1238
Redesignation	4		12	62	138	274	490
Σ Edges	80	290	1428	832	176	338	3144

The measures are grouped into four possible state transitions of a network edge: (i) Abandonment, (ii) activation of a newly constructed edge, (iii) upgrade/ redesign, or (iv) a redesignation of the public encumbrance to another entity - typically at county or community level. A preliminary breakdown by measure types and road classes is given in Table II.

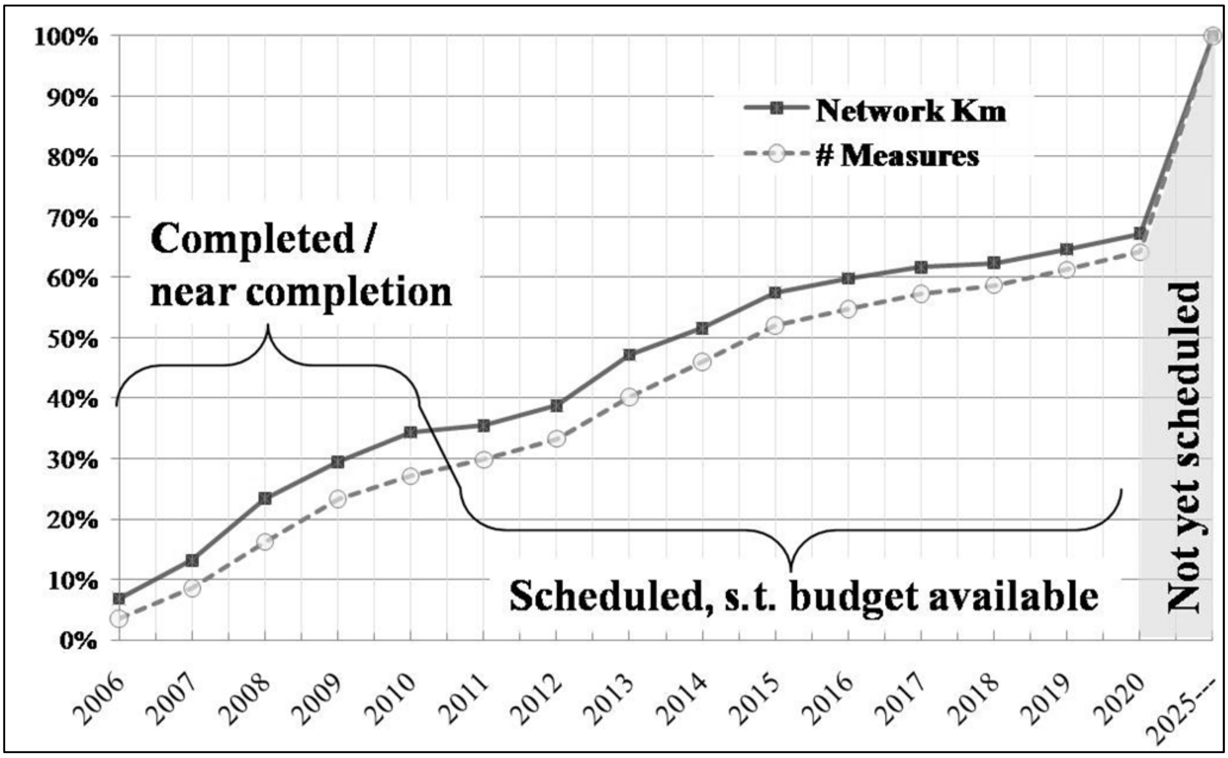

Figure 6: Goal realization levels implementing the state road network programme (Source: Own representation)

The State Road Construction Authority schedules the remodelling projects according to its priorities (e.g. safety issues, capacity increase, cost savings), the benefit cost ratios (BCR) and subject to the assigned budgetary funds. Since the German planning legislation is known to be quite complex, the time of completion may only be conclusively predicted as soon as the construction plan is no more appealable.

Based on experiences regarding past planning durations until a legally binding approval notice as well as the required construction period - depending on the project characteristics, a projection to 2025 and beyond was made. As shown by the cumulative chart in Figure 6, the completion in terms of the number of measures and the network kilometres affected is relatively evenly spread over two decades.

However, due to a current and foreseeable scarcity of resources, only two thirds of the preconceived remodelling measures could be scheduled so far. The rivalry between investment opportunities defines a choice situation. This raises the question on the extent at which network enhancement and improved accessibility within the central place grid - measured by the RIN scheme - may coincide.

The call for consistency is bidirectional, characterized by a division of labour in the search for a joint optimum in the network context: The upgrading programme – as far as travel times may be cut – shall include as many links with an urgent need for accessibility improvement as in the realm of the budget. Conversely, the designation of a road corridor for any central place connection shall be geared to goal of the network operator, e.g. cost savings through a better channelization etc.

4.3 Assessment of Results

The software-assisted findings to date are twofold: At first, we assume the timely realization of the project portfolio, given the current schedule, analyzing whether the accessibility standards will be met and which CP network is obtained by 2025. Secondly, we seek to identify opportunities for accessibility improvements, to be realized by a partial rescheduling of the remaining projects and/or a specification of new measures.

a) Effects of the Remodelling Projects Portfolio

A statistics of results is shown in Table III. The influences of the road remodelling projects on accessibility improvements within the CP grid can be justified, as far as the 2007 draft version of the RIN parameter set is deployed. The figures point on some instabilities and difficulties in applying them to decentralized, sparsely populated areas.

Table III: Percentage of CP Connections with satisfactory (= "C") RIN 2008 level of service; results of draft parameter set of 2007 in brackets; for the years 2005/2013/2025 (Source: Own analysis)

Year CP Connections	2005	2013	2025
Tier 0/I: 33	87.9 (87.9)	97.0 (87.9)	97.0 (87.9)
Tier II: 185	100.0 (37.3)	100.0 (44.1)	100.0 (64.1)
Tier III: 814	99.3 (68.3)	99.6 (72.6)	99.8 (79.7)

The massive renewal of the infrastructure between 1990 and 2005 widely accounts for the surprising finding: The federal accessibility standards on small-scale "Tier III" grid have been met entirely already back in 2005. The vast majority of the successfully completed projects were indeed consistent with the ideas of accessibility improvements with a central place structure. As a consequence of this, an argumentation in favour of forthcoming projects from on the grounds of accessibility improvement fails. Thus the current guideline is leaving hardly any room for manoeuvre at a small-scale level. Taking the more rigorous RIN draft version, the accessibility on the lowest-possible "Tier III" is still mostly satisfactory, and subject to further improvement until 2025. In the case of the distant connections the top "Tier 0/I" there is fewer ambiguity between the RIN versions.

As aforementioned, the investigation of accessibility is also parameterized by the underlying central place structure. Its density in Thuringia is well above the national average, yielding to unusually short distances to be covered. Assuming a future, more realistic "thinned-out" grid in the light of the ongoing socioeconomic developments, this will certainly bias the results to the negative direction.

The display window of Figure 7 substantiates the assumption of remarkable changes in the use of physical networks by connections of the investigated CP grid. Shortest paths are increasingly established by high-performing of motorways, federal and state roads. Explicit comparisons of details in the network assignment graphs of 2025 versus 2005 predominantly suggest a process of traffic concentration, while a lot of minor road become dispensible. According to the computational results, the overall length of the functional network 2025 vs. 2005 is reduced by 8.0 per cent. A future coarse CP grid, of course, would reduce the required network lengths drastically.

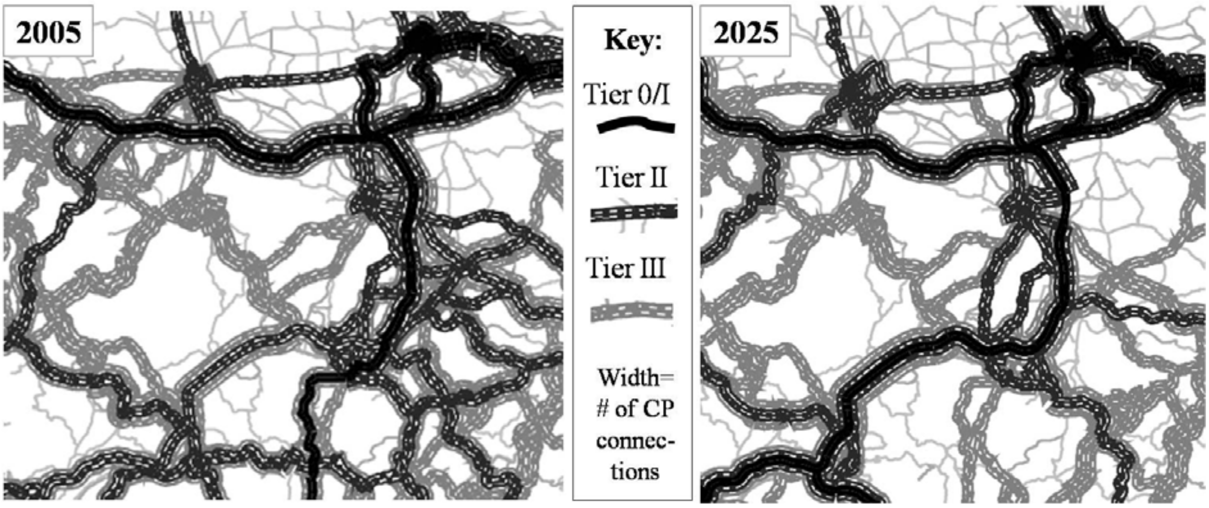

Figure 7: Detail of the CP grid to road network assignment results 2005 vs. 2025 (Source: Own representation)

b) Identification of Individual Projects

The second research task was to explore possibilities to intervene in the road remodelling plan from the viewpoint of spatial development considerations. Requirements of rescheduling of the remaining projects and/or the proposition of new projects may be addressed on the state territory only. The unified problem formulation allows for computing a different order of the projects for 2014 and beyond, possibly leading to earlier gains in terms of accessibility.

The process of identifying and scheduling appropriate projects for CP axes with accessibility deficits coincides with the previously mentioned inverse search problem for an a-priori stated search goal – here: a sufficient accessibility of “C”. Figure 8 exemplary depicts the 14 CP connections of Tier III as of year 2005.

This showcases the virtues of a unified onset and systematic, software-supported search instead of undertaking laborious manual efforts. The semantics of the constraint network reproduces the chain of the necessary reasoning steps as follows:

(i) Prescribe a global minimum service level for the base year
(ii) Determine those CP connections not meeting the accessibility requirements
(iii) Determine the road network edges in question
(iv) Determine an intersection set with all remodelling projects (scheduled/unscheduled) (In case there is not such a project, define a new project and add it to the portfolio.)
(v) Impose a “desired accessibility” constraint onto CP connection for a cut-off year
(vi) Reschedule the project set by observing that

$$G_p \le G_{p'} \Leftrightarrow BC_p \ge BC_{p'} \big| \forall p, p' \in \mathrm{P} \quad . \qquad \text{(Eq.15)}$$

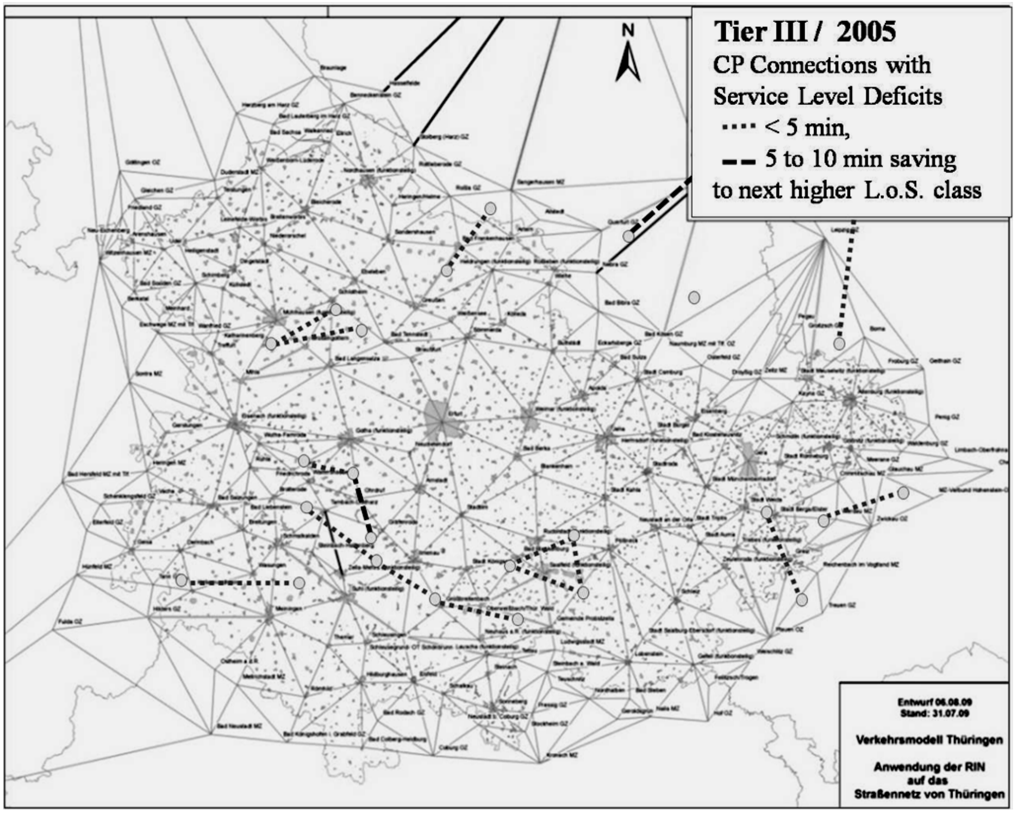

Figure 8 – Identification of accessibility improvement needs at Tier III central place grid (Source: Own representation)

5 CONCLUSIONS

1. The prioritisation of road investment proposals in accordance with a regionally balanced accessibility strategy supports a better target-orientation of public spending. In practice, it clarifies the need for consistency. The scientific question is: How an alignment of these spatial planning goals may amend or substitute a ranking of individual projects by their benefit cost ratio? As for the investigation area, we performed a test for consistency of the road improvement programme to date. It was found that the expansion and upgrading of the road networks mostly correspond to accessibility improvements within a central place grid.

2. The unified approach presented aims at an even higher level of consistency by merging the assessment paradigms of spatial planning and road network costs. We demonstrated how to formalize and apply an incremental decision support to a state road authority. The interval scheduling is posed as a not straightforward optimization problem.

3. The approach pursued reduces the problem size by focusing on infrastructure that is actually needed to maintain the CP grid. Furthermore, the idea was to dissect the planning task into a number of corridor-specific sub-problems of central place connections competing for the earliest begin of (accessibility-improving) remodelling projects. Instead of evaluating a complete origin-destination matrix ($O(n^2)$), a central place grid only refers to a small, yet expressive subset of o-d pairs. This formulation in conjunction with the usage of reasoning techniques to satisfy above described sets of constraints distinguishes our approach from previously known methodologies

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ANNEX

Table III: List of model dimensions (Source: Own representation)

Model Dimension	Set	Enumerated Set Elements	Indices	Size *)
Central Places / Traffic Cells	O	1, 2, 3, … (Origin / Destination)	i , j	≈ 120
Central-Place Functionalities	Z	None, GZ (County Centre), MZ (District C.), OZ (Regional C.), ME (Metropolis)	z	6
Central-Place Connection	R	e.g. 1-6, 4-9	r	≈ 210
Connection Significance Tier	S	0,1, 10, 100, 1000, 10000 - symbolizing {“none”,“I”, “II”, “III”, “IV”, “V”}	s	6
C-P Relation Level of Service	L	0,1, 2, 3, 4, 5 - symbolizing {“F”, “E”, “D”, “C”, “B”, “A”}	l	6
Road Network Set of Edges	E	1, 2, 3, …	e	≈ 40,000
Edge Cross-Section Types	T	Stolz-Maecke Classes \/ “inactive” (t=0)	t	≈ 20
Road Classification	K	“A” (Interstate), “B” (Federal Rd.), “L” (State Rd.), “K” (County Road), “OD” (Cross-town link), …	k	5
Calendar Year	Y	0, 1, 2, 3, ... (Index)	y	100
Netw. Remodelling Projects	P	1, 2, 3, ... (Index)	p	≈ 300
Projects’ Tackled Edges Set	H_p	1, 2, 3, ... (Index)	h	≈ 5

Table IV: List of endogenous variables (Source: Own representation)

Variable Name	Symbol	Unit	Domain Bounds
Actual (Average) Link Speed (e, y)	V	km/h	{0, 130}
C-P Relation Level of Service (r, y)	L	< L >	Set
Average Traffic Volume (AADT) (e, y)	Q	1000 Veh./24h	{0, 1000}
Link Capacity Utilization (e, y)	U	100 * %	{0, 1000}
Travel Time / (r, y) or (e, y)	Θ	min	{0, 1000}
Number of C-P-Connections (e, y)	N	#	{0, 10}
Current Link Classification (e, y)	k_e	< K >	Set
Connection Significance (e, y)	$S*$	-	{0, 10000}
Infrastructure Costs (e, y)	C	1000 €	{0, 10000000}
Scheduled Project Start Year (p)	G	-	{0, 100}
Annual Project Expenses (p,y)	M	1000 €	{0, 10000000}

Table V: List of exogenous variables / constants and parameters (Source: Own representation)

Constant Name	Symbol	Unit	Dimension
Surface Coordinates	GL, GW	deg	i
Central-Place Presetting *[1]	CP	< Z >	i, y
Connection Significance Presetting *	CS	< S >	r,y
Air-Line Distance	AL	km	$\{i, j\}$
Access Time *	AT	min	i, j, y
Dimensioned Link Capacity	DC	1000 Veh./24h	t
Egress Time[2]	ET	min	i, j
Network Edge Length	EL	km	E
Network Corridor Designation *	CD	< E >	$\{ \{e\}\}_{r,y}$
Speed-Flow Curve	CR	km/h	t, Q, k
Required Minimum Speed (L.o.S.)	RS	km/h	$\{q, L\}$
Marginal Infrastructure Unit Cost	UC	€/ 1000 Veh./km/a	t, Q, k
Marginal Social Cost	SC	€/ 1000 Veh./km/a	t, Q, e
Edge Upgrade Investment Cost	EI	1000 €/km	$\{t,t'\}$
Fixed Investment Cost [Project]	FI	1000 €	p
Benefit Cost Ratio Class [Ratio]	BC	-	p
Total Infrastructure Budget / Year	TB	1000 €	y
Individual Remodelling Measure	IM	< E,T,T,K,K >	$\{ (e,t,t',k,k') \}_p$
Precedence between Projects	PM	< P, P >	$\{ (p,p') \}$
Project Cost	PC	1000 €	p
Project Duration	PD	a	p

Table VI: List of functional coefficients used (Source: Own representation)

Coefficient Name	Symbol	Dimension
RIN function, linear factor "0"	$\beta_{0,l}$	l (= levels of service)
RIN function, linear factor "1"	$\beta_{1,l}$	
RIN function, exponent	γ_l	

[1] Presettings marked with the asterisk (*), i.e. the CP set, the connection significances as well as the network corridor designation for each connection, are assumed to be fixed at least for a five-year period. This also holds for the zonal access and egress times.
[2] In agreement with the RIN guidelines, the road "egress times" include search time for parking space.