Public-Private Partnerships: A Dynamic Discrete Choice Model for Road Projects

ABSTRACT: Public-Private Partnerships (PPPs) are an effective vehicle for delivering critical infrastructure worldwide, particularly road transport assets (e.g., bridges, toll roads and tunnels). However, PPPs have been and continue to be controversial forms of project delivery as there are concerns about their ability to provide taxpayers with value for money (V*f*M). Current practice to determine V*f*M focuses on a 'simplistic' *ex-ante* evaluation referred to as the Public Sector Comparator (PSC), aiming to take a life-cycle approach to cost and benefits assessment. However, the complexity of transport projects renders the PSC ineffective and static evaluation of cost and benefits across their life-cycle. Therefore, the PSC cannot accommodate a project's environment's dynamic and changing nature. Acknowledging the limitations of the PSC, we develop and examine a dynamic discrete choice model that can be used to provide a V*f*M assessment for 'road projects'. By validating the proposed model using two illustrative cases, the results suggest it can capture a more comprehensive assessment of cost components, functionality, and benefits specific to road projects and quantify the relationship between the consideration of different assessment elements and choice utility. Therefore, utilising the new model to assess V*f*M can enable policymakers to make more informed decisions about the employment of PPPs.

Keywords: Decision-making, policy-making, public-private partnerships, procurement, roads, value for money

1.0 Introduction

Transport infrastructure describes the assets that facilitate socio-economic activities and thus is pivotal for enabling the well-being of people and an economy. Consequently, the procurement of transport assets is a vital topic for governments worldwide. Over the past decades, Public-Private Partnerships (PPPs) have been widely adopted to deliver both economic (i.e., transport) and social (e.g., hospital, schools, and stadiums) infrastructure. For example, approximately 700 infrastructure projects with a total amount of £56 billion investment have been procured via PPPs in the United Kingdom (UK) (HM Treasury, 2019). In Australia, 32 projects with capital investment around AU$30.1 billion were contracted with private sectors in Victoria and over AU$25 billion was invested into 39 PPP projects in New South Wales (NSW) (Department of Treasury and Finance, 2019; NSW Treasury, 2019).

A prerequisite for employing a PPP instead of engaging with traditional procurement is to acquire better value for money (V*f*M) for taxpayers using a Public Sector Comparator (PSC) (Grimsey, 2005; DeCorla-Souza, 2013; Boardman and Hellowell, 2016). Noteworthy, the PSC "is used by a government to make decisions by testing whether a private investment proposal offers value for money than the most efficient form of public procurement. The PSC would estimate the hypothetical risk-adjusted cost if a project were to be funded, owned and implemented by the government" (Grimsey, 2005: p.347). The UK HM Treasury (2006), for example, states that PPPs can only be used when they can demonstrate better V*f*M than traditional approaches. Thus, an assessment of V*f*M needs to be robust and consider a wide range of issues such as a project's life-cycle and quality-related issues (Boardman and Hellowell, 2016; Liu *et al.*, 2018b).

Current practice to determine V*f*M focuses on a 'simplistic' *ex-ante* evaluation referred to as PSC, which aims to take a life-cycle approach to cost and benefits assessment (HM Treasury 2006; National Audit Office – NAO, 2013; Liu *et al.*, 2015). However, the complexity associated with transport infrastructure projects often leads to the PSC, providing an ineffective and static assessment of cost and benefit outcomes (Grimsey and Lewis, 2005). For example, the PSC of the first eight roads PPPs in the UK had been overestimated, providing misleading information that using traditional procurement would cost £100 million more for such projects (Edwards *et al*., 2004). Moreover, road projects are complex as they need to consider their cost and service-related issues and traffic volumes during the delivery process (Department for Transport, 2017; World Bank, 2020). In this stance, the PSC cannot accommodate this dynamic and changing environment within which transport assets are procured (Liu *et al.*, 2018b). We acknowledge this limitation and develop a dynamic choice model, particularly for road-based infrastructure projects (e.g., bridges, motorways and tunnels) to assess a project's V*f*M. Policymakers can use the developed model to make more informed decisions about the employment of PPPs to deliver their assets.

2.0 Public-Private Partnership Value for Money Assessment

A PPP is a long-term contractual relationship between the public and private sectors. This relationship aims to introduce private resources and/or expertise to deliver public assets and provide relevant services (European Investment Bank - EIB, 2004). We have seen, worldwide, over the last three decades that PPPs have been widely applied to procure a variety of infrastructure assets such as airports, bridges, railways, toll roads, tunnels, car parks, schools and hospitals (Reeves, 1999; Grimsey and Lewis, 2005, Regan *et al.,* 2011; Liu *et al.*, 2015). The corollary is a wealth of studies being undertaken, which can be categorised under seven main themes (Liu *et al.* 2018a): (1) critical success factors; (2) concessionaire selection; (3) the roles and responsibilities of governments; (4) risk management; (5) time performance under different types of contracts; (6) project finance; and (7) performance evaluation. We highlight in Table 1 some of the most notable works over the past decade that has tended to focus on the critical success factors (CSFs) or risks (demand- and supply-side) of transport PPPs. However, despite the extensive amount of PPP research that has been undertaken, the assessment for V*f*M has received limited attention in the context of transport projects (Cui *et al.*, 2018; Liu *et al.* 2018b).

Table 1. Fundamental research into transport PPPs

Type of Asset	**Research Themes**	**Authors**
Metropolitan subways	Cost/Finance	de Jong *et al.* (2010)
Metropolitan transport systems	CSFs	Yuan *et al.* (2010)
Toll road	Cost-related risk management	Gross and Garvin (2011)
Metro	Cost/finance	Chang (2013)
Metro	CSFs	Liu and Wilkinson (2013)
Metro	Finance	Chang (2014)
Light rail	Risk sharing and cost effectiveness	Carpintero and Petersen (2014)
Motorway	Risk allocation and mitigation	Carbonara *et al*. (2015)
Entire transport sector	Finance	de Albornoz and Soliño (2015)
Urban rail	Cost management	Hong (2016)
Metro	CSFs (economic perspective)	Liao (2016)
Entire transport sector	CSFs	Zhang and Soomro (2016)
Urban rail	CSFs	Ke *et al.* (2017)
Urban rail	Cost-related management (recovery ratio/land value)	Chang and Phang (2017)
Airport	Demand risk management	Engel *et al.* (2018)
Road	Demand risk management	Feng *et al.* (2018)

Toll road	Interest rate risk	Pellegrino *et al*. (2019)
Bridge	Concession price and subsidies	Yuan *et al*. (2019)
Highway	Performance management	Yuan *et al*. (2020)
Port	Failure factors	Feng *et al*. (2021)

2.1 Public Sector Comparator

The PSC is underpinned by Net Present Value (NPV) (Grimsey, 2005; DeCorla-Souza, 2013). In this case, the NPV for a project's life-cycle is compared with a benchmark identified from a hypothetical procurement scenario where the government handled the design, construction, finance, and maintenance functions (Boardman and Hellowell, 2016). To enable an optimal cost comparison, different governments apply various criteria based on their experience delivering similar projects and relevant key stakeholders' expectations to adjust the PSC to assess V*f*M (Boardman and Hellowell, 2016; Kweun *et al.*, 2018). As a result, cost comparisons based on a PSC are fundamentally flawed (Andrew and Cahill, 2009) and meaningless (Gopalkrishna and Karnam, 2015). In summary, the PSC overlooks essential elements in different contexts. For example, a V*f*M assessment report released by the NSW Government in Australia has been criticised for excluding service delivery in its assessments (Andrew and Cahill, 2009).

We also need to acknowledge the PSC is simply a comparison between the hypothetical cost derived from the traditional approach to procurement and the whole-life cost of PPPs. In this instance, a comparison with 'apples and oranges' are being made, and therefore an assessment (i.e., qualitative and quantitative aspects) of a project's context is unfeasible (Gopalkrishna and Karnam, 2015). More importantly, the PSC overly relies on NPV, which depends on selecting a discount rate. Consequently, the rate's selection can be readily manipulated to accommodate a preference for using PPPs (Wall and Connolly, 2009; Whiteside, 2020). We often see that ridership forecasts are manipulated to recommend a PPP (Siemiatycki and Friedman, 2012). However, in reality, they fall well below the original forecasted levels, for example, the CLEM7 Motorway in Brisbane, Australia (Department of Infrastructure and Regional Development, 2016).

Non-financial considerations such as environmental and social impacts and service quality are often neglected in calculating the PSC within the context of transport projects (Opara, 2018). Cost-Benefit Analysis (CBA) is regularly used to complement the PSC to quantify and monetise the benefits engendered by a transport project to address this issue (DeCorla-Souza, 2013; Rouhani *et al*., 2016; Almarri and Boussabaine, 2017). While CBA provides insights into the expected benefits of transport investments, it is prone to inaccurate estimates and has several shortcomings. For example, ‘pricing the priceless benefits’, ‘distorting the future using inappropriate discount rates’ and ‘ineffective capturing dynamic uncertainties’ (Ackerman, 2008, p. 3-7).

The PPP market is mature in Australia, Canada, and the United States (US). Thus, considerable strides have been taken to improve the current V*f*M assessment approach. However, it relies on quantitative cost comparisons (e.g., PSC/CBA) and only considers a limited number of non-financial benefits (Table 2). Despite attempts to incorporate qualitative issues within the PSC, such as economic and environmental impacts, it is still vulnerable due to high degrees of subjectivity and analysis from expert reviews (Kweun, 2018).

Table 2. V*f*M assessment in developed PPP markets

Country/Region	Publisher	Document	Practice
UK	Department for Transport (2017)	V*f*M Framework: Moving Britain Ahead	The benefit-cost ratio and the net present public value
Europe	European PPP Expertise Centre (EPEC) (2015)	The Guide to guidance: How to prepare, procure and deliver PPP projects	PSC plus non-financial benefits
Australia	Department of Infrastructure and Regional Development (2008; 2015)	'National PPP Guidelines Volume 4: PSC Guidance' and 'National PPP Policy Framework'	PSC plus qualitative aspects regarding service quality and ranges
Canada	Infrastructure Canada (2015)	Case reports	PSC specific for the cash flow of Design-Bid-Build (DBB) and Design-Build Finance Operate (DBFO) contracts as well as qualitative factors (e.g. competition, innovation and life-cycle maintenance)
US	US Department of Transportation (2012)	V*f*M Assessment for PPP: A Primer	PSC

A V*f*M assessment of transport PPPs needs to consider costs and their impacts and benefits to society (e.g., functionality) (Department for Transport, 2017). However, extant approaches (e.g., PSC, CBA and qualitative assessment) have not met this need. Moreover, as we pointed out above, they are 'static' in nature and unable to reflect the project's utility within their dynamic and changing environment (e.g., natural, economic and social) (Boardman and Hellowell, 2016; Liu *et al.*, 2018b). In making headway to address this problem, we propose a dynamic conceptual model based upon a robust theoretical underpinning, which policymakers may draw upon to assess a PPP project's V*f*M.

3.0 Dynamic Model for Evaluating V*f*M

Within the engineering context, value can be defined as the ratio of *function* to *cost* and mathematically represented as Equation (1) below.

$$Value = \frac{Function}{Cost} \qquad \text{[Eq.1]}$$

where function depicts customers' needs and is normally presented in the form of verb-nouns, such as 'provide light' and 'pump water', and it is evaluated against the lowest cost to enable 'Value' (Miles, 1962; Palmer *et al.*, 1996). Accordingly, V*f*M in terms of government infrastructure procurement has been identified as a matter of maximising values to the public by saving costs and/or enhancing functionality (i.e., a higher quality service) with more comprehensive non-financial benefits throughout the asset's dynamic life-cycle (Macário *et al.*, 2015; Department for Transport, 2017; NAO, 2018). By considering this perspective, V*f*M can be expressed as a function of cost, service (quality) and other non-financial benefits within the context of infrastructure procurement. We can express V*f*M using Equation (2).

$$VfM = f(cost, functionality, benefits_{nf}) \qquad \text{[Eq.2]}$$

The principle indicated in Equation (2) enables an ideal environment for applying Random Utility Maximization (RUM) theory to selecting an appropriate method to procure transport assets based on the V*f*M criterion. In this instance, RUM theory is specifically helpful for choosing a solution that maximises key stakeholders' values from multiple alternatives by providing weights to attributes (McFadden, 1978). Therefore, the RUM can be represented as follows.

True utility:

$$U_{ij} = V_{ij} + \varepsilon_{ij} \quad \text{[Eq.3]}$$

Choice probability:

$$P_{id} = Prob(U_{id} > U_{ij} \ \ \forall j \neq d) \quad \text{[Eq.4]}$$

where $V_{ij} = V(x_{ij}, s_i) \ \forall j$; x_{ij} denotes the observed attributes of alternative j (i.e., costs); s_i represents the attribute of decision-maker i (i.e., i intends to select a j to maximise its utility), and ε_{ij} is a random variable. Based on the RUM theory, a theoretical model that is referred to as the Dynamic Discrete Choice Model (DDCM) shown as Equation (5) has been developed by Heckman (1981).

$$V(x_{i0}) = \max_{\{d_{it}\}_{t=1}^{T}} E\left(\sum_{t'=t}^{T} \sum_{d=1}^{j} \beta^{t'-t} (d_{it} = d) U_{idt}(x_{it}, \varepsilon_{idt})\right) \quad \text{[Eq.5]}$$

where x_{it} represents state variables while x_{i0} signifies the decision-maker's initial condition; d_{it} is *i's* decision from among j discrete alternatives; U_{idt} stands for the flow utility; and T is the time horizon. Cirillo and Xu (2011) explicitly note that "DDCM describes the behaviour of a forward-looking economic agent who chooses between multiple alternatives over time" (p.1). As indicated by Equation (5), the observed choices in DDCM are assumed to be an agent's maximisation of the value of utility over a certain period. This assumption fundamentally aligns with V*f*M.

Since the 1980s, DDCM has been widely applied in economics to deal with decision-making problems such as selecting occupations or commodities (Miller, 1984; Lorincz, 2007; Melnikov, 2013). Rust (1987) suggests that DDCM is ideal for decision-makers who intend to determine a choice that can potentially maximise the value of their expectations, as it is capable of capturing changing dynamics such as time, price, technology and customer heterogeneity. Contrastingly, traditional discrete choice models only consider static information and overlook the changing nature of the economy and society (Keane and Wolpin, 2009).

Real-world decision-making is based on discrete rather than interdependent choices. Thus, DDCM can consider real-world decisions and determine the interrelationships between variables that exist between them. The aforementioned 'feature' of DDCM has enabled it to be applied to transport research such as choice of travel mode and direction, transport policy, and promoting green vehicles (Haghani and Sarvi, 2018; Liu and Cirillo, 2018; Qin *et al.*, 2019). Furthermore, it is widely accepted that DDCM is a robust technique for capturing the uncertainties that can change dynamically over time (Cirillo and Xu, 2011; Qing *et al.*, 2018).

4.0 Decision-Making Model

Given the robustness of DDCM in transport decision-making as mentioned above, the problem is formulated in Figure 1. That is, decision-maker i, in this case, the government, needs to determine a procurement route j, such as a PPP or the traditional method, by considering a series of the observed variables X_j and unobserved variables D_j of the transport project that impact its V*f*M (u_{ijt}) over a project's life t. To solve this, by integrating Equation (2) into (5) and considering the choice between PPPs and the traditional procurement method [Equation (6)], an initial decision-making model (DDCM-binominal logit model) for the selection of procurement method of transport infrastructure projects is developed [Equation (9)]. Notably, we have not considered political bias that may arise during the decision-making process [Equation (7)] as our model's development assumes that the tendering/ bidding process is competitive and impartial [Equation (8)].

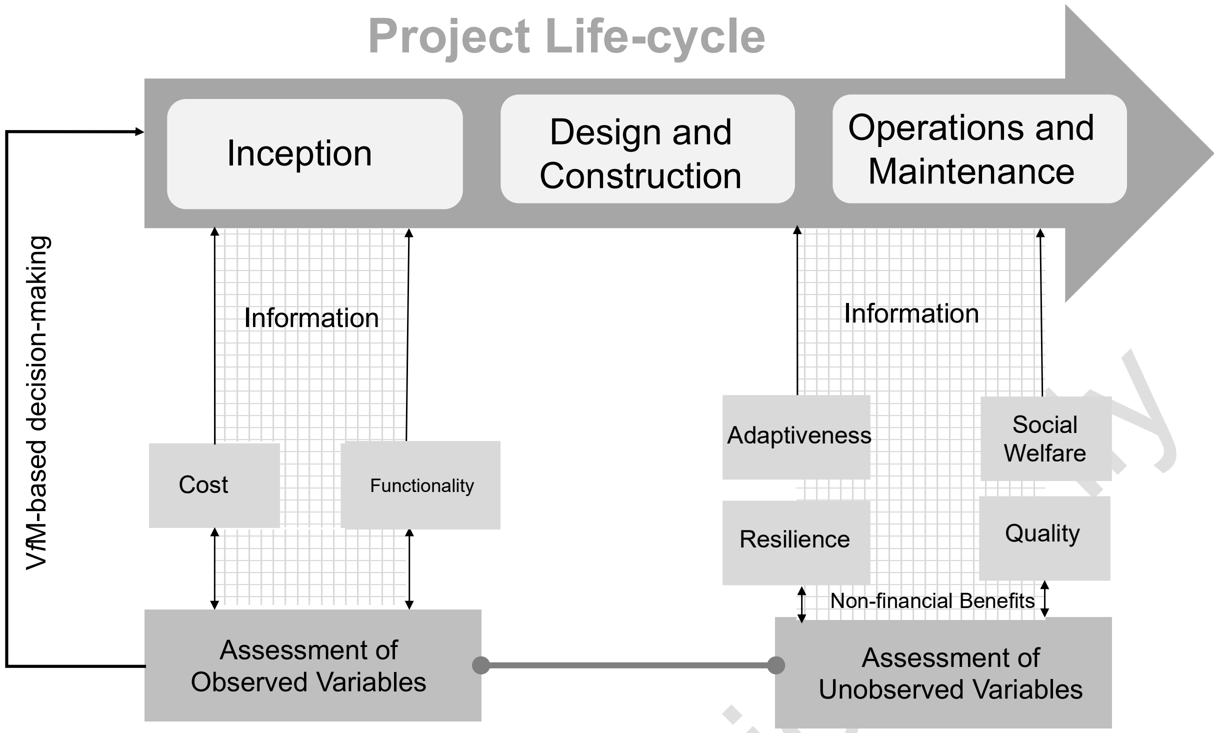


Figure 1. Conceptual framework for determining V*f*M using the developed model

$$j = \begin{cases} 1, \text{ PPPs;} \\ 0, \text{ traditional procurement method} \end{cases} \quad \text{[Eq.6]}$$

$$j = \sum_{q=1}^{n} f_{ijt}^{n}, \ i = 1, \ f_{i1t}{}^{1} = f_{i0t}{}^{1} \quad \text{[Eq.7]}$$

$$AR{=}MR{=}P \quad \text{[Eq.8]}$$

where f_{ijt}^{n} are all the factors that i consider at time t when making the decision j, and 1 means the political or managerial bias. Moreover, in Equation (8), AR is the private-sector entity's average revenue; *MR* is its marginal revenue, and *P* is the bidding price.

$$U_{ijt} = \text{Logit}\left(\frac{\text{P}_{ijt}}{1-\text{P}_{ijt}}\right) = \alpha_0 + \alpha_i^{X^d} X_{jt}^{d} + \beta_i^{D} D_j + \zeta_{ijt} \quad \text{[Eq.9]}$$

where α_0 is a constant, $\alpha_i^{X^d}$ and β_i^D are coefficients of explanatory variables X_{jt}^d and D_j, respectively, X_{jt}^d and D_j are vectors and ζ_{ijt} is a random vector depending on i, j, t. We also consider an asset's whole life-costs, functionality and non-financial benefits to communities (Penyalver *et al.*, 2019), and therefore formalise Equation (9) as:

$$u_{ijt} = \mathrm{Ln}\left(\frac{\mathrm{P}_{ijt}}{1-\mathrm{P}_{ijt}}\right) = \alpha + \alpha_i^{x_1^o} x_{jt1}^o + \alpha_i^{x_2^o} x_{jt2}^o + \sum_{z=1}^{4} \beta_z^{d_z} d_{jz} + \zeta_{ijt} \quad \text{[Eq.10]}$$

Here $\alpha_i^{x_1^o}$ and $\alpha_i^{x_2^o}$ are coefficients which indicate explanatory variables' (e.g., life-cycle cost and functionality) influence on the decision-maker *i's* utility at time t; α is a constant; and d_{jz} is a dummy vector, which may contain multiple non-financial benefits (e.g., social welfare such as new employment) d_1, quality (e.g., design innovation) d_2, adaptability d_3, and resilience d_4, (Love *et al.*, 2017; Liu *et al.*, 2018a, b; Liu *et al.*, 2019).

In Equation (10), if a government i is choosing between two alternatives from set j (j=1: choosing PPP; j=0: choosing traditional procurement method), the method to be selected can maximise the expected value of utility, though this will be dependent on the information being held (i.e., both current and simulated future effects) from set j at time t, and the decision probability follows as Equation (11). Set j consists of observed dynamic characteristics X_j (e.g., cost components x_{jt1}^o and functionality x_{jt2}^o) and unobserved characteristics D_j relating to the future state of an asset. For example, its future impacts on the environment, future-proofing and adaptability to future change. It is also assumed that D constantly maintains during the assessment process. The techniques adopted to model Equation (11) components are described in Figure 2, with details explained in the following sections.

$$P_{ijt} = \frac{e^{\alpha + \alpha_i^{x_1^o} x_{jt1}^o + \alpha_i^{x_2^o} x_{jt2}^o + \sum_{z=1}^{4} \beta_z^{d_z} d_{jz} + \zeta_{ijt}}}{1 + e^{\alpha + \alpha_i^{x_1^o} x_{jt1}^o + \alpha_i^{x_2^o} x_{jt2}^o + \sum_{z=1}^{4} \beta_z^{d_z} d_{jz} + \zeta_{ijt}}} \qquad \text{[Eq.11]}$$

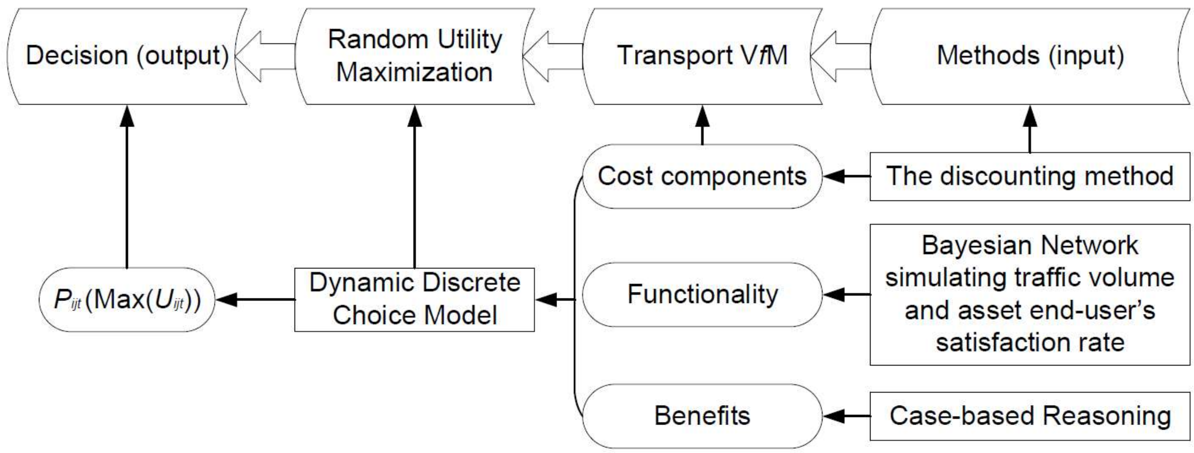


Figure 2. Mathematical methods adopted for decision-making modelling in this study

4.1 Cost Components

In practice, x_{jt1}^{o} [Equation (10)] can be broken down into preliminary engineering fees C_1, construction cost C_2 and operation/maintenance cost C_3 (Turochy *et al.*, 2001; RICS, 2016). Moreover, other components, such as transferred risk value C_4 and transaction costs C_6 (e.g., tendering, negotiation and monitoring cost), need to be addressed by the specific features of the transport asset to be delivered. We need to acknowledge a clear interrelationship between the asset and the external environment. Therefore, an external cost C_5 relating to the cost of environmental impacts, which has been previously ignored in previous V*f*M assessment approaches, has been established. Such a cost item could, for example, apply to possible environmental hazards by a project such as air and noise pollution. Hence, the general x_{jt1}^{o} can initially be written as:

$$x_{jt1}^{o} = \sum_{i=1}^{6} C_i = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \quad \text{[Eq.12]}$$

As specifically indicated by the UK measurement standards, C_2 [Equation (13)], comprises: (1) demolition expense C_2^1; (2) direct construction fee C_2^2 (e.g., terminals, tracks, tunnels, roads etc.); (3) facilities purchase fee C_2^3; (4) loan interest C_2^4; and (5) other fees C_2^5 (e.g., reserve fund) (Hendrickson and Au, 1998; RICS, 2016). In light of the same standards, C_3 [Equation (14)], consists of: (1) remuneration C_3^1; (2) depreciation fee C_3^2; (3) maintenance fee C_3^3; (4) management and financial fee C_3^4; and (5) other fees C_3^5 (e.g., taxes).

$$C_2 = \sum_{i=1}^{5} C_2^i = C_2^1 + C_2^2 + C_2^3 + C_2^4 + C_2^5 \quad \text{[Eq.13]}$$

$$C_3 = \sum_{i=1}^{5} C_3^i = C_3^1 + C_3^2 + C_3^3 + C_3^4 + C_3^5 \quad \text{[Eq.14]}$$

Practically, C_4 equals to 10-15% of C_2 and C_3 (Grimsey and Lewis, 2005), while C_5 can be estimated through unit parameters (i.e., measuring the costs caused by individuals per km) (Lu *et al.*, 2016). In addition to C_4 and C_5, transaction costs C_6, in practice, should account for no more than 20% of the total project value (Hall, 2015). Specifically, C_4, C_5 and C_6 can be described as in Equations (15), (16) and (17), respectively. By considering these components under a discount rate *i'*, x_{jt1}^{o} can be written as Equation (18):

$$C_4 = 15\% \sum_{i=2}^{3} C_i = 15\%(C_2 + C_3) \quad \text{[Eq.15]}$$

$$C_5 = L \times \max\left\{x_{jt2}^{o}\right\} \times c_5 \quad \text{[Eq.16]}$$

$$C_6 = 20\% \sum_{i=1}^{3} C_i = C_1 + C_2 + C_3 \quad \text{[Eq.17]}$$

$$
\begin{aligned}
x^{o}_{jt1} = {} & C_1 \frac{\left(1+i'\right)^{m_1}-1}{i'\left(1+i'\right)^{m_1}} + \frac{\left(\sum_{i=1}^{5} C_2^i + 15\% C_2 - C_7\right)\left[\left(1+i'\right)^{m_2}-1\right]}{i'\left(1+i'\right)^{m_2}\left(1+i'\right)^{m_1}} \\
& + \frac{\left(\sum_{i=1}^{5} C_3^i + 15\% C_3 + L \times \max\left\{x^{o}_{jt2}\right\} \times C_5 - C_8\right)\left[\left(1+i'\right)^{m_3}-1\right]}{i'\left(1+i'\right)^{m_3}\left(1+i'\right)^{m_1+m_2}} \\
& + 20\% \sum_{i=1}^{3} C_i \frac{(1+i')^{m_1+m_2+m_3}}{i'\left(1+i'\right)^{m_1+m_2+m_3}}
\end{aligned}
\qquad \text{[Eq.18]}
$$

where C_5 is the cost incurred by every 100 passengers per kilometre. C_7 and C_8 are revenues to be generated during construction and operation phases, respectively; L is the duration/length of the project; m_1 is the period between the discounted timing and design process; m_2 is the period between the completion of design and construction process; and m_3 is the period between the time when construction is completed and operation stage.

4.2 Functionality

Functionality, x^{o}_{jt2}, has been addressed in the developed decision-making model [Equation (10)]. Within the context of transport infrastructure, functionality is defined as the quality of being served for satisfying end-user's transport/traffic demand (Department for Transport, 2018). Based on this definition, the functionality of transport infrastructure comprises: (1) demand for the service provided by the asset; and (2) quality of the service.

Transport demand, in practice, is referred to as an asset's usage referring to traffic and ridership volumes (Department for Transport, 2018). This paper uses the service quality dimension based on the expectancy-disconfirmation paradigm. This dimension assumes that end-user satisfaction is represented by the 'gap' between their expectations (expected service) and perceptions (perceived service). End-user satisfaction has been acknowledged as an essential key performance indicator of the service provided by transport systems (Mouwen, 2015; Wu *et al*., 2016).

Traffic volume and asset end-user satisfaction rate are ideal for serving as the proximity variables (e.g., traffic demand and service quality) of transport functionality. To enhance an asset's profitability government would expect the PPP to improve its functionality and usage by providing high levels of service quality (Yong, 2010). Typically, PPPs rely on demand-based payment and revenue-sharing mechanisms. The private entity holds the demand risk and depends on the asset's revenue determined by the usage volume (PwC, 2017; Fernandes *et al*., 2019). For example, in Australia's Sydney Cross City Tunnel and WestConnex (road) projects, the NSW state government can share agreed percentages of the additional revenue above the projected profits of the asset operations (NSW Treasury, 2008; 2019). Examples of this nature can also be seen in the PPPs delivered elsewhere globally, such as the M25 Motorway, UK and Jiyuan-Dongming Highway, China (House of Commons, 2011; APEC, 2014).

To determine how the introduction of the private sector will impact a transport asset's functionality (x_{jt2}^{o}), a variable x_o has been constructed with x_{jt2}^{o} to serve as an 'impact factor', specifically for modelling the relationship between private-sector-provided service and asset usage (i.e., traffic volume). Consequently, x_{jt}^{o} in Equation (10) is a variable comprising service quality (x_s) that is represented by end-user satisfaction, transport demand (traffic volume) (VOL_{kqm}) and an impact factor (x_o) mathematically describing the causal relationship between x_s and VOL_{kqm}.

Bayesian Networks (BN) have been adopted to underpin the development of a mathematic model to estimate x_o addressed above. The BN is based on probability and graph theories and is powerful in dealing with conditional independencies among a group of variables, in which G=(E, F) is a directed acyclic graph and X=(X_e), e∈E is a set of random variables indexed by E, then if possible, a BN joint conditional probability can be rewritten as:

$$p(x) = \prod_{e \in E} p(x_e / x_{pa(e)}) \quad \text{[Eq.19]}$$

where $pa(e)$ is the set of parents of e; E is a vertex and F is a single edge (Jordan *et al*., 1999). Compared with regression models, BNs can capture causal interrelationships between variables using past data and thus are suitable for forward-looking decision-making such as modelling traffic volumes (Sun *et al*., 2006; Li *et al.*, 2019).

The BN-based modelling used in this paper is based on the assumptions presented in Sun *et al.* (2006), where factors determining the observed volume are independent. Therefore, let (s, o) be a partition of the node indices of the BN, so that it converts to disjointed subsets, and then let (x_s, x_o) be a partition of the corresponding variables. Accordingly, the marginal probability of x_s can be written as:

$$p(x_s) = \sum_{x_o} p(x_s, x_o) \quad \text{[Eq.20]}$$

Consequently, the conditional probability $p(x_o|x_s)$ derived from BN can be reformulated as:

$$p(x_o \mid x_s) = \frac{p(x_o, x_s)}{p(x_s)} = \frac{p(x_o, x_s)}{\sum_{x_o} p(x_s, x_o)} \quad \text{[Eq.21]}$$

Then with the help of the Gaussian mixture model (Sun *et al.*, 2006) and a lemma proved in Rao (1973), Equation (21) can be further represented as below.

$$p(x_o \mid x_s) = \sum_{l=1}^{M} \beta_l G(x_o; \mu_{lo|s}, \textstyle\sum_{lo|s}) \quad \text{[Eq.22]}$$

where $G(x_o; \mu_{lo|s}, \sum_{lo|s})$ is a multidimensional normal density function with mean $\mu_{lo|s}$ and covariance matrix $\sum_{lo|s}$;

$$\beta_l = \frac{\alpha_l G(x_s; \mu_{ls}, \sum_{lss})}{\sum_{j=1}^{M} \alpha_j G(x_s; \mu_{js}, \sum_{jss})}$$

$$\mu_{lo|s} = \mu_{lo} - \textstyle\sum_{los} \sum_{lss}^{-1} (\mu_{ls} - x_s)$$

$$\textstyle\sum_{lo|s} = \sum_{loo} - \sum_{los} \sum_{lss}^{-1} \sum_{lso} \quad \text{[Eq.23]}$$

And, optimal forecasting of x_o after the calculation of minimum mean square error equals to:

$$x_o = E(x_o \mid x_s) = \int x_o p(x_o \mid x_s) dx_o$$

$$= \sum_{l=1}^{M} \beta_l \int x_o G(x_o; \mu_{lo|s}, \textstyle\sum_{lo|s}) dx_o = \sum_{l=1}^{M} \beta_l \mu_{lo|s} \quad \text{[Eq.24]}$$

Finally, x_o is integrated into the annual average daily traffic AADT forecasting method (US Department of Transportation, 2018) to simulate x_{jt2}^{o}, which is represented as:

$$x_{jt2}^{o} = \frac{1}{12} \sum_{m=1}^{12} \left[\frac{1}{7} \sum_{q=1}^{7} \left(\frac{1}{n_{qm}} \sum_{k=1}^{n_{qm}} VOL_{kqm} \right) \right] \left(1 \pm \sum_{l=1}^{M} \beta_l \mu_{lo|s}\right) \quad \text{[Eq.25]}$$

where VOL_{kqm} is the daily volume for k^{th} occurrence of the q^{th} day (1 to 7) of the week within the m^{th} month (1 to 12); k is occurrences of day q in month m for which traffic data are available; n_{qm} is the number of events of day q in month m for which traffic data is available.

4.3 Other Non-Financial Benefits

Non-financial benefits, $Benefits_{nf}$, have also been considered in the V*f*M function [Equation (2)], as governments expect more comprehensive other non-financial benefits to be generated from a PPP. Such benefits include enhanced delivery and resilience and adaptability to environmental changes (EIB, 2011; Mota and Moreria, 2015; Liu *et al.*, 2018b). Typically, it is challenging to model and quantify these benefits as they are unobservable attributes. Hence, a dummy (D_j) has been developed in Equation (9). The dummy variable is associated with the value '1' or '0' to indicate the presence or absence of categorical effect expected to influence the outcome. While the determination of '1' or '0' is a daunting task in practice, this can be achieved by using simulation techniques such as case-based reasoning (CBR) underpinned by the data of past similar projects. For example, suppose the private sector is expected to deliver an asset resilient to economic and social changes. In this instance, our model can be used to determine whether an injection of equity would stimulate positive outcomes when compared to PPP projects of a similar nature. If the simulation result indicated by the CBR is significant, the relevant dummy (i.e., d_1) will be set as '1' or '0'.

4.4 Dynamic Discrete Choice Model

By integrating Equations from (18) to (25) into Equation (10), we can create a theoretical dynamic decision-making model that can be applied to determine V*f*M for transport PPP road projects. Our mathematical model is represented in Equation (26):

$$u_{ijt} = \alpha + \sum_{z=1}^{4} \beta_z^{d_z} d_{jz} + \zeta_{ijt} + \begin{pmatrix} \alpha_i^{x_1^o} & \alpha_i^{x_2^o} \end{pmatrix} \bullet \begin{pmatrix} C_1 \dfrac{\left(1+i'\right)^{m_1} - 1}{i'\left(1+i'\right)^{m_1}} + \dfrac{\left(\sum_{i=1}^{5} C_2^i + 15\%C_2 - C_7\right)\left[\left(1+i'\right)^{m_2} - 1\right]}{i'\left(1+i'\right)^{m_2}\left(1+i'\right)^{m_1}} \\ + \dfrac{\left(\sum_{i=1}^{5} C_3^i + 15\%C_3 + L \times \max\left\{x_{jt2}^o\right\} \times C_5 - C_8\right)\left[\left(1+i'\right)^{m_3} - 1\right]}{i'\left(1+i'\right)^{m_3}\left(1+i'\right)^{m_1+m_2}} \\ +20\% \sum_{i=1}^{3} C_i \dfrac{(1+i')^{m_1+m_2+m_3}}{i'\left(1+i'\right)^{m_1+m_2+m_3}} \\ \dfrac{1}{12} \sum_{m=1}^{12} \left[\dfrac{1}{7} \sum_{q=1}^{7} \left(\dfrac{1}{n_{qm}} \sum_{k=1}^{n_{qm}} VOL_{kqm} \right) \right] (1 \pm \sum_{l=1}^{M} \beta_l \mu_{lo|s}) \end{pmatrix} \quad \text{[Eq.26]}$$

where all notations therein have the same meaning as above.

We can see that the DDCM model comprises observable variables distinguished from the PSC focused on the cost comparison between the life-cycle of a PPP option and the hypothetically benchmarking cost based on traditional procurement. In other words, by using the developed model, the governments do not need to identify a hypothetical cost for comparison. As a result, the cost estimate process of the decision-maker (government) will be simplified, leading to enhanced efficiency of the entire decision-making process. Also, the model considers future changes throughout the asset's dynamic life cycle by capturing its functionality and impacts of other unobservable issues (e.g., adaptiveness, resilience, quality and social welfare).

The assessment of V*f*M, as indicated by Figure 1, is conducted at the inception stage of a project when decision-makers lack actual data about the asset's design and construction, operation and maintenance. Therefore, selecting an appropriate method to procure the asset has to be based on forecasting and extant data/information of the past similar types of projects (Figure 1) (Tavakoli and Nourzad, 2019). For instance, an application of the developed model would consider inputting end-user satisfaction (x_s), which can be achieved by using the data of similar awarded transport projects under the governments as proximities. As addressed above, the determination of the dummy variable's (D_j) value for other non-financial benefits can be based on simulation of the PPPs special purpose vehicle's performance. A robust database of previous public sector projects that considers an asset's functionality, adaptability to environmental changes, ability to provide economic and social benefits and performance outcomes (e.g., life-cycle) must be established to support the decision model. The quality of the data/information on past projects plays a decisive role in using the developed model and can determine the reliability of a transport PPP life-cycle performance.

4.5 Applicability of the Developed DDCM

Two illustrative cases from the UK are used to demonstrate the applicability of our developed model. The first case is based on a 52-kilometre carriageway (A419/A417 road, Case A), and its contract value is around £112 million. The second case is a 21-kilometre motorway (A1(M) road, Case B), and its contract value is approximately £154 million. Accordingly, a stated-choice experiment with hypothetical scenarios was designed to examine how our model can be applied to the decision-making process of real-world projects above.

Both financial and non-financial benefits displayed in Figure 1 are considered. Based on Equation (25), the functionality is quantified by adopting proximities as traffic volume and end-user satisfaction. The functionality variable is categorised as 'improved' and 'unchanged'; that is, does PPP result in better functionality. Also, the cost items displayed in Equation (18) are divided into two categories, 'equal or less' and 'more'. Furthermore, each of the four unobserved attributes (e.g., adaptiveness, social welfare, resilience and quality) above (Figure 1) is set up with potential 'significant' or 'insignificant' impact to indicate whether or not the procurement option available will significantly affect the project in terms of adaptiveness, social welfare, resilience and quality. Thus, six attributes are included in each option (i.e., PPP or traditional procurement), comprising two categories, Functionality – 'Improved' or 'Unchanged', Cost – 'Equal or Less' or 'More', and Unobserved Attributes – 'Significant' or 'Insignificant'. Consequently, a full factorial design that consists of 2^{12} (=4096) choice sets for each case can be generated.

Tables 3 and 4 present a series of representative scenarios to quantify and interpret the possible effects of different procurement options for Cases A and B, respectively. For example, in the first row of Table 3, we compare only cost in the PPP option with functionality in the traditional procurement option to display different impacts. A 'none of them' option is provided if neither choice is preferred by the client *i*. Let the observed attribute vector *X*= (equal or less/more, improved/unchanged), where 'equal or less/more'= (equal or less=1, more=0) and 'improved/unchanged'= (improved=1, unchanged=0). The same configuration applies to the unobserved attribute *D*, a dummy vector. Therefore, a complete variable vector can be (1, 0, 1, 1, 0, 1).

Table 3. Sampling choice sets for Case A

A PPP (a)	A traditional procurement method (b)	Others (c)
(1, 0, 0, 0, 0, 0)	(0, 1, 0, 0, 0, 0)	None of them
(0, 1, 0, 0, 0, 0)	(1, 0, 0, 0, 0, 0)	None of them
(1, 1, 0, 0, 0, 0)	(1, 1, 0, 0, 0, 1)	None of them
(0, 0, 1, 0, 0, 0)	(0, 0, 0, 1, 0, 0)	None of them
(1, 0, 0, 1, 0, 0)	(0, 1, 0, 0, 1, 0)	None of them
(0, 1, 0, 0, 1, 0)	(1, 0, 0, 1, 0, 0)	None of them
(1, 1, 0, 0, 0, 1)	(1, 1, 0, 0, 0, 0)	None of them
(1, 1, 1, 1, 1, 1)	(1, 1, 1, 1, 1, 1)	None of them

Table 4. Sampling choice sets for Case B

A PPP (a)	A traditional procurement method (b)	Others (c)
(0, 1, 0, 0, 0, 0)	(1, 0, 0, 0, 0, 0)	None of them
(1, 0, 0, 0, 0, 0)	(0, 1, 0, 0, 0, 0)	None of them
(1, 1, 0, 0, 0, 1)	(1, 1, 0, 1, 0, 0)	None of them
(0, 0, 1, 1, 0, 0)	(0, 0, 1, 0, 0, 1)	None of them
(0, 1, 0, 0, 1, 0)	(1, 0, 0, 1, 0, 0)	None of them
(1, 0, 0, 1, 0, 0)	(0, 1, 0, 0, 1, 0)	None of them
(1, 1, 0, 0, 1, 0)	(1, 1, 0, 0, 0, 1)	None of them
(1, 1, 1, 1, 1, 1)	(1, 1, 1, 1, 1, 1)	None of them

It is identified that the contributions of each attribute of PPP and of traditional procurement to the asset's utility u_{ijt} of Case A are (0.85, 0.68, 0.37, 0.49, 0.30, 0.51) and (0.79, 0.63, 0.30, 0.49, 0.27, 0.53), respectively, according to the relevant information of asset utility published by the managing authority of the project (NAO, 1998). For Case B, the contributions are (0.61, 0.65, 0.47, 0.53, 0.52, 0.41) and (0.69, 0.71, 0.63, 0.54, 0.37, 0.42). The different priorities attached to the PPP and traditional procurement in Case A and Case B can be compared to indicate how our model facilitates decision-making. Also, we compare the PSC with our model to address the robustness of the developed DDCM. Initially, the sensitivity analysis for the PSC, which considers cost only, suggests PPP is the preferred option in Case A. In this instance, a cost-saving of up to £11 million can be achieved when the discount rate is set to 8%. However, the result is negative, which indicates a PPP would be an unpreferable option and at an additional cost of £3 million when the rate is lowered to 6%. By comparison, PPP remains the preferred choice in Case B for both discount rates. Here a cost-saving of £50 million when 8% is applied and £30 million when 6% is applied.

With the calculated attribute and contribution vectors, the combined effects of $\sum \beta \cdot D$ and $\sum \alpha \cdot X$ can be yielded using Equation (26). Taking the first row in Table 3 as an example, the two alternatives are 0.85×1=0.85 and 0.63×1=0.63, respectively. The rest is shown in Equation

(27) and Equation (28) for Case A, and Equation (29) and Equation (30) for Case B where i is the managing authority and t is the road's inception time.

$$U_{i1t} = (0.85, 0.68, 0.37, 0.49, 0.30, 0.51) \cdot \begin{vmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{vmatrix} = \begin{vmatrix} 0.85 \\ 0.68 \\ 1.53 \\ 0.37 \\ 1.34 \\ 0.98 \\ 2.04 \\ 3.20 \end{vmatrix} \quad \text{[Eq.27]}$$

$$U_{i0t} = (0.79, 0.63, 0.30, 0.49, 0.27, 0.53) \cdot \begin{vmatrix} 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 0.63 \\ 0.79 \\ 1.95 \\ 0.49 \\ 0.90 \\ 1.28 \\ 1.42 \\ 3.01 \end{vmatrix} \quad \text{[Eq.28]}$$

$$U_{i1t} = (0.61, 0.65, 0.47, 0.53, 0.52, 0.41) \cdot \begin{vmatrix} 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} = \begin{vmatrix} 0.65 \\ 0.61 \\ 1.67 \\ 1.00 \\ 1.17 \\ 1.14 \\ 1.78 \\ 3.19 \end{vmatrix} \quad \text{[Eq.29]}$$

$$U_{i0t} = (0.69, 0.71, 0.63, 0.54, 0.37, 0.42) \cdot \begin{vmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 1 \\ 0 & 1 & 1 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \end{vmatrix} = \begin{vmatrix} 0.69 \\ 0.71 \\ 1.94 \\ 1.05 \\ 1.23 \\ 1.08 \\ 1.82 \\ 3.36 \end{vmatrix} \quad \text{[Eq.30]}$$

Based on Equation (11), the probabilities of the sampling choice set for each option in Case A are (0.048, 0.040, 0.094, 0.029, 0.078, 0.054, 0.157, 0.500) and (0.043, 0.051, 0.163, 0.038, 0.057, 0.083, 0.096, 0.469), while the probabilities of each option for the sampling choice sets are (0.701, 0.664, 0.882, 0.591, 0.792, 0.727, 0.885, 0.961) and (0.348, 0.312, 0.125, 0.380, 0.289, 0.218, 0.195, 0.047). This suggests that PPP would generate a higher level of asset utility in the given sampling choice sets for both options (Columns a and b of Table 3). Regarding

Case B, the probabilities of the sampling choice set for each option are (0.040, 0.038, 0.110, 0.056, 0.067, 0.065, 0.123, 0.502) and (0.036, 0.037, 0.126, 0.052, 0.062, 0.053, 0.112, 0.522), while the probabilities of each option for the sampling choice sets are (0.657, 0.648, 0.842, 0.731, 0.763, 0.758, 0.856, 0.960) and (0.666, 0.670, 0.874, 0.741, 0.774, 0.746, 0.861, 0.966). This indicates that PPP continues to be the preferred option (for the sampling choice sets of the Column A of Table 4), despite higher contributions assigned to the traditional procurement approach. The relationship between the utility of the roads and the decision is depicted in Figures 3 (Case A) and 4 (Case B).

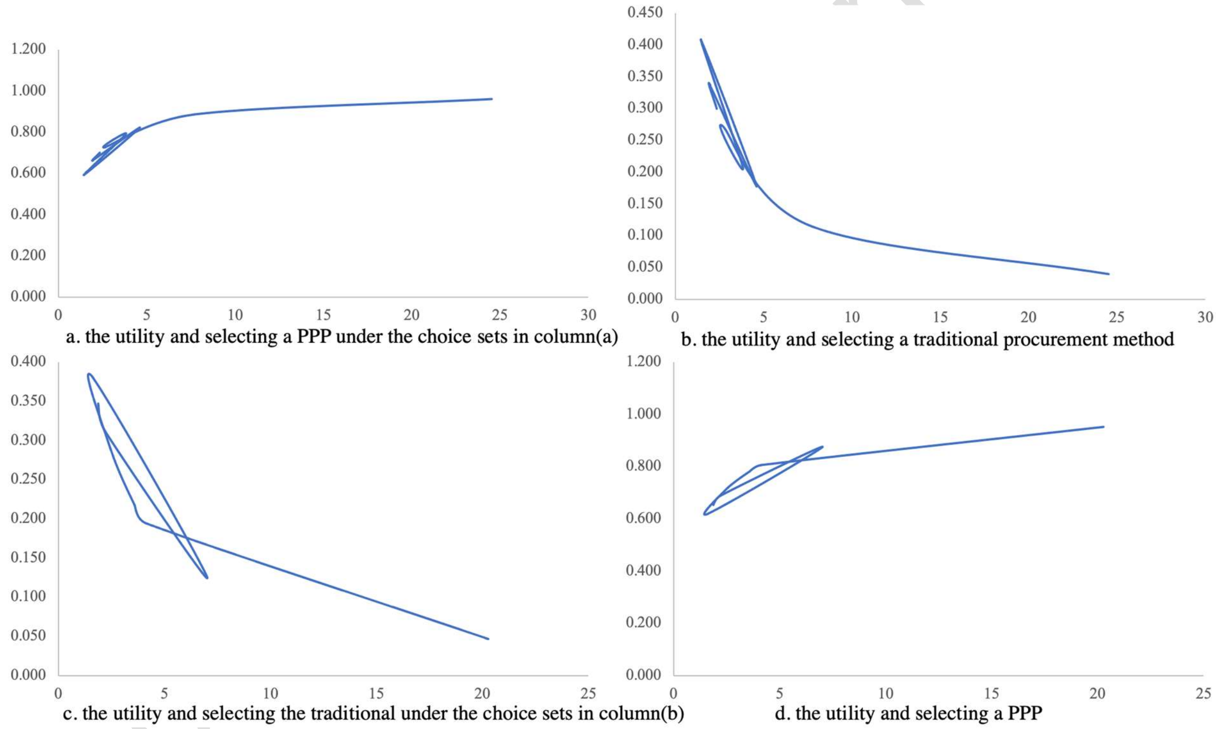
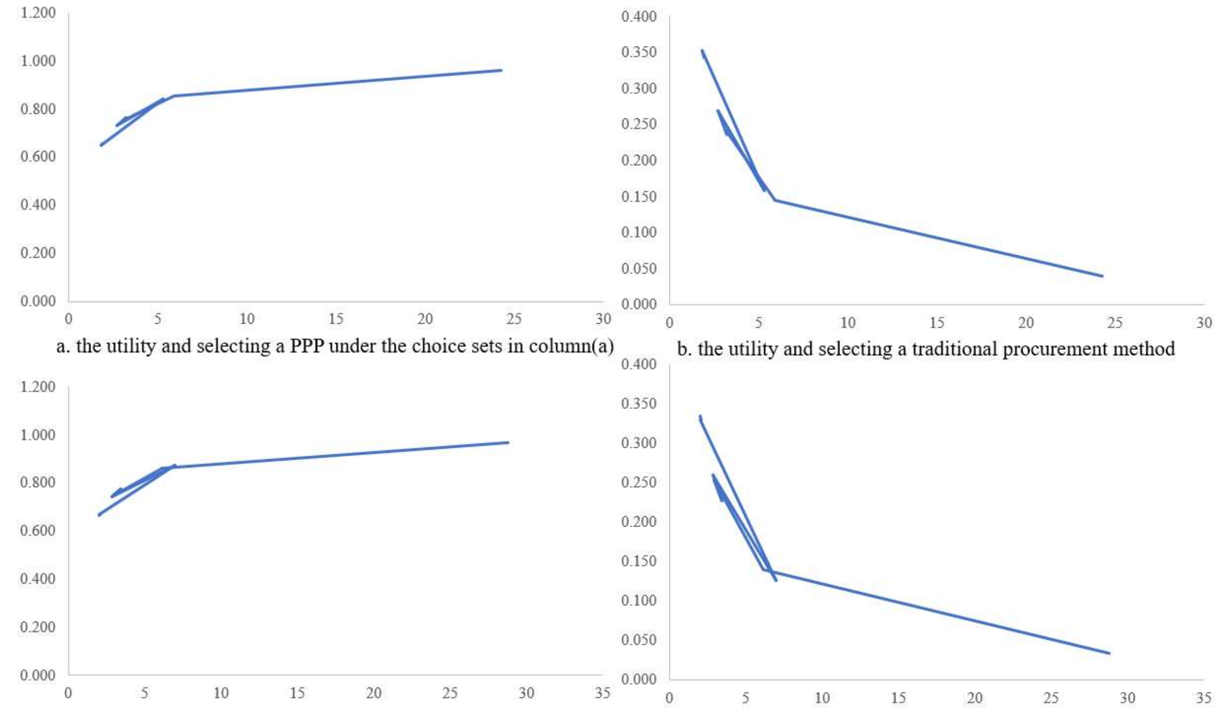


Figure 3. The relationship between the utility and the decision for Case A



a. the utility and selecting a PPP under the choice sets in column(a)
b. the utility and selecting a traditional procurement method
c. the utility and selecting the traditional under the choice sets in column(b)
d. the utility and selecting a PPP

Figure 4. The relationship between the utility and the decision for Case B

The stated choice example above reveals that governments should select PPPs to procure roads to enable better V*f*M for taxpayers. These results comply with the actual decision to use a PPP for the A419/A417 and A1(M) roads by the UK government, supporting the applicability of the developed DDCM. More importantly, Case B demonstrates that PPP can deliver better V*f*M even when a higher contribution weight is allocated to the traditional procurement method. This provides evidence to NAO (1998) stating that Design-Build-Finance-Operate, a form of PPP, allows better road construction output. Compared with PSC, where the sensitivity analysis of Case A shows the NPV of PPP would be negative, our model is more robust and demonstrates cost-saving, and a higher asset utility would be obtained. It can also illustrate how the government's decision should be changed to adapt to changing elements due to the dynamic business environment (Figures 3 and 4). The above robustness of dynamically estimating financial and non-financial benefits enables our model to significantly surpass the widely-used PSC, which has been criticised that governments prefer to exaggerate the benefits of PPPs but was unable to quantitatively demonstrate how better they are than other procurements (Siddiquee, 2011; NAO, 2021). Furthermore, as noted from the cases, the application of our model does not rely on identifying a hypothetical cost for comparison (i.e., PSC), thereby facilitating the decision-making process.

As indicated by the model, there are positive relationships between functionality and the choice sets for the traditional procurement approach (refer to 1st row and column b in Table 3) and PPPs (i.e., 1st row and column b in Table 3). Furthermore, functionality is a variable that is significant for both choice groups (0.094 and 0.096). These probabilities support our model where the observable functionality quantified using proximity variables as traffic volume and end-user satisfaction rate is critical. Similarly, the choice of using PPP is significantly affected by the unobservable variables (refer to adaptiveness 4th row and column a). Thus, this reinforces our suggestion, embedded within the model, that procurement evaluation needs to consider observed not only variables (cost and functionality) but also unobserved elements (Figure 1).

The two cases also indicate that a larger asset utility would lead to a higher possibility of selecting a PPP. This finding supports the rationale of our model, as there is a reality that governments expect an engagement with the private sector for the delivery of transport projects will result in an enhanced usage of the asset (Department for Transport, 2017). Our case B further corroborates this by showing a higher utility and probability of selecting a PPP (column a in Table 4) despite higher weights being assigned to the traditional procurement method. Notably, the illustrative case above was undertaken at t_0 (= inception stage of the project) for a specific client i (the project's managing authority). However, the developed DDCM model can be expanded to t_1(= projects' life-cycle) for decision-making relating to the asset's future operations and maintenance when relevant data is available (Figure 1).

5.0 Implications for Policy and Practice

As addressed above and indicated by the case scenarios, central to the practical application of our developed model is the quality of the information acquired from past similar projects. Thus, information policies facilitate and regulate the development and implementation of an Information Sharing Platform (ISP) that can store the information about transport PPPs that have been procured across their life-cycle are needed. The public and private sectors should access the ISP. Thus, both public authorities and private entities of PPP projects would be required to provide performance-based information throughout all the project's life-cycle stages. The ISP would serve as a 'real-time' database for the public authorities and private-sector entities of transport PPPs to store, exchange and manage the life-cycle of their assets, which will be useful for learning lessons for future project delivery. This data platform would enable the governments to gain the adequately necessary information for effectively applying the developed model to conduct V*f*M assessments for their future transport infrastructure projects.

The developed model, for example, embraces the cost items of the asset's future operations (e.g., environmental impact), which is represented as the percentage value that can be determined by using the data of past projects. Governments should, therefore, adopt technologies such as Building Information Modelling and Internet of Things to record the information relevant to the environmental effects of their transport PPP projects on the local communities (e.g., noise and pollution as well as the rate of traffic accidents). Furthermore, such information needs to be regularly uploaded into the ISP.

Having access to the information within the ISP will provide the public sector with the ability to efficiently and accurately determine the costs relating to a project's impacts on the environment and then enhance the accuracy and reliability of the model's result. Furthermore, a transport infrastructure project is initiated to provide end-users with services to satisfy their transportation demand (Filion and McSpurren, 2007). Service quality, therefore, has been embedded into the developed decision-making model. Thus, the public and private sectors should work together to acquire information about end-user satisfaction from their PPP projects, which can be stored in the ISP. As a result, this would improve data quality, enhancing the service quality of PPPs and their ability to provide V*f*M.

Our research, additionally, has generated a set of theoretical implications. It contributes to expanding the epistemology of V*f*M based on the RUM theory and the paradigm of V*f*M-oriented decision-making for PPPs by addressing functionality and long-term non-financial impacts within the context of transport infrastructure. As such, we mathematically developed and empirically examined a theoretical and practical model that sheds light on how to make an informed decision to select an appropriate procurement approach for procuring transport assets.

6.0 Conclusions

While governments have relied on PPPs to procure transport infrastructure assets, they have been plagued with controversy. There is a perception that they have been unable to provide V*f*M to taxpayers. As a result, V*f*M assessment has been a critical stage of a government’s infrastructure procurement process worldwide. Despite the attention paid to V*f*M and its drawbacks (e.g., inability to quantify intangible life-cycle impact), there has been a lack of alternative approaches propagated in the literature. Recognising the shortcomings of the PSC, we develop a dynamic approach for assessing the V*f*M of road projects, which is underpinned by a DDCM to compare PPPs and traditional procurement methods. Our developed decision-making model considers the whole life-cycle cost, environmental impacts, transport asset’s functionality and non-financial benefits that may materialise. Two illustrative cases based on two UK road projects have been created to examine the developed model. The results generated from the cases support the applicability of our model within the real-world context.

To this end, the contributions of our paper are twofold as we: (1) developed and validated a robust mathematical decision-making model for assessing the V*f*M, which can address the current limitations with the PSC and capture the dynamic complexities of procuring transport assets; and (2) proposed the need to develop an information policy and regulations to support the practical application of our model so that the performance of transport PPPs can be managed over their life. To this end, our paper provides policymakers with a platform to re-calibrate their approach to assessing whether a PPP project can provide V*f*M.

Acknowledgements

The authors would like to acknowledge the financial support from the Research Development Fund administrated by Northumbria University, UK (RDF18ABELIU).

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