Cost–Benefit Analysis for Road Infrastructure Projects

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Cost–benefit analysis (CBA) is considered an effective evaluation method for fostering optimal decision-making and ranking of road infrastructures over decades. Eight distinct modelling categories used for CBA implementation were determined, each encompassing three different modelling approaches for capturing the data risk assessment (deterministic or probabilistic), CBA's parameters interactive behavior (static or dynamic) and the considered economies (microeconomic or macroeconomic). In-depth content analysis led to the interpretation of the current status of extant models and the identification of three main knowledge gaps: the absence of the CBA's inputs updating into a probabilistic environment, the deficiency of a dynamic interdependent framework and the necessity of homogenous cost datasets for road projects. Future research directions and a conceptual framework for modelling CBA into a microeconomic, probabilistic and dynamic environment are proposed providing decision-makers with new avenues for more reliable CBA modelling.

cost–benefit analysis | life-cycle cost | road infrastructure projects | conceptual model | project evaluation | asset management

1. Introduction

The Road infrastructure projects (RIPs) underpin countries' economic, social and numerous other important aspects of lifecycle development [1][2]. Decision-making in road infrastructure planning relies extensively on various impact assessment methods, with the cost–benefit analysis (CBA) being the most common contemporary appraisal method [3][4]. CBA has been an essential tool over several decades, particularly for evaluating, ranking [5] and identifying the transport investment with the best cost–efficiency to provide transportation planners and decision makers with more objective and unquestionable choices [6].

In contrast to the extensive extant literature on various forms of CBA studies, only two literature review papers were found concerning CBA in the road transport field, examining the issue in different contexts. Beria et al. [7] reviewed the role assigned to CBA assessment in the infrastructure planning systems of six European countries and made comparisons among the different procedures applied in each country. Donais et al. [4] reviewed 66 papers between 2000–2018 regarding the CBA and multicriteria decision analysis (MCDA) methods in terms of the possible ways to combine them, their capability for covering sustainability in transport and strengths and weaknesses.

2. In-Depth Content Analysis of Modelling Approaches Used for Performing CBA in Road Infrastructure Projects

2.1. Studies Performing CBA via the Mi-D-S Modelling Category

This category is the core and the traditional way for performing CBA, serving as the prerequisite ground for the existence of the other categories. Consequently, several sources in the literature (18% of the studied papers) have utilized this method of calculation; papers detailed attributes can be seen. Indicatively, DeCorla-Souza et al. [8], Greer and Ksaibati [9] and Uddin and Mizunoya [10] developed Mi-D-S tools for evaluating conventional parameters of CBA, such as reduction of accident, travel time and vehicle operating costs.

While all the studies reported above highlighted a specific CBA framework, Hanssen et al. [11] investigated how CBAs outcomes differ against the applied model by comparing three different national CBA models from the Nordic countries, concluding that the choice of national model is crucial since different results can derive depending on the model used.

Furthermore, several national authorities and organizations developed practice guidelines for assessing policies via CBA in a Mi-D-S environment. Four out of the five national guidelines, Minnesota DOT [12], Transport Infrastructure Ireland [13], UK Department for Transport [14] and World Bank [15], offered technical instructions or theoretical principles concerning consumer surplus, producer surplus and externalities. In contrast, California DOT [16] developed the so-called Cal-B/C software, a Microsoft Excel spreadsheet-based tool that provides economic CBA for a range of TIPs. The basic version of Cal-B/C does not contain risk analysis and it is focused on specific project-based applications, meaning that a series of input variables, namely annual average daily traffic (AADT), international roughness index (IRI), vehicles speed, etc., should be provided by the user for software's running.

2.2. Studies Performing CBA via the Ma-D-S Modelling Category

However, crucial considerations might be lost in conventional CBAs leading to suboptimal investment strategies because, in reality, markets are distorted direct and indirect impacts may differ [17]. Hence, this category seeks to narrow down the gap between actual and captured impacts by incorporating additional impacts ignored in the conventional CBAs for estimating over and above traditionally measured project's user benefits. The WEIs studied in the literature ranged from economic to environmental to social aspects.

Two extant studies, Calthrop et al. [18] and Kidokoro [19], developed general equilibrium (GE) models to explicitly incorporate all effects of transport investment on all economic markets, advocating that capturing only the direct costs and benefits of an investment may yield misleading unrealistic CBA results. The former [18] considered distortions on all markets and distributional effects for adapting the traditional cost–benefit rules to correct the unrealistic assumptions considered in the conventional CBAs. The latter [19] investigated a basic agglomeration economy model to incorporate the agglomeration effect into conventional CBAs and produce results comparable with conventional CBAs and directly applicable to individual TIPs, such as roads. Accordingly, Laird and Venables [20] recognized the importance of an appraisal framework that ensures all relevant impacts are captured in CBAs beyond conventional benefits. Specifically, they analysed three additional WEIs types, namely the productivity effects, the investment and land-use changes and labour market effects. These WEIs types had been further examined by ITF/OECD [21], which emphasized mechanisms through which transport may create wider benefits and presented well-established methodologies for their comprising into CBAs, as adopted for instance by UK Department for Transport. Moreover, from a UK perspective, OECD/ITF [22] theoretically reviewed the state of WEIs of agglomeration economies, imperfect competition benefits and labour supply effects.

Moreover, Pienaar [23] conducted a regional economic income analysis displaying the significant contribution of the RIP to the primary macroeconomic goal of local wealth. An and Casper [24] conducted CBA combined with regional travel demand analysis using the commercial TREDIS software for evaluating regional transportation projects by examining their economic impacts. Gühnemann et al. [25] developed an innovative procedure for modifying CBA results to facilitate CBA and multi-criteria analysis (MCA) combination as a means of providing a closer alignment between transport policy and the tools used to support projects' effective prioritization.

As regards environmental terms, Manzo and Salling [26] integrated the UNITE-DSS model with a life-cycle assessment (LCA) module for evaluating how the indirect environmental impacts affect the final project evaluation. From the comparison made between CBA's results of the two alternative approaches, namely with and without the LCA module, it was concluded that the LCA module highly affects the CBA's socioeconomic indicators.

From a social point of view, Turró and Penyalver [27] introduced the Intergenerational Redistributive Effects Model (IREM) that incorporate intergenerational fairness into present decisions for detecting investments that could reduce the wellbeing of affected future generations. Contrary to conventional CBAs that assumes that projects are generationally neutral, IREM provides indicators on the intergenerational redistributive effects arising from major TIPs. Thus, IREM is useful to establish to what extend the project's impact is positive for society from a broader perspective than the traditional CBA.

Until the mid-2000s, the road infrastructure field lacked a generally approved comprehensive way of combing CBA with quantitative risk analysis (QRA). The first attempt to provide risk-based CBA of RIPs was conducted by Salling and Leleur [28][29]. They introduced an Excel-based software, the so-called CBA-DK model, for assessing TIPs combing deterministic CBA with MCS via @Risk software. In this way, decision makers could have more profound and informed knowledge since CBAs' outputs were presented within confidence intervals rather than single-point estimates. A set of suitable PDFs, defined by a PhD thesis [30] for critical input variables into the CBA-DK framework, was used. In general, for running QRA into the CBA-DK, users should choose the PDF type among those available and define their specific parameters, thus limiting its use to those who have detailed knowledge for producing a high level of knowledge (LoK) PFD for each input parameter in order to avoid bias issues derived from low LoK PDFs.

Hence, a special issue recognized by Salling and Banister [31] was the pursuit of the most representative PDFs for capturing the inherent uncertainty of input parameters into the CBA-DK framework. The authors proposed the Reference Class Forecasting (RCF) method for shifting the LoK concerning processing uncertain input variables from a low LoK to a high one by expressing the variables with a statistical distribution formulated by similar projects values. Thereafter, Salling and Salling and Leleur [32][33][34] presented the UNITE-DSS, an Excel-based decision support model, which contains an integrated approach to socio-economic analysis, risk-based simulation and the so-called UP database containing almost 200 specific European TIPs (e.g.,: roads, fixed-links, rails) between 2009–2013. Again, among various CBA's inputs, construction costs and demand forecasts were proven to be affected by a substantial degree of uncertainty and their PDFs were further examined for obtaining reliable estimates.

Furthermore, various "case-study" papers performed traditional CBA combined with MCS each of them examining a specific objective within roads' economic evaluation. All these papers used commercially available risk assessment tools integrated with Microsoft Excel that can be applicable for RIP evaluation, such as @Risk and Crystal-Ball software. Particularly, Korytárová and Papežíková [35] estimated the total inaccuracy of economic efficiency ratios calculation in ex-ante project appraisals using QRA and noted that the benefits inaccuracies between ex-ante and ex-post approaches presented very inconsistent results, with the travel time savings occupying the largest share of inaccuracy among studied benefits. Del Giudice et al. [36], Prakash [37], Vagdatli and Petroutsatou [38] and Varbuchta et al. [39] supported that probabilistic CBAs of RIPs render the evaluation process more transparent and responsible since they provide additional information to the decision makers compared to the deterministic ones. All these papers used PDFs with low LoK, while the last two acknowledged that a database of similar projects would be beneficial for extracting more appropriate PDFs for input variables, leading to more robust probabilistic NPV results. Except for the well-established MCS used for copying with uncertainty of RIPs, some authors considered the uncertainty in the CBA models using alternative risk-based procedures. Maravas et al. and Maravas and Pantouvakis [40][41] presented an alternative mathematical approach based on fuzzy set theory for modelling the inherent uncertainty of TIP into CBA. They concluded that fuzzy-CBA is much easier to computerize than MCS obtaining useful results very quickly. Likewise, Bağdatlı et al. [42] investigated the utility of a fuzzy cognitive map approach for minimizing the effects of uncertainty in highway CBAs. Nguyen et al. [43] presented an enhanced functional CBA framework providing six functions and four main processes regarding the holistic picture of project evaluation.

Additionally, there is a broad grey literature covering the issue from a Mi-P-S perspective. Seven government and organizational reports incorporate risk analysis into the CBA framework and provide either theoretical or technical guidelines for accomplishing it. Four of these reports, British Columbia [44], OECD/ITF [45], Queensland Treasury [46] and Treasury Board of Canada [47], were conceptually compiled, referring solely to the conventional impacts and risk analysis being addressed in the structure of CBA within Canadian, Mexican, Australian and British Columbia framework, respectively. All these guides reported sensitivity analysis as a method for considering uncertainty, while British Columbia [44] added the scenario analysis (SA) and the Treasury Board of Canada and Queensland Treasury [46][47] added the MCS for risk assessment. From a quantitative assessment point of view, the Asian Development Bank and European Commission [48][49] offered methods for sensitivity analysis and MCS for identifying projects' critical variables, allocating appropriate PDFs to them and performing QRA. Finally, the State of Queensland [50] proposed a PC-based tool, the so-called CBA6 software, for evaluating rural and urban RIPs. As in the case of Cal-B/C software, CBA6 performs project-based CBA, implying that a series of input variables—namely

AADT, vehicles speed, road length, life-cycle costs, etc., should be provided by the user for software's running. Regarding the risk analysis, CBA6 conducts sensitivity analysis for some specific input variables, such as vehicle operating cost and travel-time savings.

2.3. Studies Performing CBA via the Ma-P-S Modelling Category

Articles in this category differ from those in the previous one only in terms of the examined markets, namely they consider a macroeconomic approach considering the interaction between the transport sector and the overall economy. The two approaches that complement the analysis remain probabilistic and static.

Two studies, Salling et al. and Shiau [51][52] combined CBA and MCA for assessing a macroeconomic set of distributional and other impacts under uncertainty. The former [51] presented a special hybrid version of the CBA-DK, the Excel-based CLG-DSS model, for decision makers to be facilitated to assess various uncertainties of TIPs. This model consisted of two modules, the COSIMA-module (CBA and MCA combination) and the computable general equilibrium (CGE) model. Their coupling was regarded as well-suited to address both the direct and indirect effects of TIPs. They examined the WEIs of network and mobility, employment and logistics and goods effects. Ten different scenarios regarding the regime of the market mechanism were considered in the CLG-DSS model, with MCS via @RISK software to be used for handling uncertainty. The latter [52] introduced a hybrid approach using the Dempster–Shafer theory for handling uncertainty due to missing information and synthesized monetary and non-monetary criteria into a utility unit. Moreover, Parker and Rommelaere [53] synthesized a reliability ratio for integrating the travel time reliability into the CBA as an additional benefit of TIPs and created the AutoCASE model, a commercial version of the proposed models applicable in the USA and Canada regions. All model's results were presented in probabilistic terms using MCS.

Six national guidelines addressed the CBA in Ma-P-S terms. In five out of six national guidelines (European Investment Bank [54], United Kingdom HM Treasury [55], Commonwealth of Australia [56], Transport of New South Wales [57] and AIReF [58]) the most common techniques for risk were sensitivity and full risk analysis, with the latter making use of MCS for providing a comprehensive picture of the potential variability of a project. Additionally, decision trees [55] and SA [58] completed the reported set of risk analysis techniques. OECD [59] analysed except sensitivity analysis and various other techniques for risk assessment, such as comparative risk assessment, risk–benefit analysis, and risk–risk analysis. Furthermore, equity [59] and distributional effects [56] were among the most highly reported WEIs.

2.4. Studies Performing CBA via the Mi-P-D and Ma-D-D Modelling Category

Two articles considered the Ma-D-D perspective for performing CBA (4% of the total cases). Nguyen et al. [60] introduced a hybrid conceptual framework for capturing the dynamic relationships between CBA's costs and benefits over time, using a combination of agent-based modelling (ABM) and System Dynamics (SD) with multi-criteria method (MCM). The first two approaches captured the behaviour of the heterogeneous agents in the transport, supply chain system and real estate market leading to a macroeconomic consideration of CBA and examined the socioeconomic factors and their relationships. Rothengatter [61] presented various approaches for WEIs measurement and analysed the usefulness of connecting them with conventional CBA. Among the analysed approaches was the SD, which allows the investigation of dynamic relationships between the elements in order to understand complex systems and their development in space and time.

A crucial feature of most of the extant literature is that "risk" and "uncertainty" terms were interchangeably used when conducting probabilistic CBA. Only Li and Madanu [62] separated the two concepts and proposed a new methodology for highway project life-cycle CBA, which except for certainty analysis, introduced risk analysis for input variables with known probabilities and uncertainty analysis for inputs with unknown probabilities. Under a Mi-P-D environment, they approached the dynamic relationship among the examined annual maintenance and user costs using a geometric growth rate between two successive treatment intervals based on the first year's values for each interval.

3. Gaps of CBA Approach and Future Research Directions

3.1. Model's Probabilistic Inputs Updating

Among probabilistic methods used for risk assessment within CBAs models, the MCS gained ground and became the most widely used method longitudinally for handling uncertainty and exporting results within confidence intervals. The remaining approaches, except fuzzy logic, do not perform full probabilistic analysis for exporting PDFs but scenario analysis for specific values given a probability. Although it is well-documented that some limitations regarding the accuracy of inputs PDFs into MCS have been filled by new studies, what is yet missing is a straightforward way to update model parameters in the light of new evidence. Since there is no interactive link between data and output variables in MCS, model parameters can be updated via a reasonably complex, iterative process that requires new simulation. Such validation is frequently arbitrary because more than one combination of parameter values may yield similar output [63]. Therefore, this probabilistic approach is robust when PDF types of inputs are already known, but this is often not the case.

A good alternative to overcome this problem regarding inputs variability is to apply Bayesian analysis. This method is generally superior to an MCS primarily because it can combine different sources of information, namely experts' judgment (prior distribution) and actual data (likelihood function), formulating a posterior distribution using the Bayes inference [63]. Moreover, if additional data are available for a given model's parameter, its posterior distribution is updated given the new evidence, keeping the system constantly informed [64]. Furthermore, a special feature of Bayesian networks (BNs) is that they provide an intuitive graphical visualisation of the knowledge, including the interactions among the various sources of uncertainty. Consequently, BNs can be used to both display the effects of input variables' changes on output variables (forward propagation) and, if desired, the effects of output variables' changes on the PDFs of preceding variables (backward propagation) with great simplicity.

3.2. Dynamic Interdependent Framework

With the partial exception of three papers (Rothengatter [61], Li and Madanu [62] and Nguyen et al. [60]) the bulk of the studied papers investigated the topic from a static viewpoint, revealing the scarcity of dynamic approaches mainly due to two reasonable reasons. From a modelling point of view, interrelations between model's parameters make the whole system much more complex, while from a practical perspective, the actual measurement of the interdependencies among parameters stands difficult. However, since the service life of road infrastructure extends over several decades, its service level does not remain unchanged due to natural and human deterioration factors [65]. In an evolutionary environment such as this, the static CBA approach may result in misleading economic outputs since the variations caused to the financial (construction, operation and maintenance) and economic (user) annual costs by the crucial factor of their interdependencies are remaining uncaptured.

From the three sources dealt with the dynamic nature of CBAs approaches, two examined the issue conceptually from a macroeconomic aspect without considering the uncertainty. Only one Mi-P-D study [62] assumed a geometric growth rate for the longitudinal variation of critical parameters, such as maintenance and user costs, demonstrating that any form of road treatment cannot leave the user's impacts unaffected. Yet, none provided a specific empirical correlation structure, derived from real-world observations, regarding the dynamic interrelation among the model's parameters and how one's actual change could affect both other parameters behaviour and the final outcome.

3.3. Homogenous Data Collection and Componentization of Road Assets

Moreover, five out of thirty-two studied papers used a pool of transport projects for applying risk-based CBA models (Li and Madanu [62], Salling and Banister [31], Salling [32] and Salling and Leleur [33][34]). The first paper used a database of 7380 Indiana highway projects, the second used a historical TIPs dataset of 20 nations, while the UP database, containing 200 TIPs, was utilized by the three remaining papers. Even though each contract details are confidential and are presented as black box information in articles, making the homogeneity of the historical data challenging to judge, the relatively giant number of these projects deriving from different countries suggests the heterogeneity of the samples in terms of projects' key features such as lanes, length and AADT. Even if there is a differentiation between mode types (e.g., road, rail and fixed links), there is still a further need for classification into specific road functional categories (e.g., highways, other principal arterials and collectors) as well as independent categories of tunnels and bridge to formulate homogenous datasets for providing more reliable decision making, since aggregated data from all type categories lead to misleading cost results, inept of being used as a reference point for future projects. Moreover, it is unattainable for these publications to involve the system's dynamics (as explained in Section 3.2) since their costs are not fragmented into individual categories (roads, tunnels and bridges) and project components.

3.4. Proposed Conceptual Model for Future Research

As stated in the previous sections, the existing software are project-oriented since users should determine a number of inputs specific for each project (AADT, lanes, PDF types, life-cycle costs, etc.) for running the simulation and obtaining the final outcome. Hence, neither software's outcome can be generalized for representing a category of similar projects.

Since cost information is sensitive and thus limited and difficult to be gathered, one significant key attribute of this model is the detailed collection of actual cost datasets from a homogenous environment of similar projects for individual assets such as roads, bridges and tunnels for life-cycle cost analyses. This could ensure that nearly all cost deviations will be related to the project's studied independent variables with very little disturbance from exogenous factors [66], such as noise of various countries' tax regimes and other payment policies. Moreover, by fragmenting the costs into individual categories, the interdependencies between the financial and economic cash flows could be investigated (in particular, if one component is improved via maintenance treatments, this will affect the economic impacts and, thus, the final cashflows of the whole CBA study), leading to the integration of dynamics of systems into the CBA's examination. Furthermore, when conducting probabilistic CBA, the more precise the definition of the random input PDFs, the more closely the simulation model mimics real-life conditions [64]. In the proposed model, these databases will be constantly enriched with new data from managers or constructors after authorized audit via Bayesian analysis for capturing real-world uncertainty. Overall, the proposed CBA model will perform into a dynamic interdependent programming environment (e.g., dynamic Bayesian network or ABM), that will consider the interlink between financial and economic costs over the life-cycle of each asset.

4. Conclusions

The issue of road infrastructure evaluation has always constituted a meaningful research field due to its importance in the decision-making process. The BA divided the entire CBA's literature into three representative clusters and along with the descriptive statistics provided an overview of the whole scientific knowledge and key issues concerning CBA approaches till today. Specifically, the CBA's existing modelling approaches were classified into eight categories. Each category was comprised of a combination of three distinct modelling approaches regarding the type of data risks assessment, the interrelation among CBA's parameters and considered economy's sectors respectively. By far the most analysed category was the Mi-P-S one, while Ma-P-D and Mi-D-D categories were not studied in the literature.

From the in-depth content analysis, three gaps were recognized to be diffused among the studied literature body regarding the CBA's probabilistic approach, variables dynamic interrelation and homogeneity of used databases, supporting the argument that existing models require further improvements and structural changes to facilitate decision making reliably.

In summary, considering the prevailing uncertainty in a project's whole life cycle, cost predictions are more trustworthy if they are updated given any further available data, thus improving decision-making in the feasibility phase of the projects. Bayesian analysis was proposed for capturing the inherent uncertainty of CBAs variables since it has a comparative advantage against MCS in terms of inputs variables updating with new data, as well as its two sides propagation, forward and backward. Furthermore, it was observed that the complexity of the issues related with interrelations among CBAs parameters led most of the studies to assume static approach. However, when performing static CBA, there is a substantial bias in the output indicators, since this approach does not represent actual conditions, thus a more realistic scenario should be adopted. Hence, the proposed conceptual model will operate into a dynamic programming environment (e.g., dynamic Bayesian networks or ABM environment). Moreover, since cost datasets are sensitive and rarely published, there is an imperative need for using homogenous datasets regarding the costs and benefits of RIPs for certifying reliable decision-making when conducting life-cycle analysis estimations.

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