INTERDEPENDENCE AMONG TRANSPORT INFRASTRUCTURE PROJECTS – A CHALLENGE FOR COST-BENEFIT ANALYSIS

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ABSTRACT

Transport (infrastructure) master plans – at regional, national or supra-national level – comprise a set of infrastructure measures. The financial crisis has stimulated national governments to develop fiscal stimulus packages, in several cases including transport infrastructure investment projects. In many countries the infrastructure projects are subject to an evaluation procedure to select the best projects or to set priorities according to economic criteria. Usually the evaluation methods follow the ›with/ without‹ principle, i.e., the costs and benefits of a project are calculated for a base case without the project and compared with the results including the project for a future time period. This presupposes that the projects are independent of each other. However, it is just the characteristics of a transport network that the links are interdependent and, as infrastructure projects add new or improve existing links, this also holds for the projects to be evaluated. Some infrastructure projects might be characterised by substitutive interdependence, while others might interact in a synergetic context. Thus, benefits and costs of a project are strongly dependent on the existence/ non-existence of other projects. This paper intends to tackle this issue by firstly stating the nature of the formal problem by a dynamic mixed integer programme and secondly elaborating a heuristic method using a network algorithm and reducing the complexity of the combinatorial problem.

Keywords: assessment, interdependence, cost-benefit analysis, transport infrastructure, project appraisal, transport infrastructure package, transport policy, substitutability, complementarity, Trans-European Networks.

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1 INTRODUCTION AND MOTIVATION

Transport (infrastructure) master plans – at regional, national or supra-national level – often comprise a set of infrastructure measures, and thus represent investment packages or project bundles. In some cases, infrastructure measures of transport master plans contain »mega infrastructure projects« in the dimension of investments critically discussed by FLYVBJERG ET AL. (2003), which involves an increase in risks and considerably enhances the challenges of project assessment. The current financial crisis has two impacts: firstly, national Governments have developed economic stimulus packages, in several cases consisting of transport infrastructure investment packages; secondly, the requirement to save public funds has resulted in national Governments' decision to skip or to postpone infrastructure projects which have already been agreed on.
The infrastructure projects contained in such master plans or economic stimulus packages are subject to an evaluation procedure, whose outcome determines whether or not a project will be realised or which priority should to be assigned to project implementation.

Such transport infrastructure investment programmes however, may consist of interdependent projects: some infrastructure projects might be determined by substitutive interdependence, while others might find themselves in a synergetic context. Thus, project appraisal for each individual project of an infrastructure package poses a challenge, since the level of benefit an individual project generates, may depend on the assumption on the realisation of other components of the infrastructure package.

In the case of significant substitutive interdependence among projects of an investment package the evaluation on the base of the ›with/ without‹ principle will lead to an overestimation of overall benefits of the package and foster overinvestment. In the case of complementary interdependence among projects the classical evaluation approach will lead to an underestimation of the overall benefits. In particular, the indirect benefits for other sectors of the economy often can only be captured, if network-wide or at least corridor-wide project packages are evaluated together.

This paper intends to elaborate a method to allow project appraisal approaches considering interdependencies between projects of an investment package, which will be based on particular components of the ›Interdependency Evaluation Framework‹ developed by SZIMBA (2008).

The paper is organised as follows: Section 2 gives – from a European perspective – a state-of-the-art as concerns the consideration of interdependence for the appraisal of transport infrastructure projects. In section 3, selected key features of interdependence analysis are discussed. Section 4 gives a brief summary of the theoretical approaches to solve the combinatorial problem. Section 5 represents the core of the paper by drafting a methodology for integrating the issue of interdependence into a cost-benefit scheme, before a few outcomes of an application example on interdependence analysis are highlighted within section 6. Conclusions are drawn in section 7.

2 STATE OF THE ART OF CONSIDERATION OF INTERDEPENDENCE

This section – based on SZIMBA (2008) – gives an overview on in how far the matter of interdependence among infrastructure projects of an investment programme is tackled in project assessment in Europe.

The European Conference of Ministers of Transport (ECMT) emphasises the importance of the consideration of interdependencies for the evaluation of the impact of transport infrastructure projects that are part of an infrastructure programme:

> »The assessment […] must address the programme and not simply component projects, and must evaluate the return on a given infrastructure as additional or competing links are added» (ECMT 2004: 3).

The guidelines of the European Commission for ›Socio-Economic Cost Benefit Analysis of Transport Infrastructure Project Appraisal‹ recommend that projects which are part of an investment programme and which may generate interdependencies are to be assessed both as »stand-alone projects« and as part of the whole infrastructure programme (UN/ECE 2003). Within the TEN-STAC[1] project, infrastructure measures have been assessed from these two points of view (SZIMBA ET AL. 2004; TEN-STAC 2004A; TEN-STAC 2004B). ›The Railway Project Appraisal Guidelines‹ emphasise – with regard to rail infrastructure investment programmes – that:

> »the implementation of related projects […] can have important effects on the profitability of the whole investment programme« (EC, EIB 2006: 23).

Furthermore, the need for further research is stressed about the impacts a rail infrastructure investment has on other parts of the rail network. However, in the evaluation sheets[2] for the current practice of project appraisal in Europe (ODGAARD ET AL. 2005) prepared within the HEATCO[3] project, the consideration of interdependencies among infrastructure projects is explicitly mentioned in the case of a few countries like Germany and Hungary. In the case of Germany, the benefits are calculated for each project individually, with regard to the following two infrastructure configurations: the minimum infrastructure configuration, in which none of the other projects of the investment programme are assumed to be realised and the maximum infrastructure configuration, in which all projects of the investment programme are assumed to be implemented. More specifically, this method has been applied to determining interdependencies between infrastructure projects in order to pre-select and define transport infrastructure projects for the revision of the German Transport Master Plan (SSP CONSULT

[1] TEN-STAC: Scenarios, Traffic forecasts and Analysis of Corridors on the Trans-European Network.
[2] The following 25 countries were in the scope of the analysis: EU member states (without Luxembourg, Bulgaria and Romania) and Switzerland.
[3] HEATCO: Developing Harmonized European Approaches for Transport Costing and Project Assessment.

2002). In the case of Hungary, infrastructure projects, which may create interdependencies, are considered in additional sensitivity and risk analyses.

In the summary of their national comparison of methodologies of transport project appraisal, HAYASHI AND MORISUGI (2000: 88) conclude that the consideration of »network-wide analysis […] may also require a more standardized system» – an aspect which in a wider sense may embrace the consideration of interdependence.

Summarising the current state-of-the-art of consideration of project interdependence in transportation planning, it can be stated that the phenomenon is treated – if treated at all – as an exceptional case for which simple extensions of the conventional ›with/ without‹ approach are suggested.

3 KEY FEATURES OF INTERDEPENDENCY ANALYSIS

3.1 Type of Interdependencies

First of all, interdependencies can be classified into horizontal and vertical relationships among projects. Horizontal relationships are given if the utility of a project is influenced by the existence of another project for the same period of time. Vertical relationships mean that influences occur over time, i.e. investment action at time period t influences the decision on an action at time period t+k. For instance the evolution of demand can justify an investment in two small projects p_t at time period t and p_k at time period t+k. If, instead, the project p_i is designed at a higher capacity then the realisation of project p_k can be cancelled (or vice versa). It will be shown in section 4 that the consideration of vertical interdependencies increases the complexity of the problem significantly such that we focus in the first instance on treating horizontal interdependencies.

Formally, horizontal interdependence can be measured as follows:

Assuming two infrastructure projects p_k and p_l to be under evaluation, the utility balance can be formulated as:

(3.1) $$U(p_k \cup p_l) = U(p_k) + U(p_l) + \varepsilon(p_k, p_l)$$

where

$U(p_k)$	benefit caused by the implementation of project p_k,
$U(p_l)$	benefit caused by the implementation of project p_l, and
$U(p_k \cup p_l)$	benefit caused by the implementation of the project combination $p_k \cup p_l$

Solving for $\varepsilon(p_k, p_l)$, results to:

(3.2) $$\varepsilon(p_k, p_l) = U(p_k \cup p_l) - U(p_k) - U(p_l)$$

$\varepsilon(p_k, p_l)$ is denoted as ›ε-value‹ or ›interdependency measure‹. Evaluating $\varepsilon(p_k, p_l)$ allows insight into the type of interdependency prevailing between p_k and p_l. If $\varepsilon(p_k, p_l) > 0$, the utility of the project bundle $p_k \cup p_l$ exceeds the sum of utilities attained by realising p_k and p_l individually: $U(p_k \cup p_l) > U(p_k) + U(p_l)$. This type of interdependency is called **complementarity** and can be synonymously used with **synergy**.
In the field of transport infrastructure planning the emergence of »synergy effects that can be generated by an integrated transport network design« is one of the reasons for the state to »act as a provider of transport infrastructure or at least to have this provision take place under its strict control« (ROTHENGATTER 2000: 90).

$\varepsilon(p_k, p_l) < 0$ implies the utility of a combination of sets of projects $p_k \cup p_l$ being below the sum of utilities resulting from an isolated realisation of the measures: $U(p_k \cup p_l) < U(p_k) + U(p_l)$. In this case, the interdependence between p_k and p_l is characterised by **substitutability**.

If $\varepsilon(p_k, p_l) = 0$ is fulfilled, the utility generated by the combination of projects equals the sum of the utilities arising from the realisation of the measures in isolation: $U(p_k \cup p_l) = U(p_k) + U(p_l)$. Thus, with regard to the considered utility component, the relationship between p_k and p_l is characterised by **additivity**. This means that the benefits of the projects are additive and the overall utility of a programme can be measured by adding up the stand-alone evaluations.

Interpreted in the concept of economies of scope, »investment in a complementary part of the network will feed additional traffic lowering unit costs«, while »conversely investment in a competing network will abstract traffic, reducing density and raising unit costs« (LAIRD ET AL. 2005: 539).

The benefit of an infrastructure project p, U(p), is defined by the cost savings associated with the implementation of p:

(3.3) $$U(p) = C(p\ \text{not realised}) - C(p\ \text{realised})$$

Where:

C(p not realised) costs arising in a situation in which p is not realised, and
C(p realised) costs arising in a situation in which p is realised.

The cost values C(p not realised) and C(p realised) refer to the utility component under consideration for the interdependency analyses, such as time costs, costs caused by the emission of air pollutants or costs caused by the emission of greenhouse gases. It does neither embrace investment costs nor wider economic benefits of construction activities.

3.2 Pre-Conditions of the Occurrence of Interdependence

Due to the characteristics of networks, changes on a network link may generate effects throughout the whole network and – if they affect mode choice – of other networks of competing modes. Therefore, each transport infrastructure measure A has the potential of affecting demand characteristics on another infrastructure measure B.
However, an important pre-condition for the emergence of mutual interdependencies between project pairs is the existence of a potential for common demand: the reason for the emergence of both interdependencies is that the infrastructure measures of two projects affect the generalised cost of the same origin/ destination (O/D) relations (BMVBW 2002: 43). If infrastructure projects belong to the same mode and have impacts on the generalised cost of the same O/D relations, interdependencies are indicated by interactions regarding route choice. For infrastructure improvements relating to different modes, but with impact on the generalised cost of the same O/D relations, interdependencies are characterised by interactions regarding market shares and transport volumes by mode.
Interdependencies may also occur for O/D relations which are only indirectly concerned by the projects under consideration: assuming an O/D relation r, whose routing is completely invariant to the infrastructure investments A and B. If project A is implemented, traffic demand of r's route is shifted towards A, so that the travel time on O/D relation r is reduced. If project B is implemented, a certain share of the demand on the routing of r is shifted towards B. If both A and B are implemented, the travel time on r's routing is further reduced, since demand on r's route is shifted to both A and B.
In any case, one can expect the highest extent of interdependencies among projects that have a high level of common demand, since such O/D relations profit directly from an implementation of both projects or either of them[4].

3.3 Two Basic Viewpoints of Evaluation

The evaluation of transport infrastructure projects is based on the performance difference of impact variables in configurations ›with‹ and ›without‹ implementation of a project. Thus major importance has to be attached to define the ›base case‹ and the ›project case‹ (VAN EXEL ET AL. 2002), as well to determine, in how far effects on the broader network can be expected to be relevant and hence, should be in the scope of assessment (BUTTON 1993).
If interdependence occurs, the benefit of a project depends on the infrastructure configuration the project is added to. In order to examine the variation of projects' benefits under different network configurations, the concept of marginal benefits is introduced. The marginal benefit of a project p in respect to the infrastructure configuration L, U(p|L), is determined by the following equation:

$$U(p|L) = U(p \cup L) - U(L) \tag{3.4}$$

where:

[4] However, one has to be aware of the possibility, that interdependency can also be caused by O/D relations that are only indirectly affected by the infrastructure projects.

$U(p \cup L)$	utility of an infrastructure configuration, in which p and the infrastructure configuration L are implemented, and
$U(L)$	utility of an infrastructure configuration, in which the infrastructure configuration L is realised.

Thus, U(p|L) expresses p's utility, if p is added to the infrastructure configuration L.

When evaluating transport infrastructure projects of an investment package, there are two basic points of departure: the ›minimum‹ infrastructure configuration, i.e. the network without investments to which the projects or programmes are added, and the ›maximum‹ infrastructure configuration, which includes all projects or programmes, from which the single projects or programmes are deleted to measure their contribution to the overall utility. Therefore, in general heuristic approaches to the interdependence problem use "add" or "drop" approaches:

- Evaluation with respect to the ›minimum infrastructure configuration‹ implies analysing the impacts of projects that are added to the Reference scenario (in this case: L=Ref). In the Reference scenario none of the infrastructure projects are assumed of being implemented. Hence the benefit can be measured occurring from adding projects to the Reference situation.
- The assessment relating to the ›maximum infrastructure configuration‹ is based on the assumption that all projects of the investment package are realised (in this case: L=P_all). Thus the loss of benefit can be measured which is expected to occur, if projects are dropped from the P_all scenario.

Figure 1 (source: SZIMBA 2008) gives an overview of the scope and the applied denotation of infrastructure scenarios. Ranging from the "Ref" infrastructure configuration, in which none of the projects are realised, to the P_all scenario, in which all projects of the investment programme are assumed of being realised, all possible combinations are depicted in the matrix. The column labels of the matrix in Figure 1 indicate, how infrastructure configurations are addressed: for instance, the notation $\{p_k\}$ refers to a network configuration in which the project p_k is added to the Reference scenario, whereas $\{P \backslash p_k\}$ implies the realisation of each project of P besides p_k.

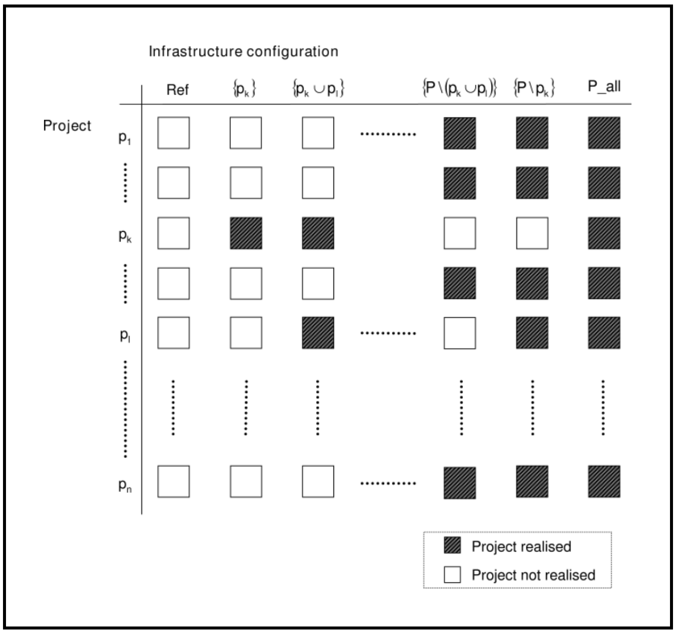

Figure 1: Transport infrastructure scenarios applied and their denotation

3.4 The Combinatorial Challenge

Interdependencies between transport infrastructure projects can occur between pairs of projects or between individual projects and certain project combinations. Assuming an investment programme of n projects, a given project could be assessed with respect of Z project combinations:

$$Z = \sum_{k=1}^{n-1} \binom{n-1}{k} = \sum_{k=1}^{n-1} \frac{(n-1)!}{k!(n-k-1)!} = 2^{n-1} - 1 \qquad (3.5)$$

where

n is the number of infrastructure projects of an investment package;
Z is the number of possible combinations for an individual infrastructure project to be assessed for.

Such high number of possible combinations (more than 500 million combinations in case of an investment package consisting of 30 elements) raises a combinatorial challenge and requires a methodology, which allows the number of relevant combinations to be restricted to a reasonable dimension.

4 OPTIMAL NETWORK DESIGN CONSIDERING INTERDEPENDENCE AND EVOLUTION DYNAMICS

Before formulating a heuristic procedure to solve the interdependency problems stated in section 3, it is useful to formulate the underlying optimization problem. This makes it easier to evaluate the simplifications made in the heuristic approach. It has been shown in the literature that the dynamic network design problem can be formulated as a mixed integer programming problem, which captures all types of interdependencies, including horizontal and vertical. Problems of this type have been investigated intensively already about 40 years ago, e.g. by BOYCE ET AL. (1974), ROTHENGATTER (1977, 1979), or BOYCE AND JANSON (1980). LEBLANC and ROTHENGATTER (1983) have formulated the type of network algorithms which in principle can be applied to solve the optimal network problem.

A rough summary of the modeling approaches is as follows:

(4.1) $$\max_{x_{tr}, y_{tr}} \quad \sum_{r=1}^{R} \sum_{t=1}^{T} u_{tr} y_{tr},$$

subject to the constraints

(4.2) x_t is user- or system-optimal, $\forall t$, (presupposing de-central or central control of network activities);

(4.3) $\sum_{\tau=1}^{t} \sum_{r=1}^{R} k_{\tau r} y_{\tau r} \leq \sum_{\tau=1}^{t} B\tau,$ (as an example for budget interdependence);

(4.4) $\sum_{t=1}^{T} y_{tr} \leq 1,$ (as an example for static interdependence);

(4.5) $\sum_{\tau=1}^{t} y_{\tau r} - \sum_{\tau=1}^{t} y_{\tau l} \leq 0,$ for some *r, l* (as an example for dynamic interdependence);

where

(4.6) $u_{tr} = \int_{\tau=t}^{T_r} b_r \left[x_\tau \left(y_{1,\dots,} y_\tau \right), t \right] \exp(-i\tau) d\tau$
(capturing the dynamic interdependence between projects stemming from the evolution of demand);

t is the time of realisation of a project (provision of a link);

$b_r(\tau)$ is the gross benefit of project *r* in time period τ, with τ representing an indexed variable;

x_t is a vector of activities on the network in time period *t*,
$x_t = (x_{t1},...,x_{t2}...,x_{tN}), x_{tr} \geq 0$

y_t is a vector of decision variables for the provision of infrastructure in time period *t*,
$y_t = (y_{t1},...,y_{tr},...,y_{tR}), y_{tr} \in \{0,1\}$

N is the number of links in the network, including all new and replacement investments;

R is the number of candidate projects;

T is the number of time periods;

i is the social discount rate;

T_r is the lifetime of project *r*;

$k_{\tau r}$ is the costs of project r in time period τ , with τ representing an indexed variable;

B_τ is the cost budget of time period τ, with τ representing an indexed variable;.

The theoretical formulation shows that it is possible to treat interdependency by an appropriate formulation of the objective function (4.5) and the adjustment of constraints. It also considers the basic problem of the optimal design of road networks, which is the difference between systems and user optimal load patterns (4.2). The above optimization problem is only convex, if a systems optimal solution is guaranteed for the network loads (LEBLANC and ROTHENGATTER 1983). In the case of user optimal load patterns the BRAESS paradox can occur, i.e., adding a link to the network can reduce overall utility or increase total costs of the network activities.

In the seventies and eighties of the 20th century manifold approaches have been tried to solve the above problem by branch-and-bound or branch-and-cut algorithms. More recent research works in this area focus for instance on the temporal scope of infrastructure investments in the context of demand uncertainty (UKKUSURI AND PATIL, 2009), or under consideration of revenue collection (HONG AND SZETO 2009).

Generally speaking, such algorithms work for small networks and a small number of projects. Large scale network problems of practical dimension can in general not be solved optimally, because the network computations are time consuming: the VACLAV model, a strategic network-based passenger model at European scale (see SCHOCH 2004); takes – depending on the number of iterations – up to four hours for one model run. The TRANS-TOOLS model, a network-based transport and assessment model newly developed on behalf of the European Commission (see e.g. BURGESS ET AL. 2008), even takes several days for one model run. Moreover, the number of project combinations might be quite large (see section 3.4). A simplification of the network model is in most cases not a promising approach, because a good estimation of benefits on a project scale requires an accurate modeling of the network flows. Therefore, »efficient approximation techniques are needed to solve these problems« due to the »large scale nature of transportation networks and the possibility of many […] scenarios« (UKKUSURI AND PATIL 2009: 640). Thus, the remaining possibility is to simplify the combinatorial problem by heuristic techniques, which will be the focus of the following sections.

5 A METHODOLOGY FOR INTEGRATING THE ISSUE OF INTERDEPENDENCE IN A COST-BENEFIT SCHEME

5.1 Basic Requirements and Outline of the Methodology

This section intends to sketch the basic requirements of a heuristic methodology for the incorporation of interdependence in a cost-benefit analysis (CBA).

First, the method should consider that the nature of a transport infrastructure investment programme can be very different, for instance in terms of

- the dimension of projects (large projects with international or national significance versus medium-sized or smaller projects with mainly regional or local relevance), or
- the spatial context of projects (projects within the same spatial context versus projects with completely disjunct catchment areas).

Since the general pattern of interdependence between projects within an investment package may differ significantly among different investment packages, the approach to be developed has to follow a differentiated and flexible approach, allowing its application in compliance with the specific peculiarities of an investment package.

In a first step, it can be checked by expert judgement whether a strong interdependence between projects can be expected. Geographical distance can be used as a main criterion. For instance, an orbital road, which is considered to be built in Warsaw will be independent from the existence of a further Tagus River bridge in Lisbon. All projects which are independent from other projects can be treated by conventional cost-benefit analysis.

For the remaining projects, interdependence between pairs of projects of the infrastructure bundle are identified and measured. If the pair-wise interdependence is exceeds a threshold of relevance, the corresponding projects will not be assessed independently of each other. If the relevance criterion is not met, the project pair is taken from the candidate list.

The pair-wise check of interdependence can be extended to a check of group interdependence, if there is an indication of interactions between clusters of projects. For instance all projects within a corridor A can be checked for interdependence with all projects within a corridor B. If the corridors have parallel directions and spatial proximity, substitutive relationships can be assumed. If a North-South corridor intersects with an East-West corridor, it can be assumed that there is a complementary relationship between the projects of these corridors.
The outline for the approach for the consideration of interdependence is synthesised by Figure 2.

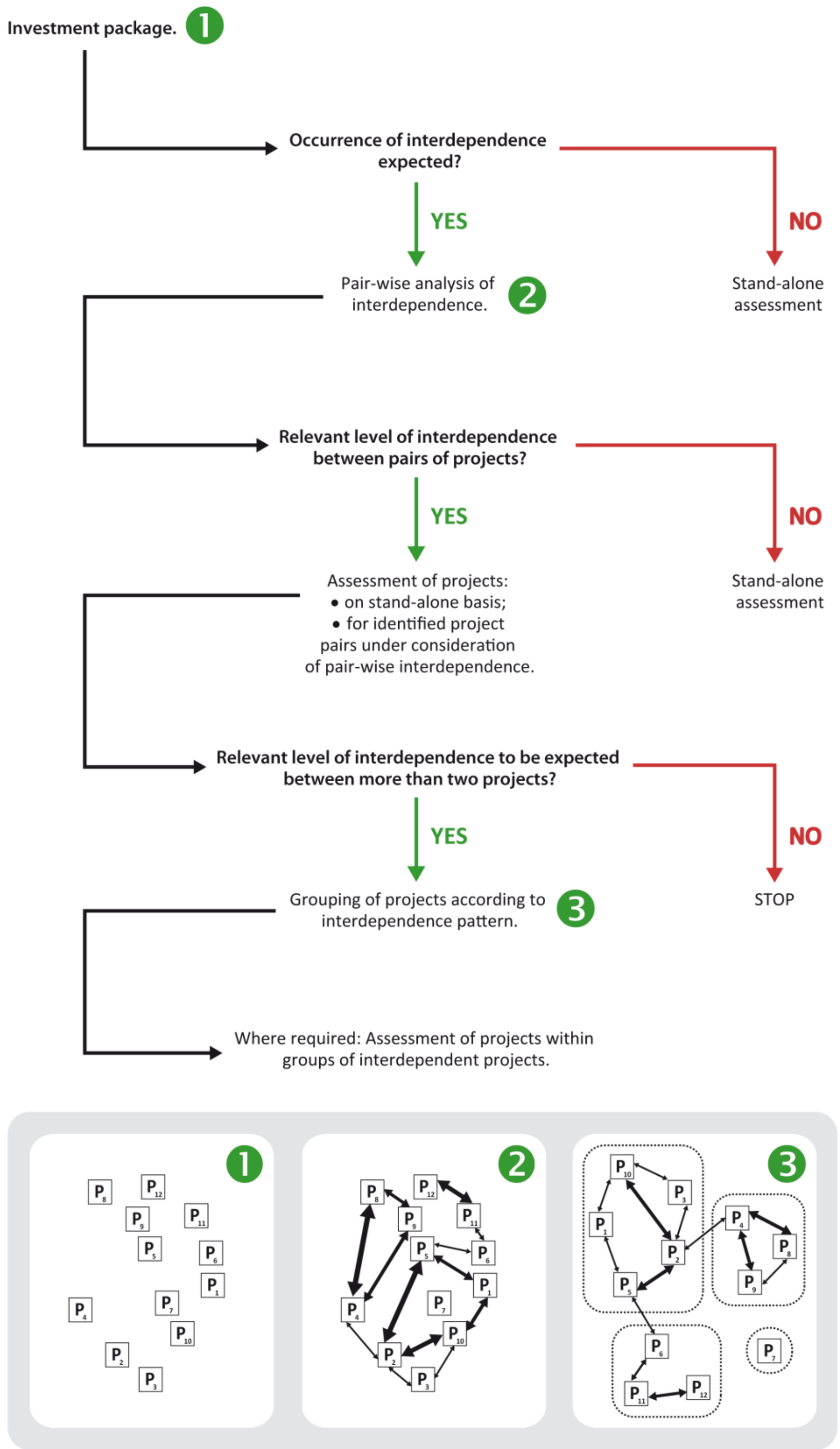

Figure 2: Outline for the consideration of interdependence

5.2 Sketch for Implementation of Consideration of Interdependence

Given the outline of the method to incorporate the matter of interdependence into cost-benefit analysis presented in the previous paragraph and taking into account the key features of interdependence analysis summarised in section 3, the approach to be developed will tackle following three objectives:

1. General check on the occurrence of interdependence within an investment programme;

2. Confinement, localisation of interdependence at the level of project pairs;

3. Grouping of projects according to potential occurrence of interdependence.

Assuming n transport infrastructure projects under examination p_k (k=1, …, n), which are part of an investment programme $P=\{p_l, \dots, p_k, \dots, p_n\}$.

5.2.1 General Check on the Occurrence of Interdependence

In order to obtain general insight in the occurrence of interdependency among projects of an investment package, the two basic points of departure drafted in section 3.3 can be applied. Comparing the benefit of a project with respect of the minimum infrastructure configuration with the benefit of the same project in respect of the maximum infrastructure configuration, first conclusions can be drawn on the indication of interdependence.

Formally, the benefit of a project p_k in relation to the Reference scenario, $U(p_k|Ref)$, is computed, determined by the difference in costs arising from the Reference scenario C(Ref) and the costs arising from a configuration in which p_k is ›added‹ to the reference scenario, $C(p_k)$:

(5.1) $$U(p_k|\mathrm{Ref}) = C(\mathrm{Ref}) - C(p_k)$$

Furthermore, p_k's benefit in relation to the maximum infrastructure scenario – the P_all scenario – is calculated by the difference of costs arising from a situation in which all other projects besides the project itself are realised, $C(P\backslash p_k)$, and the costs arising from the implementation of all the projects, C(P):

(5.2) $$U(p_k|\mathrm{P\_all}) = C(P\backslash p_k) - C(P)$$

While $U(p_k|Ref)$ measures the decrease in cost, if p_k is added to the Reference scenario, $U(p_k|P\_all)$ measures the cost reduction if p_k is added to an infrastructure configuration, in which all other projects besides p_k are realised. The reciprocal value of $U(p_k|P\_all)$ can also be regarded as the increase in costs, if p_k is dropped from the P_all scenario.

Subsequently, $U(p_k|Ref)$ is compared to $U(p_k|P\_all)$ for all projects $p_k \in P$.

If

$U(p_k|Ref) \approx U(p_k|P\_all)$ is fulfilled $\forall\, p_k \in P$,

the projects of P can be expected to be independent of each other, and the projects can be evaluated independently of each other on the fast track. If this condition is not met, interdependence among individual projects is identified, and requires to be analysed further to measure the order of magnitude.

5.2.2 Confinement and Localisation of Interdependence at the Level of Project Pairs

In case the outcome of the previous step of analysis advises a further investigation of the occurrence of interdependence, interdependence is examined for pairs of projects, which allows localising the occurrence of interdependence among the elements of the investment package.

The benefit of a combined realisation of the infrastructure projects p_k and p_l, $U(p_k \cup p_l)$ can be expressed as the sum of benefits arising from an individual realisation of p_k and p_l and $\varepsilon(p_k, p_l)$:

(5.3) $$U(p_k \cup p_l) = U(p_k) + U(p_l) + \varepsilon(p_k, p_l)$$

Applying equation (5.3) both to the minimum infrastructure configuration Ref and the maximum infrastructure configuration P_all, and using equations (5.1) and (5.2), respectively, results in following interdependency measures of the project pair (p_k, p_1):

(5.4) $$\varepsilon^{Ref}(p_k, p_l) = C(p_k) + C(p_l) - C(p_k \cup p_l) - C(Ref)$$

(5.5) $$\varepsilon^{P\_all}(p_k, p_l) = C(P \setminus (p_k \cup p_l)) - C(P \setminus p_k) - C(P \setminus p_l) + C(P)$$

The values obtained give information on the type and extent of interdependence between pairs of transport infrastructure projects. A thorough interpretation of $\varepsilon^{Ref}(p_k, p_l)$ and $\varepsilon^{P\_all}(p_k, p_l)$ is available in SZIMBA (2008).

For making a decision on whether or not the infrastructure projects p_k and p_l should be evaluated independently of each other, not only the absolute interdependency measure is of importance, but also the extent of interdependence in relation to the overall level of benefits expected from a project. For this purpose the indicator RI is introduced, which measures the relative interdependency in relation to the benefits arising from the realisation of an infrastructure measure. Thus two infrastructure projects p_k and p_l can be recommended for assessment under consideration of each other, if the relative interdependency measure is above a certain threshold $\overline{RI}$:

(I) $$RI^{Ref}(p_k, p_l) = \frac{\left|\varepsilon^{Ref}\left(p_k, p_l\right)\right|}{U\left(p_k|Ref\right)} > \overline{RI}$$, (II) $$RI^{P\_all}(p_k, p_l) = \frac{\left|\varepsilon^{P\_all}\left(p_k, p_l\right)\right|}{U\left(p_k|P\_all\right)} > \overline{RI}$$,

(III) $$RI^{Ref}(p_l, p_k) = \frac{\left|\varepsilon^{Ref}(p_k, p_l)\right|}{U(p_l|Ref)} > \overline{RI}$$, (IV) $$RI^{P\_all}(p_l, p_k) = \frac{\left|\varepsilon^{P\_all}(p_k, p_l)\right|}{U(p_l|P\_all)} > \overline{RI}$$

If any of the conditions (I) – (IV) is met, the relative interdependency among p_k and p_l is above the defined threshold level, which implies that p_k and p_l should not be assessed independently of each other. Thus, under consideration of p_l the marginal benefit of p_k, $U^{Ref}(p_k|p_l)$, is – with regard to the Reference scenario – determined by following equation:

(5.6) $$\begin{aligned} U^{Ref}(p_k|p_l) &= U(p_k \cup p_l) - U(p_l) \\ &= C(Ref) - C(p_k \cup p_l) - \big(C(Ref) - C(p_l)\big) \\ &= C(p_l) - C(p_k \cup p_l) \end{aligned}$$

The corresponding benefit value with regard to the P_all scenario, $U^{P\_all}(p_k|p_l)$, can be computed as follows:

(5.7) $$\begin{aligned} U^{P\_all}(p_k|p_l) &= U(P\_all) - (\{P\backslash p_k\}) \\ &= C(Ref) - C(P\_all) - \big(C(Ref) - C(\{P\backslash p_k\})\big) \\ &= C(\{P\backslash p_k\}) - C(P\_all) \end{aligned}$$

Analogously, the marginal benefit values of p_k in respect of p_l, $U^{Ref}(p_k|p_l)$, and $U^{P\_all}(p_k|p_l)$ are calculated.

Thus, in a CBA, the benefit values $U(p_k|Ref)$ and $U(p_k|P\_all)$ – that represent a stand-alone assessment of p_k –, are to be replaced by the formulas (5.6) and (5.7) in order to measure p_k's benefits.

Interdependencies between transport infrastructure projects are not necessarily restricted to pairs of projects. Therefore the analysis of occurrence of interdependence may have to be extended further.

5.2.3 Grouping of Projects According to Potential Occurrence of Interdependence

In case an individual project p_k reveals – under consideration of the threshold value $\overline{RI}$ – relevant interdependence with more than one project of the investment package P, it might be the case that there are relevant mutual interdependences between an individual project and projects of a group of the infrastructure package. However, following the combinatorial challenge depicted in paragraph 3.4, it is not feasible to assess projects with respect of all possible project combinations. Therefore, a method is required which results in a grouping of projects such that interdependent projects are allocated to smaller sub-groups of the project bundle. More precisely, projects should be grouped in a way that a high level of interdependence is obtained among projects within the same group, and a low level of interdependence among projects allocated to different groups.

Taking into account the main evidence of the occurrence of interdependence – i.e. the pattern that different projects are relevant for the same demand segments (see paragraph 3.2) – a method has been developed by SZIMBA (2008) in order to group infrastructure projects of an investment package according to interdependence pattern. The core of this method is a cluster analysis approach which in the first step groups projects according to similarities in their demand structures. In the second step, the results of the cluster analysis are further processed, based on the objective to maximise the level of interdependence among projects of the same cluster and to minimise the level of interdependence among projects belonging to different clusters. The approach presumes the application of a network-based transport model in order to identify the demand segments (i.e. O/D relations) which utilise each infrastructure project. Based on this project-specific O/D data, ›demand structure matrices‹ and ›volumes matrices‹ are computed. These matrices are applied to generate similarity (distance) matrices which inform on the project pair-wise level of similarity (difference) in demand structures of the projects of the investment package.

Assuming the final partition resulting from the clustering approach is represented by $P^*=\{P_l^*, \ldots, P_j^*, \ldots, P_t^*\}$. $P_j^*=\{p_j^l, \ldots, p_j^f, \ldots, p_j^s\}$ is a cluster of the final partition P^*, and $\overline{P}_j$ represents a set of projects that can be formed by combining elements of P_j^*, with $p_j^f \not\in \overline{P}_j$.
Following equation (3.4), the marginal utility of a project p_j^f in relation to the partition $\overline{P}_j$, is determined by:

(5.8)
$$\hat{U}^{Ref}\left(p_j^f|\overline{P}_j\right) = U\left(p_j^f \cup \overline{P}_j\right) - U\left(\overline{P}_j\right)$$

Applying equation (3.3) to $U(p_j^f \cup \overline{P}_j)$ and $U(\overline{P}_j)$, gives following expression:

(5.9)
$$\begin{aligned}\hat{U}^{Ref}\left(p_j^f|\overline{P}_j\right) &= C(Ref) - C\left(p_j^f \cup \overline{P}_j\right) - C(Ref) + C\left(\overline{P}_j\right)\\ &= C\left(\overline{P}_j\right) - C\left(p_j^f \cup \overline{P}_j\right).\end{aligned}$$

$\hat{U}^{Ref}(p_j^f|\overline{P}_j)$ refers to a situation in which the projects of the other clusters are not assumed to be realised.

From the point of view of the maximum infrastructure configuration, the marginal benefit is regarded with respect of a situation in which the projects of the other clusters, $\{P^* \backslash P_j^*\}$, are assumed to be realised. Thus, with regard to a situation in which the projects of other clusters are realised, the marginal utility of p_j^f in relation to a combination $\overline{P}_j$, $\hat{U}^{P\_all}(p_j^f|\overline{P}_j)$, is determined by the following equation:

(5.10)
$$\hat{U}^{P\_all}\left(p_j^f|\overline{P}_j\right) = U\left(\left(P^* \setminus P_j^*\right) \cup p_j^f \cup \overline{P}_j\right) - U\left(\left(P^* \setminus P_j^*\right) \cup \overline{P}_j\right)$$

Under application of equation (3.3), $\hat{U}^{P\_all}(p_j^f|\overline{P}_j)$ can be expressed by:

$$\hat{U}^{P\_all}\left(p_j^f|\overline{P}_j\right) = C\left(Ref\right) - C\left(\left(P^* \setminus P_j^*\right) \cup p_j^f \cup \overline{P}_j\right) - C\left(Ref\right) + C\left(\left(P^* \setminus P_j^*\right) \cup \overline{P}_j\right)$$
$$= C\left(\left(P^* \setminus P_j^*\right) \cup \overline{P}_j\right) - C\left(\left(P^* \setminus P_j^*\right) \cup p_j^f \cup \overline{P}_j\right). \quad (5.11)$$

The value $\hat{U}^{Ref}(p_j^f|\overline{P}_j)$ gives information on the amount of marginal utility arising if the infrastructure project p^f_j is added to the infrastructure configuration $\overline{P}_j$, whereas $\hat{U}^{P\_all}(p_j^f|\overline{P}_j)$ represents the utility expected if p^f_j is added to a configuration in which the projects of the other clusters, $\{P^*\backslash P_j^*\}$, and $\overline{P}_j$ are in operation.

Assuming the project p_k fulfils the requirements of being assessed within a group of projects by a CBA, p_k's benefit values are calculated according to equation (5.9) and (5.11), respectively.

6 APPLICATION EXAMPLE

The drafted approach has not been applied so far explicitly for CBA. However, SZIMBA (2008) developed an ›Interdependency Evaluation Framework‹ for the measurement, identification and explanation of interdependence which has been the basis for drafting the three-stage approach of the methodology for the consideration of interdependence for CBA. The ›Interdependency Evaluation Framework‹ was applied to the priority corridors of the Trans-European Network (TEN-T) (EU 2004). The priority projects of the European Union (EU) are a set of 30 projects, most of them representing a number of large-scale infrastructure projects along pan-European transport corridors (see Figure 3 – left hand side: rail, right hand side road infrastructure projects). The investment volume of the investment package amounts to 225 billion € (estimations on the basis of the year 2004).

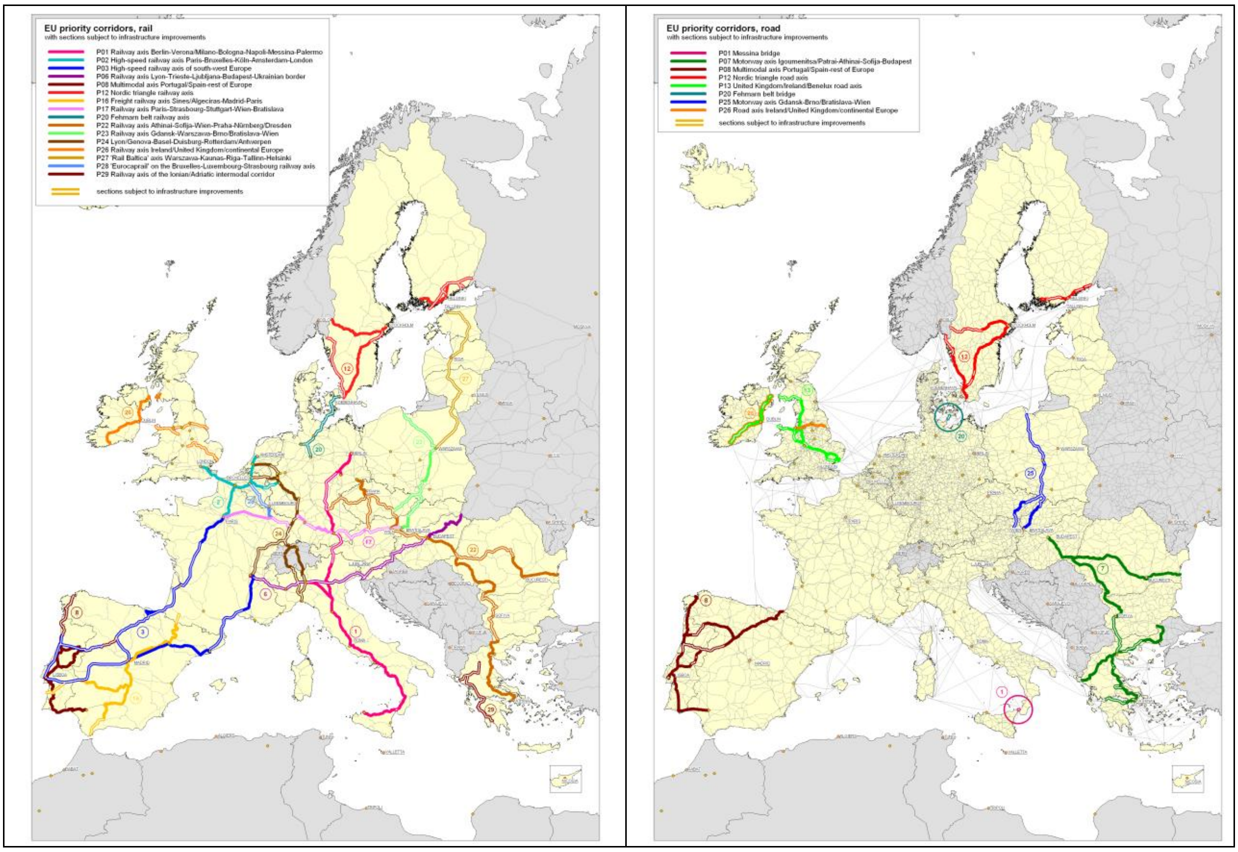

Figure 3: Scope of the EU priority projects along corridors (rail and road)

The application example proved the applicability of the three-stage approach on interdependence analyses to a real-world large-scale investment package, under usage of the VACLAV model, a strategic network-based (passenger) transport model running at the European scope. After computing projects' benefits on a stand-alone basis, a pair-wise interdependence analysis was performed for each project combination, followed by a cluster analysis based approach to group the projects according to occurrence of interdependence and, subsequently, the analysis of projects' benefits within these groups. A small excerpt of obtained results is highlighted in the following.

As an example, for the European priority corridor P17 (railway axis Paris – Stuttgart – Munich – Vienna – Bratislava) the analyses revealed with regard to benefits by passenger travel time savings

- at the stage of assessment on a stand-alone basis, a difference between the evaluation with regard to the minimum infrastructure configuration and the maximum infrastructure configuration by around 10 million € (M€) p.a.;
- at the level of pair-wise interdependence analysis, a relatively high level of synergetic interdependence with the priority corridors P24 (railway axis Lyon/ Genoa – Basel – Duisburg – Rotterdam/ Antwerp) and P28 ("Eurocaprail" on the Brussels – Luxembourg – Strasbourg railway axis), and relatively high substitutive interdependence with P01 (railway axis Berlin – Verona/ Milan – Bologna – Naples –

Messina – Palermo)[5] and P06 (railway axis Lyon – Trieste/ Koper – Ljubljana – Budapest – Ukrainian border);

- relatively high mutual interdependence within the group of following priority corridors: P17, P01, P06, P24, P28 and P02 (high-speed railway axis Paris – Brussels – Cologne – Amsterdam – London).

These results were – together with further outcomes of the interdependence analyses – summarised by ›Interdependence Evaluation Forms‹, as depicted exemplarily for P17 in Figure 3 (source: SZIMBA 2008).

[5] The reason for the surprising substitutive interdependence between the West-East corridor P17 and the North-South corridor P01 is explained in SZIMBA (2008).

Interdependence Evaluation Form

Priority corridor P17, Railway axis Paris-Strasbourg-Stuttgart-Wien-Bratislava

Benefit in relation to the Reference scenario (M€ p.a.) $U(P17\|Ref)$	165.40
Benefit in relation to the P_all scenario (M€ p.a.) $U(P17\|P\_all)$	175.57

i) Interdependence between P17 and all other priority corridors

Interdependency with all other priority corridors $U(P17\|P\_all) - U(P17\|Ref)$	+10.17

ii) Paired interdependencies between P17 and other priority corridors

	p_l where $c(P17,p_l) > 3$	p_l where $y(P17,p_l) > 50{,}000$
Relatively high level of common demand Reference scenario	P01, P22, P24, P25 > 3 million passengers p.a. common with P17	P01, P06, P22, P24 > 50,000 O/D relations common with P17
Relatively high level of common demand P_all scenario	P01, P22, P24, P25 > 3 million passengers p.a. common with P17	P01, P06, P22, P24 > 50,000 O/D relations common with P17

	p_l where $\varepsilon(P17,p_l) < -1$	p_l where $\varepsilon(P17,p_l) > 1$
Significant level of interdependence Reference scenario	P01, P06 ε < -1 million € p.a. (competition with P17)	P24, P28 ε > 1 million € p.a. (synergy with P17)
Significant level of interdependence P_all scenario	P01, P06 ε < -1 million € p.a. (competition with P17)	P24, P28 ε > 1 million € p.a. (synergy with P17)

	p_l where $RI(P17,p_l) < -0.03$	p_l where $RI(P17,p_l) > 0.03$
High relative interdependence Reference scenario	- competition with P17	P24 synergy with P17
High relative interdependence P_all scenario	- competition with P17	P24 synergy with P17

iii) Interdependencies between P17 and priority corridor combinations

Allocation to cluster	A, corridors in Western Europe
Further priority corridors allocated to cluster A	P01, P02, P06, P24, P28

	$\bar{P}_A$	Optimal configuration/ Minimal configuration	Value (M€ p.a.)
Maximum marginal benefit $\max_{\bar{P}_A}\left\{\hat{U}^{Ref}\left(P17\|\bar{P}_A\right);\hat{U}^{P\_all}\left(P17\|\bar{P}_A\right)\right\}$	P02, P24, P28	Cluster B, C, D, E, F, P02, P24, P28	182.24
Minimum marginal benefit $\min_{\bar{P}_A}\left\{\hat{U}^{Ref}\left(P17\|\bar{P}_A\right);\hat{U}^{P\_all}\left(P17\|\bar{P}_A\right)\right\}$	P01, P02, P06	P01, P02, P06	159.53

Figure 3: Interdependence Evaluation Form for EU priority corridor P17

Based on the outcomes of the formation of corridor clusters according to interdependence, P17's marginal benefit with respect of all project combinations within the derived group were computed. The results are illustrated by Figure 4 (source: SZIMBA 2008). The terminology for addressing certain marginal benefit values is defined as follows: the value associated with "Ref_6_24" is the marginal benefit, which is generated if P17 is added to an infrastructure configuration in which – on the basis of the reference scenario – the measures associated with the corridors P06 and P24 are realised. According to the methodology designed in section 5.2.3, the benefit value corresponds to $\hat{U}^{Ref}(P17|\{P06 \cup P24\})$. "Ref_X_6_24" implies, that – apart from P06 and P24 – the infrastructure investments on all corridors of the other clusters in which P17 is not part of, are realised, and complies with $\hat{U}^{P\_all}(P17|\{P06 \cup P24\})$.

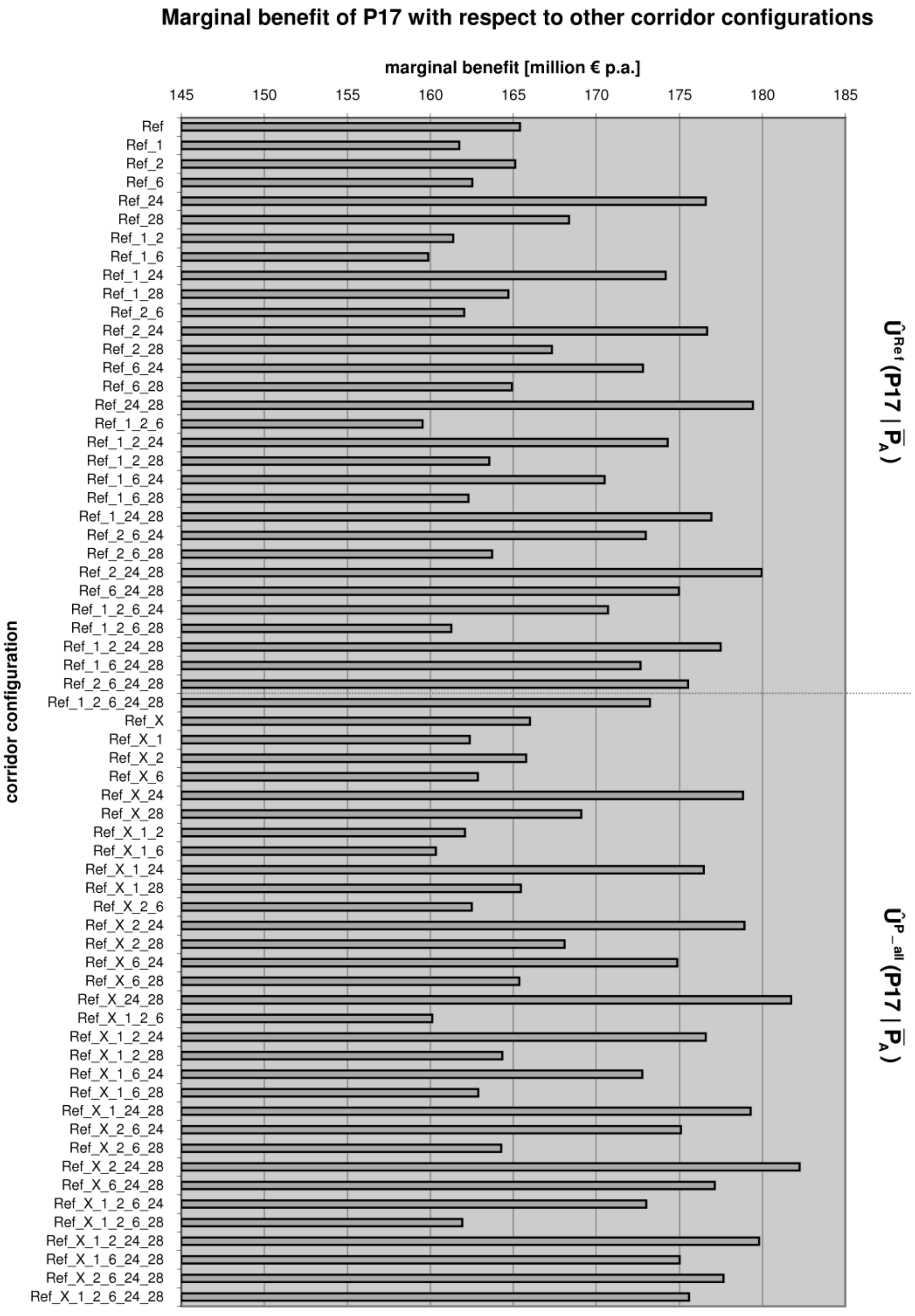

Figure 4: Marginal benefit of the European priority corridor P17 with respect to other corridor configurations

P17's marginal benefit values range from 159.5 M€ p.a. to 182.2 M€ p.a.: the highest level of marginal benefit is reached, if P17 is added to a configuration in which – apart from the corridors of the other clusters – P02, P24 and P28 are realised. The minimum marginal benefit is reached, if P17 is added to a configuration in which P01, P02 and P06 are realised. As soon as P28 or – most remarkably – P24 belongs to the set of corridors P17 is added to, the marginal benefit of P17 rises significantly. On the other hand, P17's marginal benefit is lowered if it is added to a configuration in which P01 or P06 are completed. The type of interdependence between P17 and P02 is of an ambiguous nature: P17 obtains both its highest and lowest marginal benefit value in the infrastructure configurations in which P02 is involved.

These relevant differences between benefit values of just one component of CBA, depending just on the underlying assumption on the implementation of other projects of the investment package, emphasise the relevancy of considering interdependence issues for CBA for the evaluation of investment packages.

6 SUMMARY AND CONCLUSION

In the present paper the nature of interdependencies between projects in a network has been described in qualitative terms and by using a theoretical model formulation. On this basis, a heuristic method has been developed to tackle the problem in large scale networks with a high number of projects. The number of projects and relationships is reduced stepwise to result in a smaller number of cases to be investigated for interdependence. The quantitative measurement of the magnitude of interdependency combines the "add" procedure, i.e. adding a project to a minimum network configuration and a "drop" procedure, i.e. deleting a project from a maximum network configuration. Interdependent projects are analysed together. If substitutive interdependence has been identified between projects A and B, the stand-alone evaluation of both projects will yield a higher sum of benefits compared with the joint evaluation. This implies that the stand-alone benefit values have to be corrected accordingly such that their sum is equal to the result of the joint evaluation. In the case of complementary relationships between two projects A and B the sum of stand-alone evaluations is lower than the result of a joint evaluation. In this case the stand-alone values have to be upgraded to meet the joint evaluation result.

Although the drafted approach has been applied to the priority infrastructure corridors of the EU, its principles could be applied to investment packages of national, regional or local scope, too.

It is necessary for practical application to apply a network algorithm, which is capable to compute the costs of all activities in a large-scale network within a reasonable range of time. Furthermore, in order to compute the demand data required for the cluster analysis – the assignment model to be applied requires the ability to store O/D relation that are modelled to utilise the infrastructure project. The VACLAV algorithm used for the application example comprises all transport infrastructure networks of the EU (including neighbouring countries), with a regional classification according to NUTS-3 regions. This seems accurate enough to evaluate costs and benefits of projects of interregional dimension and to generate the input data for the interdependence analysis. The application to the corridors of the Trans-European Network (TEN-T) has shown that the method generates plausible results and is able to increase the reliability of standard cost-benefit analysis significantly. This is in particular important if public-private partnerships are intended for the realisation of a project. Major failures with estimating the cash flow for the private investors and the benefits for the public can be avoided if interdependence analysis is applied in an early stage of planning. To avoid such failures has become even more important in the circumstances of the current financial crisis, in which it is indispensable that public and private funds are spent in a most efficient way.

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