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Research note

A micro-econometric framework for Participatory Value Evaluation

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ABSTRACT

This paper presents a micro-econometric framework to analyse choice data from participatory value evaluation (PVE) surveys. In a PVE survey respondents receive, similar to stated choice surveys, information on the social impacts of public sector projects before choosing the best policy portfolio according to their preferences. Respondents' choices are limited by governmental and private budget constraints. The PVE data format is characterised by a mixture of discrete and continuous choice data. Building on recent literature of Kuhn–Tucker models, particularly the MDCEV model, a range of methodological and econometric contributions are provided facilitating model estimation and policy evaluation. We derive a set of closed form choice probabilities explaining the choice for the optimal portfolio with public projects, private consumption levels and whether to spend the public budget in full or not. The proposed policy evaluation framework is centred around the notion of social welfare maximisation. The parameter estimates are used to derive the optimal public sector budget and the corresponding portfolio maximising social welfare, but also to rank the set of feasible portfolios given a restricted budget, including sensitivity analyses. The proposed framework is illustrated using an empirical example on urban mobility investments in Amsterdam, The Netherlands.

1. Introduction

Mouter et al. (2021c) and Mouter et al. (2021b) introduced Participatory Value Evaluation (PVE) as a new survey method eliciting preferences over the allocation of public budgets. In a PVE survey respondents are asked to choose the best portfolio of (public) projects given a public budget constraint. An innovative feature of PVE surveys is that respondents are in a position to adjust the public budget (and correspondingly private incomes) by increasing or reducing taxes when they believe additional or less public projects should be implemented. One of the motivations for introducing PVE surveys is to move beyond the traditional approach of eliciting preferences and welfare measures for public policy measures through the study of individual choices solely based on their private income. Mouter et al. (2021c) argue, discussing a wider literature, that such choices and accordingly private willingness-to-pay (WTP) measures may not accurately reflect individual preferences towards public policies.

The PVE survey format takes into account two types of opportunity costs. First, allocating public money to a given public project implies foregoing other projects, either today or in the future (in the same or a different government department). Second, increasing (or reducing) taxes to finance spending on public goods reduces (or increases) private consumption. Alternative survey formats studying (i) individual's WTP for public projects through a (e.g. uniform) tax increase (also known as public WTP surveys); (ii) or an individual's willingness to allocate public budget (also known as WTAPB surveys) ignore the presence of these two alternative

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types of opportunity costs related to public and private budgets. From a welfare economics perspective, the introduced link – using the tax system – between the private and public budget constraints by PVE surveys allows aligning the PVE framework with the traditional Kaldor–Hicks framework, underlying many cost-benefit analyses (Mouter et al., 2021c).

Where Mouter et al. (2021c,b) introduced the PVE survey method and positioned PVE relative to other survey and valuation methods, this paper develops a micro-econometric framework enabling the analysis of PVE data formats, and the derivation of policy recommendations regarding the optimal policy portfolio and as to which projects (not) to implement and prioritise. From a choice modelling perspective, the PVE data format is characterised by a mixture of purely discrete (the selected public project portfolio) and discrete-continuous (the remaining private and public budget) goods. The proposed micro-econometric framework provides extensions to the seminal works of Hanemann (1984) and Wales and Woodland (1983) on discrete-continuous demand and subsequent works by Phaneuf et al. (2000), Kim et al. (2002), Bhat (2008, 2018). Specifically, the public and private budget constraints in PVE are connected through the tax system whereas Castro et al. (2012), Mondal and Bhat (2021) only account for the presence of multiple independent budget constraints. Moreover, the two outside goods, respectively private consumption and any remaining public budget can have a non-linear impact on direct utility which goes beyond the Linear Outside Good MDCEV model discussed in Bhat (2018), Bhat et al. (2020), Palma and Hess (2022). The choice probabilities derived by our proposed framework are of closed form and are directly transferable to alternative data formats where a mixture of purely discrete and discrete-continuous choices is collected. The proposed micro-econometric framework is, for example, also applicable to a wider field of work focusing on basket-based choice experiments focusing on consumers selecting multiple goods for their shopping basket either in discrete or continuous quantities (Caputo and Lusk, 2022; Neill and Lahne, 2022).

In terms of policy analysis and recommendations, this paper adopts a social welfare function instead of a consumer surplus based approach. The reason for doing so is that the PVE survey is already framed in the application context and the attractiveness of public sector projects can directly be quantified and compared in terms of citizens' cardinal utility without the need for monetary valuation. Changes in social welfare are directly inferred from the estimated utility functions and can inform public policy makers on the ranking of alternative policy portfolios and on whether portfolios of public sector projects give value for money. The results from a PVE survey can show (i) whether individual projects are more attractive than not spending the required budget, and thus whether the social benefits of public sector measures outweigh the costs; (ii) what the optimal composition of the project portfolio is given a restrictive governmental budget; (iii) what the probability is that a portfolio leads to an improvement in social welfare.

Section 2 starts by introducing the policy decision and the social welfare function. Section 3 presents the underlying individual utility functions, the econometric approach to estimate preferences for portfolios of projects taking into account the private and public budget constraints. Section 4 revisits the policy analysis based on the social welfare function for the adopted utility function. Section 5 presents the empirical application of a PVE survey on urban mobility investments conducted in Amsterdam, The Netherlands. Section 6 synthesises the paper.

2. PVE and social welfare

Suppose a policy maker is faced with the decision to spend a governmental budget B on a portfolio of public sector projects. The policy maker has to decide which of the projects $j = 1, \dots, J$ should be included in the policy portfolio p. The set of possible portfolios may comprise all 2^J project combinations, including the null-portfolio which has no projects in it. Portfolios for which the total project costs exceed the governmental budget are excluded. Any remaining governmental budget can be either shifted forward to the next period (or to another department) or given back to the public in the form of a tax reduction. The former option is denoted by y_0 and the latter by $-\tau \cdot Q$, where $-\tau$ is the size of the tax reduction (which is assumed to be equal for each household), and Q is the total number of households affected by the tax reduction. Similarly, the budget (and thus the set of feasible portfolios) can be expanded by levying a uniform tax of size τ resulting in a budget increase of $\tau \cdot Q$,[1] This results in the following governmental budget constraint:

$$B + \tau \cdot Q = y_0 + \sum_{j=1}^{J} c_j \cdot y_j \tag{1}$$

In Eq. (1), c_j represents the costs of project j. Inclusion of project j in the portfolio is denoted by y_j, which is equal to 1 when the project is selected and 0 when the project is not selected. The governmental budget constraint ensures that only a limited set of projects can be included in the portfolio. Suppose, the policy maker seeks to maximise the following expected social utility function:

$$\mathbb{E}\left[SU_p\right] = \sum_{g=1}^{G} Q_g \cdot \mathbb{E}\left[U_{pg}\right] \tag{2}$$

In Eq. (2), 'society' is split into $g = 1, \dots, G$ socio-economic groups each with their own (expected) utility function $\mathbb{E}U_{pg}$ for portfolio p. Q_g denotes the number of households in group g, with $Q = \sum_{g=1}^{G} Q_g$. The utility functions can potentially include both private preferences as well as social or altruistic preferences. Altruism is not cheap because citizens voting altruistically give up private consumption in the form of tax reductions and/or private benefits from public sector projects that are not chosen. Without loss of generality, a reduced form social welfare function is adopted where each household receives the same weight.

[1] The tax payers are assumed to be the beneficiaries of the proposed projects.

Once the parameters of the utility function are estimated, selecting the optimal portfolio conditional on B and τ involves enumerating Eq. (2) for all feasible project portfolios. The optimal tax conditional on a selected portfolio is determined by the following first-order condition:

$$\frac{\mathbb{E}\left[SU_p\right]}{\partial\tau} = \sum_{g=1}^{G} Q_g \cdot \frac{\mathbb{E}\left[U_{pg}\right]}{\partial\tau} = 0 \tag{3}$$

Increasing taxes will reduce private consumption and therefore implementing more or even all public sector policies is not necessarily beneficial. Section 3 provides more details on the specification of the citizens' utility functions before revisiting the implications of the adopted functional form for policy evaluation in Section 4.

3. PVE and individual utility

In PVE surveys, citizens are presented with the decision problem faced by the policy maker and asked to choose their optimal policy portfolio. A distinction is made between *fixed* and *flexible* budget surveys. In flexible budget surveys citizens can adjust the tax, whereas $\tau = 0$ for the fixed budget setting. In both survey formats any remaining public budget is allocated to alternative projects of the department in the near future ensuring the governmental budget constraint is satisfied. Shifting public budget to the near future can be desirable to provide a buffer for future cost overruns or for investment in upcoming public sector projects.

The Multiple Discrete Continuous Extreme Value (MDCEV) model of Bhat (2008) provides extensions of earlier work by Wales and Woodland (1983), Hanemann (1984), Phaneuf et al. (2000), Kim et al. (2002), von Haefen et al. (2004), von Haefen and Phaneuf (2005) and is the suitable analysis framework for these types of PVE surveys because: (i) citizens are faced with multiple decision variables of which some are continuous (private consumption and shifting budget to a future decision periods); (ii) consumption is restricted by private and public budget constraints; (iii) there is a need to account for potential satiation effects associated with the continuous decision variables; and (iv) there is a need to account for corner solutions (inclusion or exclusion of public sector projects in the project portfolio, but also the decision whether or not to shift public budget to future decision periods). The presence of purely discrete alternatives (i.e. the public sector projects) requires a number of model extensions along the lines of Bhat (2018) which will be outlined below.

3.1. Utility maximisation problem

Citizens are denoted by $n = 1, \ldots, N$, public sector projects are indexed by $j = 1, \ldots, J$ and their inclusion (exclusion) from the project portfolio captured by the binary indicators $y_{nj} = 1$ ($y_{nj} = 0$). Following Bhat (2008), the utility derived from the selected project portfolio, the change in future budget y_{n0} and current private consumption $y_{n,J+1}$ is described by[2]:

$$U_n = \frac{\gamma_0}{\alpha_0}\left[\left(\frac{y_{n0}}{\gamma_0}+1\right)^{\alpha_0} - 1\right]\Psi_{n0} + \sum_{j=1}^{J} y_{nj}\Psi_{nj} + \frac{1}{\alpha_{J+1}} y_{n,J+1}^{\alpha_{J+1}}\Psi_{n,J+1} \tag{4}$$

The public budget can be fully exhausted and therefore corner solutions are possible for the variable y_{n0}. Any positive value for the translation parameter γ_0 allows for such corner solutions. The parameter α_0 controls for satiation effects associated with shifting budget forward. Ψ_{n0} denotes the marginal utility at $y_{n0} = 0$. Since only a single (discrete) unit can be consumed for the projects, Ψ_{nj} represents the direct utility of including project j in the portfolio including the valuation of social impacts and broader values of a citizen. The level of private consumption $y_{n,J+1} > 0$, takes the role of an outside good which will always be consumed and hence is not associated with a translation parameter. Satiation effects are taken into account via the parameter α_{J+1}. Finally, $\Psi_{n,J+1}$ is the marginal utility of private consumption at $y_{n,J+1} = 1$.

Private consumption is not included in the governmental budget constraint, but is governed by the private budget constraint (see Eq. (5)), where the change in taxes τ_n ensure the connection between the two constraints. Y_n represents gross income, t_n the income tax rate that applies and c_{J+1} the cost of private consumption. The cost of private consumption is henceforth normalised to unity and assumed equal across all citizens.

$$Y_n \cdot (1 - t_n) - \tau_n = c_{J+1} \cdot y_{n,J+1} \tag{5}$$

Assume, $y_{n0} \geq 0, y_{n,J+1} > 0$, $y_{nj} = 0$ or $y_{nj} = 1$ $\forall j = 1, \ldots, J$; $\alpha_0, \alpha_{J+1} \leq 1$ and $\gamma_0 > 0$. The Lagrangian multipliers λ and θ refer to the marginal utility of additional governmental budget and private net income, respectively. This results in the following Karush–Kuhn–Tucker (KKT) conditions:

$$\mathcal{L}_n = U_n + \lambda_n\left(B + \tau_n \cdot Q - y_{n0} - \sum_{j=1}^{J} y_{nj} \cdot c_{nj}\right) \tag{6}$$

$$+ \theta_n\left(Y_n \cdot (1 - t_n) - \tau_n - y_{n,J+1}\right) \tag{7}$$

$$\frac{\partial\mathcal{L}_n}{\partial y_{n0}} = \left(\frac{y_{n0}}{\gamma_0}+1\right)^{\alpha_0 - 1}\Psi_{n0} - \lambda_n = 0 \text{ for } y_{n0} > 0 \tag{8}$$

[2] The addition of an arbitrary constant to the utility function does not impact estimations nor the policy evaluation.

$$\frac{\partial \mathcal{L}_n}{\partial y_{n0}} = \Psi_{n0} - \lambda_n < 0 \text{ for } y_{n0} = 0 \tag{9}$$
$$\frac{\partial \mathcal{L}_n}{\partial y_{nj}} = \Psi_{nj} - \lambda_n \cdot c_{nj} \geq 0 \text{ for } y_{nj} = 1, \forall j = 1 \ldots, J \tag{10}$$
$$\frac{\partial \mathcal{L}_n}{\partial y_{nj}} = \Psi_{nj} - \lambda_n \cdot c_{nj} < 0 \text{ for } y_{nj} = 0, \forall j = 1 \ldots, J \tag{11}$$
$$\frac{\partial \mathcal{L}_n}{\partial y_{n,J+1}} = y_{nJ+1}^{\alpha_{J+1}-1} \Psi_{n,J+1} - \theta_n = 0 \tag{12}$$
$$\frac{\partial \mathcal{L}_n}{\partial \tau_n} = \lambda_n Q - \theta_n = 0 \tag{13}$$

Because the project utilities Ψ_{nj} and the baseline marginal utilities Ψ_{n0} and $\Psi_{n,J+1}$ are assumed to be stochastic in the MDCEV framework, the KKT conditions lead to portfolio choice probabilities.

3.2. Derivation of portfolio choice probabilities

This subsection describes how to derive the choice probabilities for the observed choice vector y_n^* (i.e. the optimal policy portfolio, including the change in future budgets and taxes) for citizen n. Three cases can be distinguished. Case 1 applies to citizens participating in a fixed budget PVE survey. Case 2 applies to citizens in a flexible budget PVE survey who have not spent the full governmental budget on the proposed projects. Case 3 applies to citizens in a flexible budget PVE survey who have spent the full governmental budget on the proposed projects.

3.2.1. Case 1: Fixed governmental budget

Case 1 assumes a fixed governmental budget ($\tau_n = 0$). In this context, KKT conditions Eqs. (12)–(13) do not apply since private consumption cannot be used to increase or reduce the public budget. We can divide all projects J into three mutually exclusive sets of projects for respondent n:

- M_n, the set of chosen projects, where $m = 1, \ldots, M_n$.
- K_n, the set of non-chosen projects which are still affordable given the remaining budget y_{n0}^*, after observing the set M_n, where $k = 1, \ldots, K_n$.
- Z_n, the set of non-chosen projects which are not affordable given the remaining budget y_{n0}^*, after observing the set M_n, where $z = 1, \ldots, Z_n$.
- The mutually exclusive nature of these sets ensures that $M_n + K_n + Z_n = J$

The distinction between sets K_n and Z_n is relevant, because for a given project $k \in K_n$ the utility per unit of public budget spent on k is lower than the marginal utility of the remaining public budget, i.e. $\frac{\Psi_{nk}}{c_{nk}} < \left(\frac{y_{n0}^*}{\gamma_0} + 1\right)^{\alpha_0 - 1} \Psi_{n0}$, otherwise k would have been added to the portfolio. Whereas for any project $z \in Z_n$ we are unable to determine whether z is non-chosen because of having insufficient remaining budget to add the project to the portfolio, or because the utility per unit of public budget of z is lower than the marginal utility of the remaining public budget at y_{n0}^*. Therefore, all that is known for z is that the corresponding utility per unit of public budget is smaller than or equal to the utility per unit of public budget spent on any chosen project m, i.e. $\frac{\Psi_{nz}}{c_{nz}} \leq \min_m \left[\frac{\Psi_{nm}}{c_{nm}}\right]$. When the public budget is fully exhausted, i.e. $y_{n0}^* = 0$, the set K_n is empty, and the set Z_n includes all non-chosen projects *and* the remaining budget.

When the public budget is not fully exhausted, i.e. $y_{n0}^* > 0$, Eq. (8) applies and results in a marginal utility of governmental budget of $\lambda_n^* = \left(\frac{y_{n0}^*}{\gamma_0} + 1\right)^{\alpha_0 - 1} \Psi_{n0}$. Implementing this in Eqs. (10) and (11) and taking natural logarithms provides the following for every chosen project $m \in M_n$, non-chosen but affordable project $k \in K_n$, and non-chosen but non-affordable project $z \in Z_n$:

$$\begin{aligned}
&\ln(\Psi_{nm}) - \ln(c_{nm}) \geq (\alpha_0 - 1) \cdot \ln\left(\frac{y_{n0}^*}{\gamma_0} + 1\right) + \ln\left(\Psi_{n0}\right) \ , \forall m \in M_n \\
&\ln\left(\Psi_{nk}\right) - \ln\left(c_{nk}\right) < (\alpha_0 - 1) \cdot \ln\left(\frac{y_{n0}}{\gamma_0} + 1\right) + \ln(\Psi_{n0}) \ , \forall k \in K_n \\
&\ln\left(\Psi_{nz}\right) - \ln\left(c_{nz}\right) \leq \min_m \left[\ln\left(\Psi_{nm}\right) - \ln\left(c_{nm}\right)\right], \forall z \in Z_n
\end{aligned} \tag{14}$$

Only the final line of Eq. (14) is relevant when $y_{n0}^* = 0$ because in this context the set K_n is empty. By expanding the set Z_n with the remaining public budget the first and last line represent the same constraint. At $y_{n0}^* = 0$ the log of the marginal utility of the public budget reduces to $\ln\left(\Psi_{n0}\right)$.

Assume $\Psi_{nj} = \exp(\delta_j + X_{nj} \cdot \beta - \epsilon_{nj})$ and $\Psi_{n0} = \exp(\delta_0 - \epsilon_{n0})$, where X_{nj} is a row vector of policy attributes which is specific for individual n. The taste parameters β are assumed to be homogeneous for all respondents, but interaction effects can be included where desirable. δ_j is the project constant and ϵ_{nj} denotes an Extreme Value Type I i.i.d. error term.[3] Furthermore, define

[3] Consequently, $\exp(-\epsilon_{nj})$ follows a Weibull distribution with scale parameter 1 and shape parameter $\frac{1}{\sigma}$, where σ is the scale parameter of the underlying extreme value density.

$V_{nj} = \delta_j + X_{nj} \cdot \beta - \ln\left(c_{nj}\right)$ and $V_{n0} = \delta_0 + (\alpha_0 - 1) \cdot \ln\left(\frac{y^*_{n0}}{\gamma_0} + 1\right)$ such that:

$$\begin{aligned} V_{nm} - \epsilon_{nm} &\geq V_{n0} - \epsilon_{n0},\ \forall m \in M_n \\ V_{nk} - \epsilon_{nk} &< V_{n0} - \epsilon_{n0},\ \forall k \in K_n \\ V_{nz} - \epsilon_{nz} &\leq \min_{m \in M_n}\left[V_{nm} - \epsilon_{nm}\right], \forall z \in Z_n \end{aligned} \tag{15}$$

The assumption of i.i.d. Extreme Value Type I error distribution on ϵ_{nm} together with $\min_m\left[V_{nm} - \epsilon_{nm}\right] = -1 \cdot \max_m\left[-V_{nm} + \epsilon_{nm}\right]$ allows to invoke the well-known logsum equation (Ben-Akiva and Lerman, 1985) such that:

$$\begin{aligned} V_{n0} - \epsilon_{n0} &\leq -(LS_n + \epsilon^*_n) \\ V_{nz} - \epsilon_{nz} &\leq -(LS_n + \epsilon^*_n), \forall z \in Z_n \end{aligned} \tag{16}$$

where $LS_n = \sigma \ln\left[\sum_{m=1}^{M_n} e^{\left(\frac{-V_{nm}}{\sigma}\right)}\right]$. We can then define the choice probability by:

$$\begin{aligned} \mathbb{P}_{n1}(y^*_n) = \int_{\epsilon_{n0}=-\infty}^{\infty} \int_{\epsilon^*_n=-\infty}^{\infty} \prod_{z=1}^{Z_n}\left(1 - F\left[V_{nz} + LS_n + \epsilon^*_n\right]\right) \cdot \prod_{k=1}^{K_n}\left(1 - F\left[V_{nk} - V_{n0} + \epsilon_{n0}\right]\right) \\ \cdot I\left[V_{n0} - \epsilon_{n0} \leq -LS_n - \epsilon^*_n\right] \cdot h\left(\epsilon^*_n\right) \cdot g\left(\epsilon_{n0}\right) d\epsilon^*_n d\epsilon_{n0} \end{aligned} \tag{17}$$

The choice probability comprises a product over 1-CDF expressions for the non-chosen but unaffordable projects included in Z_n, and a product over 1-CDF expressions for the non-chosen but affordable projects included in K_n (as expressed in Eqs. (15)–(16)). Since the projects included in Z_n are evaluated against the chosen alternatives, and the projects in K_n against the marginal utility of the remaining public budget, an integral is needed over ϵ^*_n and ϵ_{n0} respectively. However, in order to satisfy that the utility per unit of budget of the chosen projects in M_n is larger or equal to the marginal utility of the remaining public budget the non-stochastic indicator function $I\left[V_{n0} - \epsilon_{n0} \leq -LS_n - \epsilon^*_n\right]$ is included taking the value of one when the condition is satisfied and zero otherwise.

Given the assumed i.i.d. EV Type 1 densities with common scale parameter σ, let $\mathbf{1}_{M_n}$ describe a M_n by 1 vector of ones and A_n a vector of similar size containing $e^{-\frac{V_{nm}-V_{n0}}{\sigma}}$ for each $m \in M_n$ such that $\sum_m^{M_n} e^{-\frac{V_{nm}-V_{n0}}{\sigma}} = \mathbf{1}'_{M_n} \cdot A_n$. Define $\mathbf{W_n}$ as a matrix of size 2^{Z_n} by Z_n describing all possible combinations of non-chosen but unaffordable projects included in Z_n, including the empty set. That is, $\mathbf{W_n}$ represents a matrix containing binary indicators describing a two-level full factorial design with Z_n factors. Let W_{nc} describe a given row c of $\mathbf{W_n}$ and $|W_{nc}|$ the rowsum of W_{nc}, i.e. $|W_{nc}| = \sum_{z \in Z_n} W_{ncz}$. Let B_n be a vector of size Z_n by 1 containing $e^{-\frac{V_{nz}+LS_n}{\sigma}}$ for each $z \in Z_n$. In similar vein, define $\mathbf{Q_n}$ as a matrix of size 2^{K_n} by K_n describing all possible combinations of non-chosen but affordable projects included in K_n, including the empty set. That is, $\mathbf{Q_n}$ represents a matrix containing binary indicators describing a two-level full factorial design with K_n factors. Let Q_{nq} describe a given row q of Q_n and $|Q_{nq}|$ the rowsum of Q_{nq}, i.e. $|Q_{nq}| = \sum_{k \in K_n} Q_{nqk}$. Let C_n be a vector of size K_n by 1 containing $e^{-\frac{V_{nk}-V_{n0}}{\sigma}}$ for each $k \in K_n$. Then, following Bhat (2018), the closed form choice probability is given by (see Appendix A for the derivations)[4]:

$$\mathbb{P}_{n1}(y^*_n) = \sum_q^{2^{K_n}} \sum_c^{2^{Z_n}} (-1)^{|Q_{nq}|} \cdot (-1)^{|W_{nc}|} \cdot \frac{1}{1 + Q_{nq} \cdot C_n + \left(\mathbf{1}'_{M_n} \cdot A_n\right) \cdot \left(1 + W_{nc} \cdot B_n\right)} \cdot \frac{1}{1 + W_{nc} \cdot B_n} \tag{18}$$

3.2.2. Case 2: Flexible governmental budget, $y^*_{n0} > 0$

Tax adjustments give the opportunity for citizens to adjust their private consumption. Since the outside private good $y_{n,J+1}$ is always consumed, the marginal utility of net income is always defined and equal to $\theta^*_n = y_{n,J+1}^{\alpha_{J+1}-1} \Psi_{n,J+1}$, where $\Psi_{n,J+1} = e^{(\delta_{J+1} - \epsilon_{n,J+1})}$. Moreover, when both y_{n0} and $y_{n,J+1}$ are consumed in optimal amounts then Eq. (13) implies:

$$\lambda^*_n = \frac{\theta^*_n}{Q} = \frac{(y^*_{n,J+1})^{\alpha_{J+1}-1} \Psi_{n,J+1}}{Q} \tag{19}$$

That is, the marginal utility of governmental budget is equal to the marginal utility of net income divided by the number of households Q. For positive consumption of y_{n0} the equality condition Eq. (8) applies. For the discrete projects, the solution for the marginal utility of budget is substituted into the inequality conditions Eqs. (10) and (11) resulting in the following inequality conditions for the public projects:

$$\begin{aligned} \epsilon_{nm} &\leq V_{nm} - V_{nJ+1} + \epsilon_{n,J+1},\ \forall m \in M_n \\ \epsilon_{nk} &> V_{nk} - V_{nJ+1} + \epsilon_{n,J+1},\ \forall k \in K_n \end{aligned} \tag{20}$$

with $V_{n,J+1} = (\alpha_{J+1} - 1) \ln\left[y^*_{n,J+1}\right] + ln\left[\Psi_{n,J+1}\right] - \ln[Q]$. Here, the distinction between sets K_n and Z_n is no longer relevant, because we assume that respondents have sufficient private budget to increase the public budget for all non-chosen alternatives to be affordable,

[4] All resulting closed-form probabilities in the paper have been checked by simulation.

leaving Z_n empty. The choice probability can then be obtained by integrating over $\epsilon_{n,J+1}$:

$$\mathbb{P}_{n2}(y_n^*) = \left||G|\right| \int_{\epsilon_{n,J+1}=-\infty}^{\infty} \prod_{k=1}^{K_n} \left(1 - F\left[V_{nk} - V_{n,J+1} + \epsilon_{n,J+1}\right]\right) \prod_{m=1}^{M_n} F\left[V_{nm} - V_{n,J+1} + \epsilon_{n,J+1}\right] \cdot f\left[V_{n0} - V_{n,J+1} + \epsilon_{n,J+1}\right] \cdot f\left[\epsilon_{n,J+1}\right] d\epsilon_{n,J+1} \tag{21}$$

where $\left||G|\right| = \left|\frac{\partial(V_{n0}-V_{n,J+1}+\epsilon_{n,J+1})}{\partial y_{n0}^*}\right| = \left|(\alpha_0-1)\frac{1}{y_{n0}^*+\gamma_0} + (\alpha_{J+1}-1)\frac{1}{y_{n,J+1}^*}\frac{1}{Q}\right|$ is the absolute value of the determinant of the Jacobian matrix. The latter is needed because of the change of variable for ϵ_{n0}. It ensures that changes in equilibrium private consumption ($y_{n,J+1}^*$) due to changes in shifting money (y_{n0}^*) are properly accounted for.

In what follows, define $\mathbf{S_n}$ as a matrix of size 2^{K_n} by K_n describing all possible combinations of non-chosen but affordable projects included in K_n, including the empty set. That is, $\mathbf{S_n}$ represents a matrix containing binary indicators describing a two-level full factorial design with K_n factors. Let S_{ns} describe a given row s of S_n and $|S_{ns}|$ the rowsum of S_{ns}, i.e. $|S_{ns}| = \sum_{k\in K_n} S_{nsk}$. Let D_n be a vector of size K_n by 1 containing $e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}$ for each $k \in K_n$. Additionally, the set of chosen goods M_n is extended with good 0 such that $\sum_{m=0}^{M_n} e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}} = I'_{M_n+1} \cdot E_n$, where I_{M_n+1} is a M_n+1 by 1 vector of ones and E_n is a M_n+1 by 1 vector containing the elements $e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}$, for $m = 0, \ldots, M_n$. Then the choice probability is given by (see Appendix B for the derivations):

$$\mathbb{P}_{n2}(y_n^*) = \frac{1}{\sigma}\left||G|\right| e^{-\left(\frac{V_{n0}-V_{n,J+1}}{\sigma}\right)} \sum_{s}^{2^{K_n}} (-1)^{|S_{ns}|} \frac{1}{\left(1 + S_{ns}\cdot D_n + I'_{M_n+1}\cdot E_n\right)^2} \tag{22}$$

3.2.3. Case 3: Flexible governmental budget, $y_{n0}^* = 0$

The last case describes the outcome of the flexible budget survey when no budget is shifted to the next year implying $y_{n0}^* = 0$. The marginal utility of net income can still be pinned down using Eq. (12). The equality condition Eq. (8) is replaced by the inequality condition Eq. (9). Denote $k = 0 \ldots K_n$ as the non-chosen alternatives and $m = 1 \ldots M_n$ as the chosen alternatives. The choice probability is then given by:

$$\mathbb{P}_{n3}(y_n^*) = \int_{\epsilon_{n,J+1}=-\infty}^{\infty} \prod_{k=0}^{K_n} \left(1 - F\left[V_{nk} - V_{n,J+1} + \epsilon_{n,J+1}\right]\right) \prod_{m=1}^{M_n} F\left[V_{nm} - V_{n,J+1} + \epsilon_{n,J+1}\right] \cdot f\left[\epsilon_{n,J+1}\right] d\epsilon_{n,J+1} \tag{23}$$

Similar to Case 2, define $\mathbf{S_n}$ as a matrix of size 2^{K_n+1} by K_n+1 describing all possible combinations of non-chosen but affordable projects included in K_n, including the empty set.[5] In other words, $\mathbf{S_n}$ represents a matrix containing binary indicators describing a two-level full factorial design with K_n+1 factors. Let S_{ns} describe a given row s of S_n and $|S_{ns}|$ the rowsum of S_{ns}, i.e. $|S_{ns}| = \sum_{k\in K_n+1} S_{nsk}$. Let D_n be a vector of size K_n+1 by 1 containing $e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}$ for each $k = 0, \ldots, K_n$. Here, the set of chosen goods M_n is not extended with good 0 such that $\sum_{m=1}^{M_n} e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}} = I'_{M_n} \cdot E_n$, where I_{M_n} is a M_n by 1 vector of ones and E_n is a M_n by 1 vector containing the elements $e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}$, for $m = 0, \ldots, M_n$. Then the choice probability is given by (see Appendix C for the derivations):

$$\mathbb{P}_{n3}(y_n^*) = \sum_{s}^{2^{K_n+1}} (-1)^{|S_{ns}|} \cdot \frac{1}{1 + S_{ns}\cdot D_n + I'_{M_n}\cdot E_n} \tag{24}$$

Finally, denote I_{n1}, I_{n2}, and I_{n3} as indicator functions taking the value of 1 when case 1,2, or 3 applies for individual n and 0 otherwise. The choice probability for individual n is then given by:

$$\mathbb{P}_n(y_n^*) = \mathbb{P}_{n1}(y_n^*)^{I_{1n}} \mathbb{P}_{n2}(y_n^*)^{I_{n2}} \mathbb{P}_{n3}(y_n^*)^{I_{n3}} \tag{25}$$

This choice probability is used in the log-likelihood optimisation for determining the relevant parameters of the utility function. Straightforward extensions to cases with panel data can be made.

4. Policy analysis — the optimal portfolio and budget

Policy analysis based on the estimated individual utility functions consider two situations depending on the institutional possibilities. First, the budget can be fixed and, for example, set equal to the governmental budget as presented in the survey (B). Any remaining budget will be shifted to the next period leading to a positive value for y_0. Second, the governmental budget can be optimised. This can be done by adjusting the tax level τ in such a way that marginal benefits are equal to the marginal costs of a tax adjustment. An increase in the tax leads to additional budget and gives the opportunity to choose portfolios with more projects but leads to a reduction in private consumption.

[5] K_n includes good y_{n0}, i.e. the remaining public budget.

Each socio-economic group g in the population has a different utility function as private income levels differ. This will lead to different levels of optimal private consumption. The expected value of the estimated random utility function for a randomly sampled individual n belonging to group g is given by Eq. (26):

$$\mathbb{E}[U_g] \equiv \mathbb{E}[U_{ng}] = \frac{\gamma_0}{\alpha_0}\left[\left(\frac{y_0}{\gamma_0}+1\right)^{\alpha_0}-1\right]\mathbb{E}[\Psi_{n0}] + \sum_{j=1}^{J} y_j \mathbb{E}[\Psi_{nj}] + \frac{y_{g,J+1}^{\alpha_{J+1}}}{\alpha_{J+1}}\mathbb{E}[\Psi_{n,J+1,}] \tag{26}$$

where $y_j = 1$ if project j is included in a portfolio, $y_0 = B + \tau Q - \sum_{j=1}^{J} y_j c_j$ and $y_{J+1,g} = Y_g(1-t_g) - \tau$. Due to the public good nature of the decision problem, the implemented projects, the costs of the respective portfolio and the additional tax τ are assumed to be equal for all citizens in the policy analysis. The distributional assumptions on ϵ_{nj} imply:

$$\mathbb{E}[\Psi_{nj}] = \Gamma\,[1+\sigma]\,e^{\delta_j + \beta X_j}\ \forall j = 0, 1, \ldots, J+1 \tag{27}$$

In Eq. (26), $\Gamma(\cdot)$ denotes the Gamma function which acts as a scalar on expected utility. The ranking of the portfolios is independent of the scale parameter σ because of the assumed homoscedasticity of the error terms. Note that when the tax $\tau = 0$ and the budget is set at B, group income levels have no impact on the ranking of the portfolios as private consumption does not change across the different policy portfolios.

5. Empirical application

5.1. PVE survey on urban mobility investments in Amsterdam, the Netherlands

Together with the Transport Authority Amsterdam (henceforth: TAA) a PVE survey was designed and implemented. In collaboration with the program managers of the 'car', 'public transport', 'cycling' and 'safety' departments of the TAA, sixteen urban mobility projects that were already considered for inclusion in a transport investment scheme were selected for inclusion in the PVE survey. Table 1 provides a description of these 16 projects.

Where available, we used the project descriptions of the TAA to describe the projects to the respondents. Table 1 (column 2) presents whether the projects were originating from the car, public transport (PT), cycling or safety department. We received additional documentation to determine seven types of societal impacts (i.e. the attributes) of the projects: (1) costs; (2) number of travellers who experience travel time savings during an average working day; (3) average number of minutes of travel time savings per traveller; (4) change in traffic deaths per year; (5) change in severe traffic injuries per year; (6) additional households affected by noise pollution; (7) number of trees that have to be removed for the project. Again in collaboration with the TAA we established impact bandwidths, because we needed to differentiate the attribute levels among the participants to estimate people's sensitivity for these impacts. The remaining columns of Table 1 describe the bandwidths of the impacts for each project. Respondents were presented one of 65 experimental design versions each using different combinations of costs and societal impacts.

The fixed budget survey assumed a budget of $B = 100$ million euros. In the flexible budget survey that same value was used as the reference value, but citizens could change the budget by lowering or increasing household taxes. The additional tax needed/received was distributed equally over all one million households (Q) in the jurisdiction of the TAA. The aggregate costs of implementing all 16 projects accounts for 386.5 million euros. With only 100 million euros of public budget to spend, it was not possible for the respondents to include all projects in their portfolio. Respondents only made a single portfolio choice.

An experimental survey platform was developed for the PVE survey. An introduction page explained the purpose of the survey and citizens could watch a video in which the survey platform was explained. The video also showed how citizens could obtain quantitative and qualitative information about the different public sector projects. Within the PVE part of the survey, citizens could highlight projects and compare their impacts. Respondents were informed that the impacts will materialise over a period of 50 years. Maps were provided showing the spatial area where each project was planned.

Fig. 1 presents an example of the main PVE choice screen (in Dutch). The 16 projects are listed and the corresponding project costs (in mln €) are presented on the left in the grey-shaded circles. The project ordering can be changed by ranking them based on the seven attributes using the 'rangschikken op' feature at the top of the screen. Each individual project can be studied in more detail using the information button (black circle with the '*i*') at the end of each row. Fig. 2 describes project 12 building a new bridge for cyclists reducing travel time for 6000 cyclists (per day) by 6 min with a total project costs of €27mln. The 'vergelijk' feature in the main screen allowed respondents to compare and contrast projects on the attributes of interest. The comparison of three cycling projects (8,10 and 12) is presented in Fig. 3. To include projects in their portfolio, respondents click the project in the 'Selectie' column. In the example presented in Fig. 1, projects 16 and 9 are selected. In the top-right corner budget spent (€30mln.) and the remaining budget (€70mln.) are recorded. In the flexible PVE survey a button has been added to the top of the screen to adjust the public budget.

5.2. Sample characteristics and descriptive results

We conducted the PVE survey in four waves (June 2017, October 2017, January 2018, March 2018). In two waves, respectively waves 2 and 3, respondents were allowed to adjust the governmental budget by increasing the tax per household or by selecting a rebate (flexible budget PVEs). The survey company Kantar Public was asked to draw four random samples from the population of the TAA of 18 years of age and older. The company was not explicitly requested to draw representative samples, but it was important

Table 1
The characteristics of the 16 projects in the TAA case study.

	Type	Costs	Travellers affected (thousands)	Minutes time savings	Change traffic deaths	Change severe injuries	Households affected by noise pollution	Trees cut
(1) Faster connection to the provincial road N516 (Zaandam) at the Poelenburg/Achtersluispolder. Will decrease travel time for car/bus traffic.	Car	40/60	50/70	2/4	0	0	20/100	0
(2) Fly-over on the A10 at the junction Amsterdam Noord. Will decrease travel time for car and bus traffic.	Car	30/50	60/80	2/4	0	0	50/200	40/200
(3) Extending Mac Gillavrylaan to the Middenweg. Improves accessibility of the Science Park and reduces noise pollution at the Middenweg.	Car	7/13	30/40	3/6	0	0	−50/−150	0
(4) Extra lane on Bovenkerkerweg. Decreases travel time for car users.	Car	7/13	25/40	2/6	0/0.2	0/2	0/20	20/40
(5) New bus connection IJburg – Bijlmer Arena. Will improve public transport between IJburg, Amstelveen and Schiphol Airport.	PT	40/60	3/6	4/11	0	0	0	0
(6) Route shortening of busses running between Amsterdam CS and Zaandam by an extra entrance and exit ramp.	PT	3/7	3/7	1/2	0	0	0	0
(7) The tram connection between Diemen and the Linnaeusstraat will be accelerated through a more efficient allocation of stops and traffic lights.	PT	11/19	4/10	3/5	0	0	0	0
(8) A cycling highway will be realised between Hoofddorp–Schiphol and Aalsmeer.	Bike	5/11	2.5/4	3/6	0	0	0	0
(9) A cycling highway will be realised between the sports facilities at the Amstelveenseweg (Amsterdam).	Bike	4/8	8/15	2/4	0	0	0	20/100
(10) New bridge for cyclists/pedestrians at Hoornselaan (Purmerend).	Bike	3/6	6/10	2/4	0/−0.1	0/−2	0	0
(11) Bike tunnel will be built at the Guisweg (Zaandam) where cyclists now cross the railroad.	Bike	30/50	5/8	1/3	0/−0.2	0/−3	0	0
(12) A new bridge for cyclists will be built between Borneo-Eiland and Zeeburgereiland (Amsterdam).	Bike	25/45	6/8	5/8	0	0	0	0
(13) Ilpendam pedestrian tunnel will reduce travel time for car traffic and bus traffic and improve safety for pedestrians.	Safe	2/4	15/25	1/2	0/−0.1	0/−2	0	0
(14) A tunnel will be made for car users at The Stadhouderskade at the entrance of the Vondelpark. Cyclists/pedestrians and car traffic will be separated.	Safe	30/50	35/40	1/2	0/−0.8	−2/−6	0	0
(15) Traffic education for children in the age group 4–18 will prevent traffic accidents through improving awareness of children.	Safe	40/60	0	0	0/−1	−2/−15	0	0
(16) Five additional police officers will be hired who will specifically focus on enforcing traffic laws.	Safe	15/25	0	0	0/−1	−3/−10	0	0

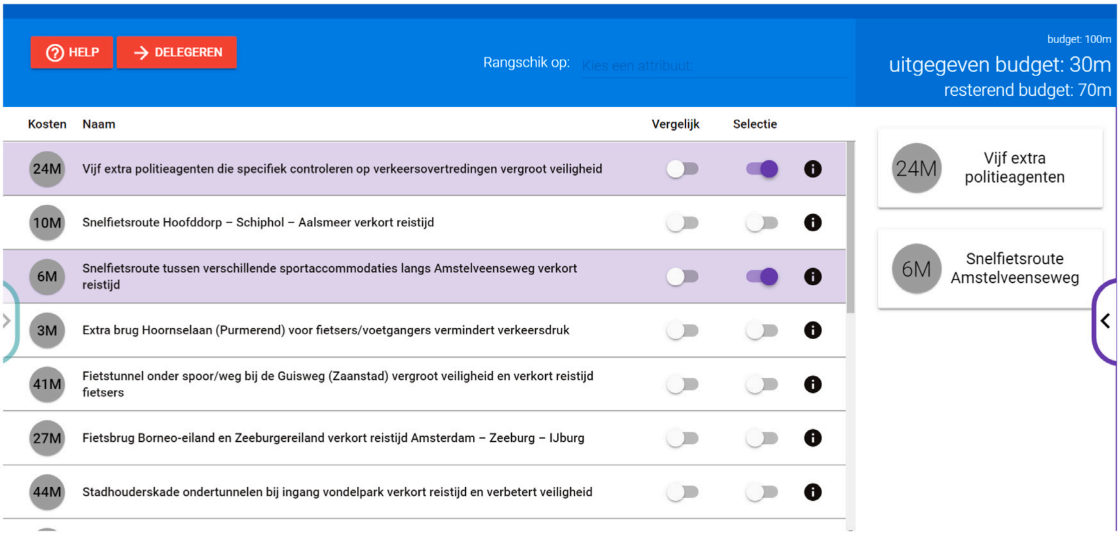

Fig. 1. Screenshot (in Dutch) of the main PVE choice screen.

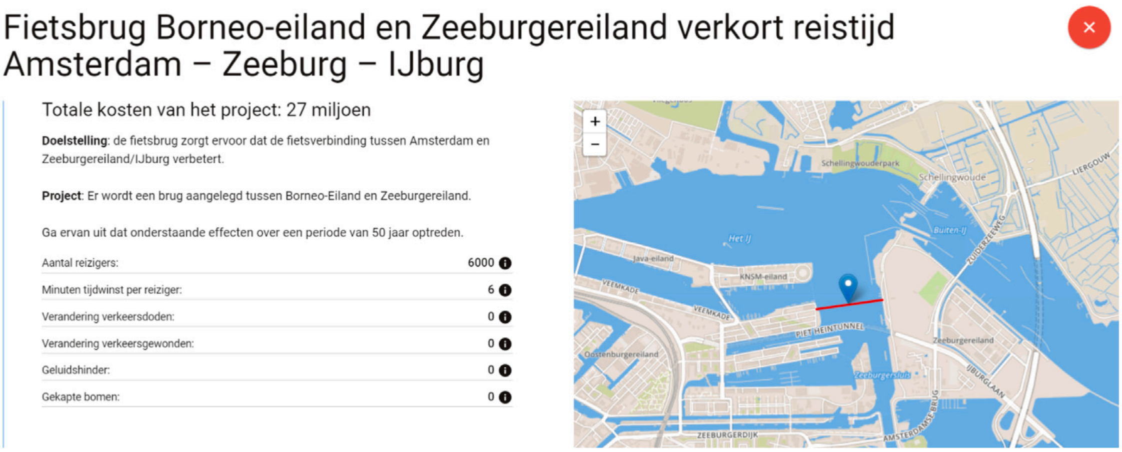

Fig. 2. Screenshot (in Dutch) of the project included in the PVE.

that all relevant demographic segments (e.g. household income, education, age and gender) were represented. Respondents who completed the survey received a monetary compensation.

In total, 4974 individuals opened the online PVE survey, and 2512 completed responses were recorded. Participants were not forced to make a portfolio choice but had the option to delegate their choice to an expert.[6] The 270 delegated responses are not included in the present paper. A further 15 responses were removed based on data quality issues leaving a sample of 2227 observations. Table 2 describes the socio-economic characteristics of the sample by wave, and for the population living within the TAA boundaries (based on four-digit postcodes). The sample is not representative in several dimensions. Males, older inhabitants (45+) and individuals with a higher household income are overrepresented.

We recorded the overall survey response times (see Table 3). As with any survey, response times display large degrees of variation — especially at the upper end. The median response time was 15 min (and 13 s) and 79% of the sample completed the survey within half an hour. In conventional stated choice surveys, based on personal experience, we would perhaps have expected a larger share of the sample completing within 15 min. We interpret the relatively longer response times to the PVE survey format as an increase in the cognitive effort required from respondents. A substantial share of the respondents really engages with the survey and devotes up to an hour (or even more) of their time. Respondents taking more than two hours display evidence of returning to the survey after a couple of hours (or days). We do not observe evidence that the cognitive load of PVE surveys increases dropout rates. The

[6] The delegates in turn also completed the survey. These experts filled in the survey which had an underlying design with the average value of the social impacts across the designs. In case respondents delegated their choice, they received a lower financial compensation from the survey company.

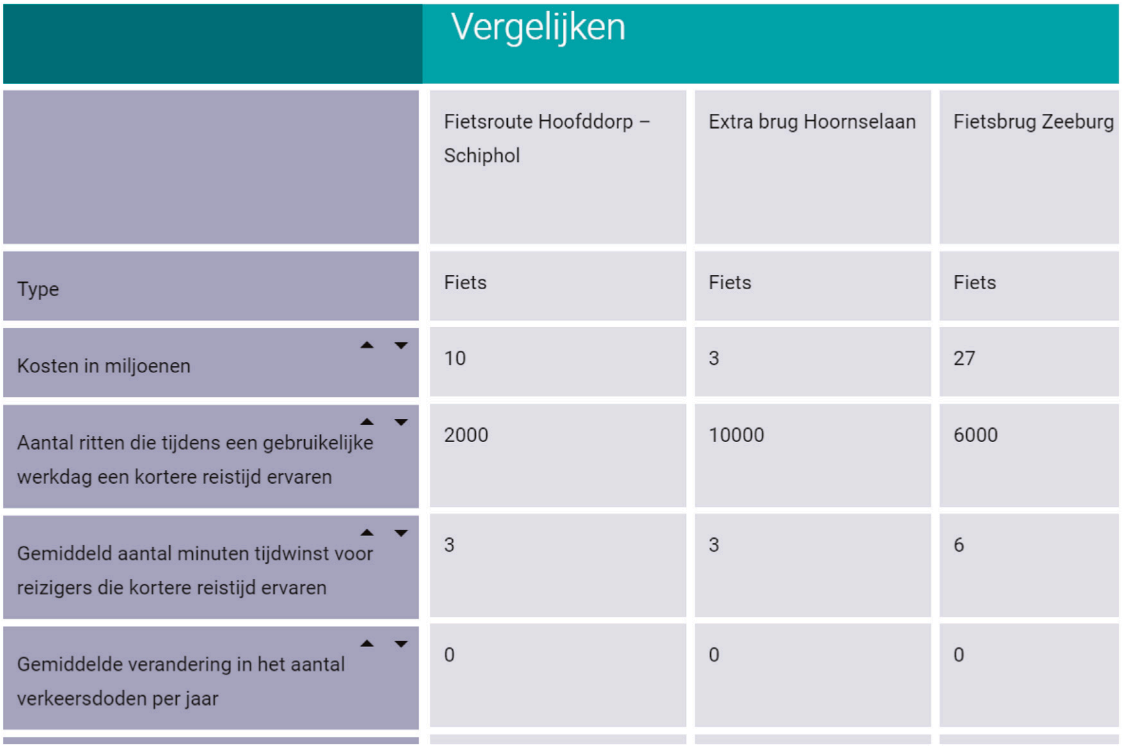

Fig. 3. Screenshot (in Dutch) comparing PVE projects.

majority of dropouts (81%) occur at early stages of the survey, i.e. before the PVE part of the survey, with most dropouts leaving within a minute from opening the survey. We, however, cannot rule out that some respondents dropping out at a later stage of the survey do because of its cognitive load.

Table 4 presents, by wave of the survey, the percentage of times that each project is included in the selected portfolios. The differences in these choice shares across the four waves of the PVE are not very large and following Mouter et al. (2021b) we therefore no longer distinguish between the four waves in the remainder of the analysis. All types of projects are represented in the selected portfolios, but particularly the safety and bike projects appear to be popular. Surprisingly, some of the more expensive projects (for example the safety projects 14 and 15) are frequently included in the portfolios. Fig. 4 contrasts the remaining public budget, i.e. after the portfolio choice has been made, between the fixed and flexible budget PVE surveys. In both settings most respondents spend the majority of the available budget on the public projects. In the flexible budget setting the option to change the budget is primarily used to exhaust the public budget. Overall, 42.4% of the respondents in the flexible budget setting exhaust the public budget (vs 20.8% in the fixed budget setting). Out of the 1184 respondents in the flexible budget setting 381 (32%) adjust the public budget from which 346 (91%) end up exhausting the budget. This picture is confirmed by Fig. 5 where increases and reductions in the public budget are primarily used to construct the desired portfolio and thereby exhaust the public budget. In the fixed budget setting, we see a larger share of respondents (55.5%) with a remaining budget between 1–10€mln since they do not have the option to reallocate the remaining budget.

Table 5 provides further insights into the size of the selected portfolios. For 58% of respondents the portfolio size comprised between 3–5 projects, with only a handful of respondents selecting more than 10 projects and a limited percentage opting for an empty or single project portfolio.

5.3. Estimation results

Table 6 presents the results from three model specifications. The three models differ in terms of the explanatory variables included in Ψ_{nj}, i.e. the utility of the public projects, and the marginal baseline utilities for the private and remaining public budget. Model 1 is a 'constants only' model, Model 2 accounts for the impact of the project attributes (as presented in Table 1), and Model 3 evaluates whether local residents are more likely to include the projects which are being implemented in their close vicinity in their optimal portfolio. Across the three models, the constant in the baseline marginal utility for the remaining public budget, i.e. δ_0, is

Table 2
Socio-demographic characteristics of the sample and the TAA population.

	Wave 1	Wave 2	Wave 3	Wave 4	Sampled
Number of respondents	742	803	381	301	Postcodes
Gender[a]					
Female	44%	47%	53%	50%	51%
Male	56%	53%	47%	50%	49%
Age[a]					
<15					16%
18–25 (15-25)	4%	5%	12%	11%	12%
26–35 (26-45)	10%	11%	13%	20%	30%
36–45	14%	16%	10%	16%	
46–55 (46-65)	23%	23%	19%	18%	27%
56–65	22%	22%	24%	16%	
65 + (65+)	27%	23%	22%	18%	15%
Education[b]					
Lower education	35%	35%	30%	37%	25%
Higher education	43%	43%	47%	42%	35%
University (of applied sciences)	21%	22%	24%	21%	40%
Household gross income (annual)					
Less than €15,000	6%	6%	15%	8%	
€15,000–€30,000	15%	14%	28%	12%	
€30,000–€60,000	40%	40%	41%	38%	
More than €60,000	39%	40%	16%	42%	
Standardised disposable household income (percentiles)[c]					
1%–20%					25%
21–40%					18%
41–60%					17%
61–80%					17%
81–100%					23%
Annual median income (national, 2017)					€34,100

[a] Source: CBS (www.cbs.nl) — Gender and age statistics by postcode (PC4) 2018.
[b] Source: CBS (www.cbs.nl) — Education levels by municipality 2019.
[c] Source: CBS (www.cbs.nl) — Household Income distribution by postcode (PC4) in 2017.

Table 3
Breakdown of survey response times.

	Observations	Share	Cumulative share
5 min or less	99	4%	4%
5–10 min	469	21%	26%
10–15 min	530	24%	49%
15–20 min	313	14%	63%
20–30 min	353	16%	79%
30–40 min	124	6%	85%
50–40 min	62	3%	88%
50–60 min	37	2%	89%
1–1.5 h	35	2%	91%
1.5–2 h	19	1%	92%
more than 2 h	186	8%	100%

normalised to zero for identification purposes (Bhat, 2008).[7] Like in Bhat (2008), the joint identification of γ_0 and α_0 is problematic, such that γ_0 is normalised to 1 and α_0 and α_{J+1} are estimated. Due to the minimal differences between the recommendations of Models 1 and 2, we base our initial discussions on Model 2 before expanding to Model 3 in Section 5.3.4.

5.3.1. The optimal portfolio and remaining public budget in a flexible PVE

With reference to all models, we observe a strong positive constant for the private budget implying individuals prefer a private euro over a public euro. Remaining public budget, however, remains attractive because giving up a single private euro results in an increase of the remaining public budget by 1 million euro due to the collective nature of the tax. Solving Eq. (19) using the estimated satiation parameters $\hat{\alpha}_0 = 0$ and $\hat{\alpha}_{J+1} = 1$ - these approached their respective theoretical bounds in estimation - provides an expression for the optimal remaining public budget of $y^*_{n0} = exp\left(-\left[\hat{\delta}_{J+1} - (\epsilon_{n,J+1} - \epsilon_{n0}) - ln(Q)\right]\right) - 1$. The optimal remaining public budget follows a log–logistic distribution and its mean does not exist because the estimated variance is larger than unity. The

[7] Since MDCEV and PVE models are estimating *direct* utility functions, instead of *indirect* utility functions in discrete choice models, it is not recommended to include prices and income as explanatory variables. These variables are already accounted for by the first order conditions.

Table 4
Choice shares across the four waves.

Project	Type	Wave 1 fixed budget	Wave 2 flexible budget	Wave 3 flexible budget	Wave 4 fixed budget	Average cost
1	Car	10.1%	13.1%	10.0%	12.3%	50M
2	Car	19.7%	17.6%	14.4%	21.3%	40M
3	Car	37.6%	33.5%	37.3%	37.2%	10M
4	Car	29.1%	24.2%	21.5%	23.3%	10M
5	PT	10.2%	6.7%	7.4%	9.3%	50M
6	PT	34.1%	35.2%	27.8%	35.9%	5M
7	PT	24.0%	25.2%	25.5%	24.9%	15M
8	Bike	35.6%	34.3%	32.6%	32.6%	8M
9	Bike	34.4%	29.1%	28.9%	31.2%	6M
10	Bike	38.0%	35.5%	30.7%	33.2%	4.5M
11	Bike	18.6%	19.7%	10.8%	15.6%	40M
12	Bike	23.9%	27.8%	25.2%	26.9%	35M
13	Safety	44.3%	37.9%	35.2%	34.2%	3M
14	Safety	38.4%	38.1%	37.3%	40.5%	40M
15	Safety	32.5%	37.4%	33.6%	28.9%	50M
16	Safety	38.5%	36.9%	39.4%	31.9%	20M
Obs		742	803	381	301	

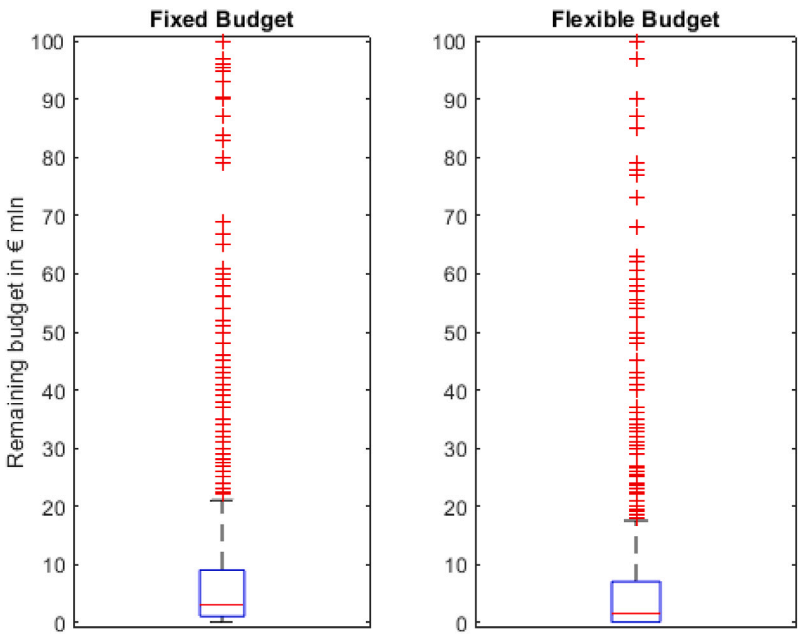

Fig. 4. Remaining budget after portfolio choice in the fixed and flexible budget PVE.

median of the optimal remaining public budget does however exist and is given by $exp(-\hat{\delta}_1 + ln(Q)) - 1$. As an example, the median of the optimal remaining public budget is 1.19 million euros in Model 2. Its order of magnitude aligns with Figs. 4 and 5.

In equilibrium, the optimal remaining public budget y^*_{n0} has a constant marginal utility, because private income is estimated to have a constant marginal utility of private income, i.e. $\hat{\alpha}_{J+1} = 1$. People will reallocate private income to and from the public budget by adjusting the tax rate to maintain the equilibrium relationship in Eq. (19). Assuming a fixed budget PVE setting the marginal probability of including a project in the optimal portfolio can be derived from $\hat{\delta}_j + X_{nj}\hat{\beta} - ln(c_{nj}) - \epsilon_{nj} \geq \hat{\delta}_{J+1} - ln(Q) - \epsilon_{n,J+1}$. Due to the assumed distributions on the error terms, the probability takes the convenient binary logit shape. The model parameters can accordingly be interpreted in the traditional way for choice modelling in relation to elasticities but not for welfare estimates (i.e. monetary welfare estimates). Intuitively, a higher $\hat{\delta}_j$ implies that the project is more likely to be included in the optimal portfolio, alike an alternative specific constant. The probability for inclusion in the optimal policy portfolio is, however, not independent of the costs of the project due to the role of $ln(c_{nj})$. The negative estimates for the safety attributes in Model 2 indicate people prefer

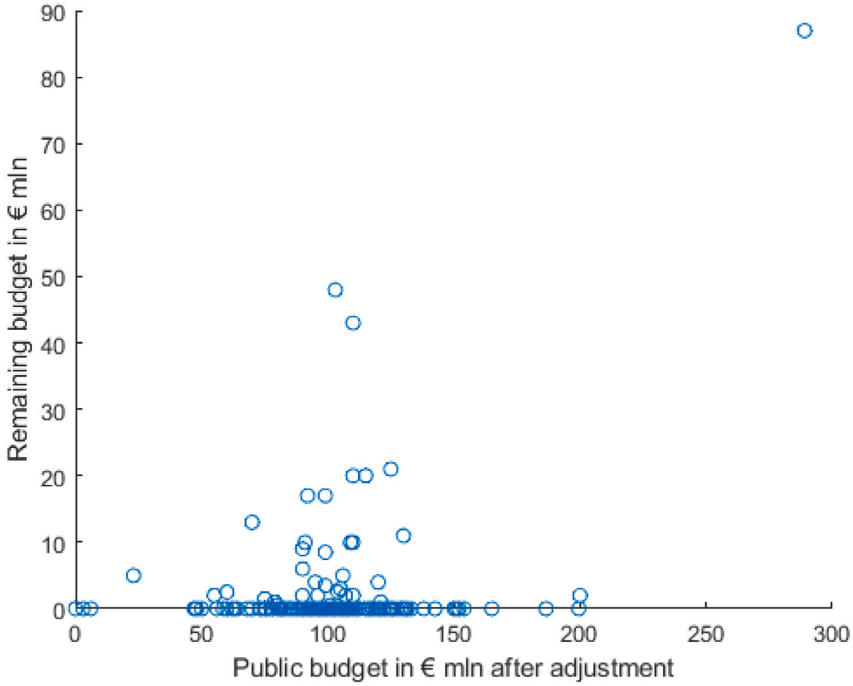

Fig. 5. Scatter plot contrasting the adjusted budget with remaining budget (n=341).

Table 5
Size of the selected portfolios.

Number of projects selected	Number of respondents
0	35 (2%)
1	42 (2%)
2	181 (8%)
3	475 (21%)
4	479 (21%)
5	362 (16%)
6	285 (13%)
7	216 (10%)
8	127 (6%)
9	23 (1%)
10	1 (0%)
11	1 (0%)

safety improvements resulting in fewer fatalities and injuries.[8] The other project attributes included in the study design were not associated with significant parameter estimates.

The penultimate column in Table 7 presents for each of the 16 public projects the probability of being included in the optimal portfolio based on Model 2. A probability of larger than 50% is required for a project to be recommended in the optimal project portfolio in a flexible PVE setting. The ranking of the probabilities (in descending order) as presented in the final column signifies their relative order of importance. That is, the highest ranked projects should be dropped from the optimal portfolio the latest. To determine the optimal policy portfolio we can make use of Eq. (26). Firstly, recognise that the remaining public budget can be ignored, because its optimal value is independent of which alternatives are included in the policy portfolio under flexible PVE. Secondly, all policy portfolios are affordable since only minor changes in private budget are required to implement all policies. Thirdly, the total cost of each potential portfolio results in a reduction of individual utility due to the associated tax burden. We can therefore derive the change in expected utility introduced by each potential portfolio, net the impact of the tax burden, and contrast this against the null portfolio as the reference case. This provides a ranking of all policy portfolios based on the expected change in utility relative to this do nothing scenario. Since the expected utility of a project is given by $exp(\hat{\delta}_j - X_{nj}\hat{\beta}) \cdot \Gamma[1+\hat{\sigma}]$

[8] Define $\Psi_{nj}^{old} = exp(\hat{\delta}_j - \epsilon_{nj})$ and $\Psi_{nj}^{new} = exp(\hat{\delta}_j + \hat{\beta} \cdot X_{nj} - \epsilon_{nj})$ such that $\frac{\Psi_{nj}^{new}}{\Psi_{nj}^{old}} = exp(\hat{\beta} \cdot X_{nj})$ denotes a scalar on the utility of an alternative and thus whether the project becomes more ($\beta \cdot X_{nj} > 0$) or less attractive ($\beta \cdot X_{nj} < 0$) than $exp(\hat{\delta}_j)$ due to its characteristics. This is conditional on a cardinal interpretation of utility.

Table 6
Estimation results.

Coefficient	Model 1			Model 2			Model 3		
	Estimate	st. error	t-ratio	Estimate	st. error	t-ratio	Estimate	st. error	t-ratio
Constants									
δ_{J+1}	13.032	0.138	94.23	13.034	0.135	96.90	13.021	0.138	94.33
δ_1	0.357	0.134	2.66	0.359	0.131	2.74	−0.462	0.157	−2.94
δ_2	0.082	0.135	0.61	0.928	0.122	7.62	0.512	0.133	3.85
δ_3	0.926	0.126	7.35	1.101	0.128	8.60	0.797	0.137	5.82
δ_4	1.099	0.133	8.28	0.088	0.127	0.70	−0.693	0.143	−4.86
δ_5	−0.015	0.126	−0.12	−0.285	0.145	−1.96	−0.383	0.150	−2.55
δ_6	−0.288	0.147	−1.96	0.122	0.125	0.98	−0.346	0.132	−2.61
δ_7	0.121	0.129	0.94	0.415	0.122	3.40	0.237	0.129	1.83
δ_8	0.414	0.126	3.28	0.629	0.125	5.04	−0.107	0.136	−0.79
δ_9	0.628	0.130	4.82	0.011	0.123	0.09	−0.390	0.136	−2.88
δ_{10}	0.010	0.128	0.08	0.056	0.129	0.43	−0.357	0.136	−2.62
δ_{11}	0.129	0.131	0.99	0.664	0.133	4.98	−0.155	0.154	−1.01
δ_{12}	0.793	0.127	6.25	1.552	0.121	12.81	1.089	0.133	8.21
δ_{13}	1.550	0.125	12.40	0.002	0.134	0.01	−0.306	0.140	−2.19
δ_{14}	3.010	0.137	21.95	2.576	0.195	13.18	1.918	0.207	9.27
δ_{15}	2.944	0.132	22.36	2.169	0.308	7.03	2.243	0.324	6.92
δ_{16}	2.050	0.134	15.25	1.133	0.319	3.55	1.196	0.337	3.55
Attributes									
Fatalities				−0.528	0.201	−2.63	−0.481	0.213	−2.25
Injuries				−0.059	0.028	−2.10	−0.053	0.029	−1.79
Resp. char.									
Region A - Project 1							4.820	0.368	13.10
Region A - Project 6							3.822	0.400	9.56
Region A - Project 11							5.591	0.412	13.56
Region B - Project 2							3.749	0.501	7.48
Region B - Project 10							4.128	0.437	9.45
Region B - Project 13							5.104	0.557	9.17
Region C - Project 14							2.617	0.274	9.55
Region D - Project 3							1.504	0.297	5.07
Region D - Project 12							2.262	0.295	7.67
Region E - Project 4							3.743	0.325	11.53
Region E - Project 8							4.081	0.359	11.37
Region E - Project 9							1.994	0.294	6.79
Region F - Project 5							0.000		
Region F - Project 7							2.869	0.649	4.42
Other parameters									
σ	3.444	0.110	31.34	3.442	0.109	31.54	3.457	0.111	31.03
γ_0	1			1			1		
α_0	0			0			0		
$\alpha_{private}$	1			1			1		
LL	−24006.6			−24001.5			−23162.9		
n	2227			2227			2227		

and this is contrasted with the constant marginal utility of the private budget $\frac{c_{nj}}{Q} \cdot exp(\hat{\delta}_{J+1}) \cdot \Gamma[1+\hat{\sigma}]$ the expected utility relies on the median of the Ψ_j's and hence the relevance of the above mentioned 50% threshold for a project being included in the optimal portfolio.

Consistent with the observation that in Model 2 only Project 14 has a probability of over 50% of being better than the private budget, it is not surprising that the highest ranked portfolio using a flexible PVE setting only includes this policy. All other portfolios in the top 10 combine Project 14 with one or two other public projects. The previously mentioned ranking of these projects is not important here. Namely, spending a little bit more budget on cheap projects (e.g. Project 13), or on projects with a limited loss in utility per unit of budget minimises the loss in utility relative to not implementing any project at all (the null-portfolio). The null-portfolio is ranked 16th in the context of Model 2. Using simulation of the error terms (500,000 random draws) we can approximate the probability of outperforming the null-portfolio for each portfolio in the top 10 (see bottom row of Table 7).

5.3.2. The optimal portfolio in a fixed PVE

A large share of the data used for model estimation corresponds to the fixed budget PVE setting. We now present the portfolio evaluation based on such a policy context using the 100 million euros as the indicated budget available for investment. Unlike the flexible PVE setting, the analytical probability for a project being included in the optimal portfolio cannot be derived since the marginal utility of the remaining public budget is decreasing with the remaining public budget. The relative ranking of the public projects in terms of their priority of including them in the optimal portfolio as presented in the final column of Table 7 is, however, not affected. Similarly, the expected utility associated with each feasible portfolio can be evaluated, whilst accounting for the expected utility derived from any remaining public budget. Due to the restrictive nature of the public policy budget, the feasible

Table 7
Flexible PVE: Top 10 portfolios using model 2.

Projects:	Top 10 portfolios										ℙ in opt. Port.	Project rank
	1	2	3	4	5	6	7	8	9	10		
1	0	0	0	0	0	0	0	0	0	0	0.31	15
2	0	0	0	0	0	0	0	0	0	0	0.36	13
3	0	0	0	0	0	0	0	1	0	0	0.47	5
4	0	0	0	0	0	0	0	0	0	0	0.39	12
5	0	0	0	0	0	0	0	0	0	0	0.27	16
6	0	0	0	1	0	0	1	0	0	0	0.45	8
7	0	0	0	0	0	0	0	0	0	0	0.39	11
8	0	0	0	0	0	0	0	0	0	0	0.45	7
9	0	0	0	0	0	0	0	0	0	1	0.43	9
10	0	0	1	0	1	0	0	0	0	0	0.46	6
11	0	0	0	0	0	0	0	0	0	0	0.35	14
12	0	0	0	0	0	0	0	0	0	0	0.41	10
13	0	1	0	0	1	0	1	0	1	0	0.48	4
14	1	1	1	1	1	1	1	1	1	1	0.51	1
15	0	0	0	0	0	0	0	0	0	0	0.49	3
16	0	0	0	0	0	1	0	0	1	0	0.49	2
Portfolio size	1	2	2	2	3	2	3	2	3	2		
Cost	40	43	44.5	45	47.5	60	48	50	63	46		
$\mathbb{P}(SU_p > SU_{null})$	0.51	0.58	0.58	0.58	0.62	0.62	0.62	0.60	0.65	0.57		

set of policy portfolios is much smaller than in the flexible budget PVE setting. Table 8 presents the top 10 portfolios based on their expected utility using Model 2. Since the public budget is less attractive than the private budget, and with respondents not having the option to implement a tax rebate, it becomes more attractive to invest in more public projects. Across the top 10, we see the optimal project portfolio comprising 3 to 4 projects, which is consistent with the observed portfolio sizes in Table 5.

As the highest ranked public project, safety project 14 is always included in the optimal portfolio costing 40 mln €. With the remaining 60 mln every other project can still be afforded. A natural candidate would be to add the second best safety project 16 costing 20 mln €. This, however, precludes spending the remaining public budget on the third ranked project 15 (since it costs 50 mln €). It turns out that project 16 is therefore not included in the optimal portfolio and it is better to always include project 15 and spend the remaining budget on smaller projects 13 (ranked 4th), and 10 (ranked 6th) or 6 (ranked 8th) to make best use of the available budget.[9] This illustrates that the restrictive nature of the public budget forces policy makers to make trade-offs about which projects (not) to implement and for the researcher to evaluate a large number of corner solutions. The bottom row of Table 8 indicates, based on simulation (500,000 random draws), that there is a large probability of these individual portfolios being better than the null-portfolio.

5.3.3. *Sensitivity analyses: project costs and impacts*

Sections 5.3.1 and 5.3.2 highlight a remarkable difference regarding the recommended best course of action due to the attractiveness of private budget. For a few public projects the probability of being in the optimal portfolio is close to 50% and hence reductions in the costs, or changes in the features of a project may significantly affect the policy recommendation. In this subsection a sensitivity analysis is presented reducing the costs of projects 15 and 16, increasing their attractiveness for implementation. Similar sensitivity tests can be conducted varying the available budget, or the project characteristics without changing the required approach.

Tables 9 and 10 highlight the impact of reducing the costs of safety projects 15 and 16 to the lower end of the range used in the experimental design, respectively from 50 mln to 40 mln, and from 20 to 15 mln euros. Safety policy 16 is now the highest ranked policy and the optimal policy portfolio in the flexible PVE setting recommend including the top 3 policy projects as each has a probability of being included in the optimum portfolio of over 50%. The next best policy is to also include 4th ranked policy (safety project 13) before it is recommended to drop third ranked policy 15.

In the fixed PVE setting the portfolio including projects 14, 15 and 16 comes out as the second best. It recommends to additionally include safety project 13 to the optimal portfolio to make optimal use of the available budget. Across the top 10 it is still recommended to always include projects 14 and 15 in the fixed PVE setting. Notably, the highest ranked policy may be recommended to be dropped to maintain a high expected utility in the lower ranking portfolios in the top 10.

Overall, the presented policy evaluation highlights that (1) the relative ranking of the public projects allows prioritising the different projects when the budget constraint is not restrictive; (2) the probability of being included in the optimal policy portfolio indicates whether it is attractive to include a project in the optimal portfolio; and (3) that it is recommendable to evaluate the range of feasible project portfolios under a restrictive public budget to determine the optimal policy portfolio which may not necessarily include the highest ranked policies due to variations in underlying project costs.

[9] With an additional budget of 10 mln €of public budget the optimal policy includes safety projects 14, 15 and 16 and would have completely exhausted the budget.

Table 8
Fixed PVE: Top 10 portfolios using Model 2 and a budget of 100 mln euros.

Projects:	Top 10 portfolios									
	1	2	3	4	5	6	7	8	9	10
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	1	0	0	0	0	1	0	1	0
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	1	0	0	0	0
9	0	0	0	0	0	0	0	1	0	1
10	1	0	0	1	0	0	0	0	1	0
11	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0
13	1	1	1	0	0	0	0	1	0	0
14	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1
16	0	0	0	0	0	0	0	0	0	0
Portfolio size	4	4	3	3	3	3	3	4	4	3
Cost	97.5	98	93	94.5	100	98	95	99	99.5	96
$\mathbb{P}(SU_p > SU_{null})$	0.86	0.86	0.85	0.85	0.83	0.84	0.85	0.85	0.85	0.84

Table 9
Flexible PVE: Top 10 portfolios Model 2 reduced cost projects 15 and 16.

Projects:	Top 10 portfolios										$\mathbb{P}$ in opt. Port.	Project rank
	1	2	3	4	5	6	7	8	9	10		
1	0	0	0	0	0	0	0	0	0	0	0.31	15
2	0	0	0	0	0	0	0	0	0	0	0.36	13
3	0	0	0	0	0	0	0	0	0	0	0.47	5
4	0	0	0	0	0	0	0	0	0	0	0.39	12
5	0	0	0	0	0	0	0	0	0	0	0.27	16
6	0	0	0	0	0	0	0	1	0	0	0.45	8
7	0	0	0	0	0	0	0	0	0	0	0.39	11
8	0	0	0	0	0	0	0	0	0	0	0.45	7
9	0	0	0	0	0	0	0	0	0	0	0.43	9
10	0	0	0	0	0	1	0	0	1	0	0.46	6
11	0	0	0	0	0	0	0	0	0	0	0.35	14
12	0	0	0	0	0	0	0	0	0	0	0.41	10
13	0	1	0	1	0	0	1	0	1	0	0.48	4
14	1	1	1	1	1	1	1	1	1	1	0.51	2
15	1	1	0	0	1	1	1	1	1	0	0.50	3
16	1	1	1	1	0	1	0	1	1	0	0.51	1
Portfolio size	3	4	2	3	2	4	3	4	5	1		
Cost	95	98	55	58	80	99.5	83	100	102.5	40		
$\mathbb{P}(SU_p > SU_{null})$	0.68	0.69	0.62	0.65	0.63	0.69	0.65	0.69	0.71	0.51		

5.3.4. Policy recommendations with observed preference heterogeneity

In the preceding discussions no income effects were present and Models 1 and 2 did not account for other sources of observed preference heterogeneity. Accordingly, the optimal policy portfolio applies to a representative consumer and is relevant for the whole population. Model 3 addresses this issue and highlights respondents prefer to implement projects in their own city region (A–F) as per Fig. 6. This set of explanatory variables results in a large improvement in model fit. Table 11 makes the preference for local projects more explicit by finding probabilities much larger than 0.50 of being included in the optimal policy portfolio under flexible PVE for all but one project in the respective city regions. Project 5 in city region F was not associated with a significant interaction term on the constant, whereas all other interaction terms show strong positive relationships.

The TAA is governed by the '*Regioraad*' a commission comprising 49 members representing the regions where membership is based on relative population size.[10] We take the relative representation in the Regioraad as a weight to arrive at a weighted expected utility representative for the whole TTA population in the social welfare approach. Most representatives of the Regioraad were easy to allocate to Regions A–F, but we had to split the 12 representatives for Amsterdam across regions C (7), D (4) and F(1) respectively based on population statistics for 2018.[11]

10 https://www.vervoerregio.nl/pagina/20160103-regioraad

11 https://onderzoek.amsterdam.nl/interactief/dashboard-kerncijfers

Table 10
Fixed PVE: Top 10 portfolios Model 2, 100 mln budget and reduced cost for 15 and 16.

Projects:	Top 10 portfolios									
	1	2	3	4	5	6	7	8	9	10
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	1	1	1	1	1	1
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	0	0	0	1	0	1	0	0	0	1
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	1	0
9	0	0	0	0	0	0	0	0	0	0
10	0	0	1	0	1	0	0	1	0	0
11	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0
13	1	0	0	0	1	1	1	0	0	0
14	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	0	0	0	0	0	0
Portfolio size	4	3	4	4	5	5	4	4	4	4
Cost	98	95	99.5	100	97.5	98	93	94.5	98	95
$\mathbb{P}(SU_p > SU_{null})$	0.88	0.87	0.87	0.87	0.89	0.88	0.89	0.88	0.87	0.88

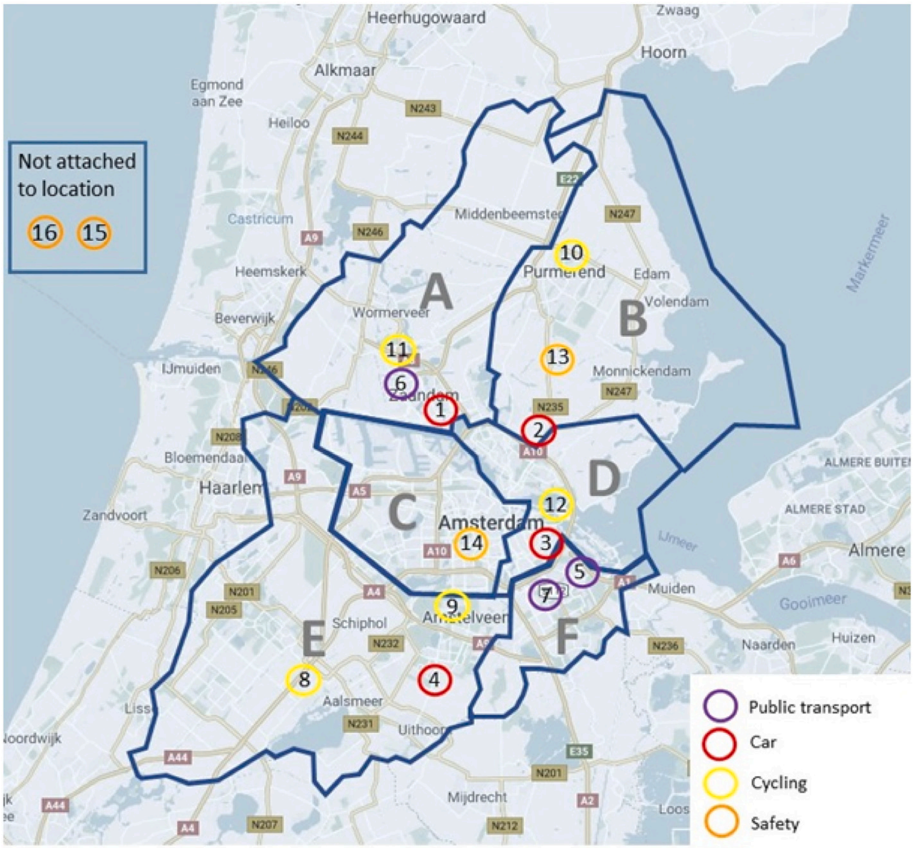

Fig. 6. City regions and location of proposed projects.

The difference in composition between the sampled population and the TAA population together with the strong interaction effects provides slightly different recommendations than those derived for the single representative consumer in Model 2 (see Table 12). The optimal portfolio size increases to eight and in addition to safety project 14, projects 2, 4, 6, 8, 10, 11 and 13

Table 11
Flexible PVE — Model 3: Probability of including project in optimal portfolio by Region.

Project	Region A	Region B	Region C	Region D	Region E	Region F
1	0.59[a]	0.26	0.26	0.26	0.26	0.26
2	0.33	0.62[a]	0.33	0.33	0.33	0.33
3	0.45	0.45	0.45	0.56[a]	0.45	0.45
4	0.34	0.34	0.34	0.34	0.60[a]	0.34
5	0.27	0.27	0.27	0.27	0.27	0.27
6	0.68[a]	0.42	0.42	0.42	0.42	0.42
7	0.38	0.38	0.38	0.38	0.38	0.59[a]
8	0.40	0.40	0.40	0.40	0.69[a]	0.40
9	0.40	0.40	0.40	0.40	0.54[a]	0.40
10	0.43	0.77[a]	0.43	0.43	0.43	0.43
11	0.68[a]	0.30	0.30	0.30	0.30	0.30
12	0.38	0.38	0.38	0.54[a]	0.38	0.38
13	0.46	0.72[a]	0.46	0.46	0.46	0.46
14	0.46	0.46	0.64[a]	0.46	0.46	0.46
15	0.49	0.49	0.49	0.49	0.49	0.49
16	0.49	0.49	0.49	0.49	0.49	0.49
Representatives in Regioraad	9	9	7	4	16	4
Weight in aggregation	0.184	0.184	0.143	0.082	0.327	0.082

[a] Include in the optimal policy portfolio.

Table 12
Flexible PVE — Model 3: Top 10 portfolios based on weighted expected utility.

Project	Top 10 portfolios									
	1	2	3	4	5	6	7	8	9	10
1	0	0	0	0	0	0	0	0	0	0
2	1	1	1	1	1	1	1	0	1	0
3	0	0	0	1	0	0	1	0	0	0
4	1	1	1	1	0	1	1	1	0	1
5	0	0	0	0	0	0	0	0	0	0
6	1	1	1	1	1	1	1	1	1	1
7	0	0	0	0	0	0	0	0	0	0
8	1	1	1	1	1	1	1	1	1	1
9	0	1	0	0	0	1	1	0	1	1
10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0
13	1	1	1	1	1	1	1	1	1	1
14	1	1	1	1	1	1	1	1	1	1
15	0	0	0	0	0	0	0	0	0	0
16	0	0	1	0	0	1	0	0	0	0
Portfolio size	8	9	9	9	7	10	10	7	8	8
Cost	150.5	156.5	170.5	160.5	140.5	176.5	166.5	110.5	146.5	116.5

are now also included in the optimal portfolio increasing recommended spending levels to 150.5 mln euros under a flexible PVE assumption.

With a constraint budget at 100 mln euros, choices will have to be made regarding implementation. Table 13 highlights that in the top 10 portfolios under a fixed PVE assumption bike projects 8, 10 and 11 are always included. Public transport project 6 and safety project 13 are included in 6 out of 10 of the portfolios, followed by car project 4 and safety project 14 represented by 4 out of 10 portfolios. The optimal portfolio includes the three bike projects 8,10 and 11, and the safety projects 13 and 14. As such accounting for observed preference heterogeneity and the use of representative weights has shifted the priority away from safety projects 15 and 16.

6. Conclusions and discussion

Participatory Value Evaluation (PVE) surveys directly involve citizens in public policy decision making (Mouter et al., 2021c,b). Similar to stated choice surveys, citizens receive information on the social impacts of public sector projects and can choose the best policy portfolio according to their preferences. Since the selection of the preferred policy portfolio is limited by the available public budget in PVE surveys, which can be adjusted at the expense of private consumption, respondents need to make trade-offs between the implementation of different projects, their impacts, and personal consumption. PVE surveys provide citizens with an opportunity to display their broader value judgements when it comes to public policy decisions. The online format of PVE surveys facilitates the participation of larger groups of citizens in a short amount of time as opposed to the use of town hall meetings where often only a

Table 13
Fixed PVE — Model 3: Top 10 portfolios based on weighted expected utility.

Project	Top 10 portfolios									
	1	2	3	4	5	6	7	8	9	10
1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	1	1	0	0
3	0	0	0	0	0	0	0	0	1	1
4	0	0	0	1	0	1	0	0	1	1
5	0	0	0	0	0	0	0	0	0	0
6	0	1	0	1	0	1	0	1	1	1
7	0	0	0	0	0	0	0	0	0	1
8	1	1	1	1	1	1	1	1	1	1
9	0	0	1	1	0	0	0	0	1	0
10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	0	0	0
13	1	0	0	1	0	1	1	0	1	1
14	1	1	1	0	1	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0
16	0	0	0	1	0	1	0	0	0	0
Portfolio size	5	5	5	8	4	7	5	5	8	8
Cost	95.5	97.5	98.5	96.5	92.5	90.5	95.5	97.5	86.5	95.5

limited set of public opinions is expressed. In the Netherlands PVE has thus far been used to inform policy making in the context of transportation (Mouter et al., 2021b; Bahamonde-Birke et al., 2024), climate change (Mouter et al., 2021d), healthcare (Boxebeld et al., 2024) and relaxing Covid-19 restrictions (Mouter et al., 2021a).

The present paper develops a micro-econometric framework allowing for the analysis of the PVE data format, which is characterised by a mixture of discrete and discrete-continuous choices. The applicability of the framework thereby extends beyond the PVE domain (e.g. Caputo and Lusk, 2022). Building on the recent literature on Kuhn–Tucker models, particularly the MDCEV model, a range of methodological and econometric contributions are provided facilitating model estimation and policy evaluation. We derive of a set of closed form choice probabilities explaining the choice for the optimal portfolio with public projects and corresponding implications for private consumption and the public budget. In the case of a flexible public budget, PVE surveys explicitly link the public and private budget constraint through the tax system. Not only does this feature allow for adjusting the size of the public budget, it also allows rooting PVE in the traditional Kaldor–Hicks welfare economic framework (Mouter et al., 2021c). Previous MDCEV models have only worked with independent constraints (Castro et al., 2012; Mondal and Bhat, 2021). Moreover, the presence of multiple continuous goods in the utility function, i.e. private consumption and remaining public budget, allows theoretical identification of satiation effects and accordingly non-linear income effects (Batley and Dekker, 2019).

Individual preferences for public sector projects are estimated empirically. Like in generic choice models, heterogeneity in preferences can be accommodated using observable characteristics of the respondents and through random parameters. Any remaining heterogeneity is captured by the distribution of the error term ϵ_{nj} for which the variance (scale) parameter can be empirically estimated. The estimated utility functions can subsequently be used to derive the individual ranking of preferences for the available public policy projects based on their average utility per unit of public budget. In the case of an unrestricted budget, i.e. a flexible PVE setting, the individual optimal policy portfolio can be constructed by sequentially adding projects based on their ranking until the opportunity costs of private budget become too high and the expected utility no longer increases from adding portfolios. In the case of a fixed public budget the presence of corner solutions requires evaluation of a larger set of feasible portfolios to determine the best use of the available budget. It is unlikely that all projects will be included in the optimal portfolio. This is due to (i) respondents systematically excluding certain projects from their portfolio choice indicating the respective project is undesirable, or (ii) a lack of budget forcing trade-offs between which projects to implement. Sensitivity tests evaluating the impact of the available government budget, project costs and characteristics on the optimal portfolio can easily be conducted to separate out the above effects. Note that the estimated variance does not influence the ranking of the feasible policy portfolios.

Using a social welfare function approach aggregating the utility implications of a given public policy portfolio, possibly using distributional weights (Nyborg, 2014; Nurmi and Ahtiainen, 2018), allows deriving a ranking of the feasible policy portfolios and identifying the optimal portfolio from a societal perspective. Corresponding budget and tax implications can also be easily expressed. A remaining challenge is to examine whether the ranking of portfolios is sensitive to any concave monotonic transformation of the direct utility function. The latter requires satisfaction of second order stochastic dominance, which falls outside the scope of the current paper. The reported probabilities in the policy analysis are, however, invariant to concave monotonic transformations of the direct utility function.

The proposed micro-economic framework is applied to a range of potential urban mobility investments in Amsterdam, The Netherlands. Our estimation results come up with a number of interesting outcomes but also challenges. One of the key outcomes from the empirical example is that respondents show a strong preference for policies aimed at improving cycling infrastructure and traffic safety. Moreover, projects taking place in respondents own city-region are more likely to be selected due to a larger probability of benefiting from them. We observe a high probability that the optimal portfolio will increase social welfare relative to the null-portfolio. The presented top 10 portfolio rankings clearly highlight which policies should (not) be included and between which ones policy makers should make trade-offs between including them when presented with a tight budget. In the specific application, a constant marginal utility is estimated for the private budget (i.e. constant opportunity costs). This is comparable to the Linear Outside Good MDCEV model specification (Bhat, 2018; Bhat et al., 2020; Palma and Hess, 2022) and allows calculating the probability of individual projects being included in the optimal policy portfolio under an unrestricted budget.

Two challenges are identified which warrant further development of the PVE survey format. First, public money is relatively cheap under most tax systems. One additional euro paid in tax by everyone in the population will increase the public budget by a significantly larger factor (one million euros in our empirical example). With only marginal changes in private consumption enabling the implementation of additional projects it is not surprising that we observe a willingness to increase the public budget. It is, however, reassuring that the optimal public budget will only finance eight out of sixteen projects and hence the model does not indicate that all projects will be selected. Future research could examine how increased or reduced trade-offs between the public and private budget, by making public budget relatively more expensive, will affect the highlighted challenge. Closely related, we assumed that any remaining budget was retained by the selected department for future years, in other applications of PVE the remaining public budget may be reallocated to other departments changing the opportunity cost of public money. Second, estimating the marginal impact of the different policy attributes proved to be challenging. In terms of fit and policy implications the attributes only have a limited impact. Most attributes turned out to be insignificant. The most likely cause for this is the heterogeneous set of alternatives that were included in the policy portfolio assigning a high importance to the policy specific constants. Moreover, the set of included policy attributes varies across policies including their levels. For example, safety impacts, i.e. traffic deaths and injuries, were only affecting seven out of the sixteen available projects. Similarly, the noise impacts and removal of trees only affected four and three projects, respectively. This makes it much harder to identify their impacts on the overall decision. This is an issue to be studied in future research by making experimental adjustments that can lead to more knowledge about the marginal utilities of policy attributes.

Although possible (see Lloyd-Smith, 2018), there is no need to derive forecasts, willingness to pay measures for policy attributes, or more general measures of consumer surplus in order to conduct policy evaluation with PVE. Namely, it is envisaged that PVE surveys are conducted in the relevant policy application context. Policymakers want to know which projects to prioritise and (not) to implement using a scarce budget. The policy evaluation based on the estimated PVE models provides this information without needing forecasts and welfare estimates. Namely, the flexible PVE setting contrasts each policy individually against the private budget and determines whether it should be considered or not for a given socio-economic group. The estimation results also provide the prioritisation of the projects (i.e. their relative ranking against each other and the private and public budget). Additionally, the policy evaluation provides a portfolio ranking – both in the flexible and fixed PVE setting – which includes the null-portfolio. Any portfolio ranked above the null-portfolio is therefore considered to result in a social welfare gain against the ‘do-nothing’ scenario. The only reason monetisation of the social welfare gain may be required is when ‘value for money’ metrics are deemed essential in the appraisal framework. Similarly, marginal WTP estimates may become relevant when the results of PVE surveys are intended to be used for benefit transfer purposes. For example, when the implicitly revealed value of travel time, or value of statistical life is intended to be used either in a wider appraisal context such as national guidance. In the same vein, forecasting is not required since the estimated PVE model is not intended to predict voting behaviour, or real life behaviour; its only intention is to provide advice to policymakers regarding the public projects of interest.

The proposed micro-econometric framework can be extended by examining substitution and complementarity effects between public policy projects. Bhat et al. (2015), Palma and Hess (2022), Pellegrini et al. (2021) have already extended the more general discrete continuous modelling framework to account for such effects. The discrete nature of the public projects would simplify the specification of the utility function relative to the referred papers and the interaction effects would be of similar form to Caputo and Lusk (2022). The latter paper, however, adopts a multivariate logistic choice model which puts the error term at the level of the individual portfolio and not at the project level as done in the PVE framework. This ignores a significant degree of correlation across the same alternatives being included in multiple portfolios not captured by the error terms. The challenge with adopting such interaction effects in the PVE model is the change in the first order conditions which ultimately affects derivation of the choice probabilities. To avoid complications Palma and Hess (2022) have, for example, adjusted the error structure of the model and removed the error term of the outside good. Careful considerations will need to be made to best accommodate interaction effects in the PVE setting.

The PVE choice models are not overly efficient, because the closed form choice probabilities evaluate all the possible combinations of the sets Z and K of non-chosen alternatives in Case 1 for which the size varies across observations. The current model running time on a standard laptop of Model 1 is 11.5 min. Running times are significantly lower in simulation settings with fewer projects. We see significant opportunity to improve on estimation time by switching to Bayesian estimation methods based on data augmentation for the price-normalised marginal utilities, which will enable us to avoid enumeration of all possible combinations and makes the method more scalable for larger choice sets. This is a particularly interesting area for future research, especially since it would facilitate estimating models including interaction terms, correlated error terms, and random parameters at limited computational costs. Finally, the Bayesian approach to data augmentation would easily extend to the standard MDCEV (and related models) setting of continuous consumption.

CRediT authorship contribution statement

Thijs Dekker: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Paul Koster:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Niek Mouter:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Derivation of choice probabilities — Case 1

The choice probability is given by:

$$\mathbb{P}_{n1}(y_n^*) = \int_{\epsilon_{n0}=-\infty}^{\infty} \int_{\epsilon_n^*=-\infty}^{\infty} \prod_{z=1}^{Z_n} \left(1 - F\left[V_{nz} + LS_n + \epsilon_n^*\right]\right) \cdot \prod_{k}^{K_n} \left(1 - F\left[V_{nk} - V_{n0} + \epsilon_{n0}\right]\right) \cdot I\left[V_{n0} - \epsilon_{n0} \le -LS_n - \epsilon_n^*\right] \cdot h\left(\epsilon_n^*\right) \cdot g\left(\epsilon_{n0}\right) d\epsilon_n^* d\epsilon_{n0} \tag{28}$$

The indicator function can be captured by the bounds of the second integral:

$$\mathbb{P}_{n1}(y_n^*) = \int_{\epsilon_{n0}=-\infty}^{\infty} \prod_{k}^{K_n} \left(1 - F\left[V_{nk} - V_{n0} + \epsilon_{n0}\right]\right) \int_{\epsilon_n^*=-\infty}^{-V_{n0}-LS_n+\epsilon_{n0}} \prod_{z=1}^{Z_n} \left(1 - F\left[V_{nz} + LS_n + \epsilon_n^*\right]\right) \cdot h\left(\epsilon_n^*\right) \cdot g\left(\epsilon_{n0}\right) d\epsilon_n^* d\epsilon_{n0} \tag{29}$$

Substituting the cumulative density $F(\cdot)$ and the probability density functions $g(\cdot)$ and $h(\cdot)$ associated with the EV Type 1 distribution gives:

$$\mathbb{P}_{n1}(y_n^*) = \frac{1}{\sigma^2} \int_{\epsilon_{n0}=-\infty}^{\infty} \prod_{k}^{K_n} \left[1 - e^{-e^{-\frac{V_{nk}-V_{n0}+\epsilon_{n0}}{\sigma}}}\right] \int_{\epsilon_n^*=-\infty}^{-V_{n0}-LS_n+\epsilon_{n0}} \prod_{z=1}^{Z_n} \left[1 - e^{-e^{-\frac{V_{nz}+LS_n+\epsilon_n^*}{\sigma}}}\right] \cdot e^{-\frac{\epsilon_n^*}{\sigma}} \cdot e^{-e^{-\frac{\epsilon_n^*}{\sigma}}} \cdot e^{-\frac{\epsilon_{n0}}{\sigma}} \cdot e^{-e^{-\frac{\epsilon_{n0}}{\sigma}}} d\epsilon_n^* d\epsilon_{n0} \tag{30}$$

Use the substitutions $t = e^{-\frac{\epsilon_{n0}}{\sigma}} \Leftrightarrow d\epsilon_{n0} = -\frac{\sigma}{t} \cdot dt$ and $s = e^{-\frac{\epsilon_n^*}{\sigma}} \Leftrightarrow d\epsilon_n^* = -\frac{\sigma}{s} \cdot ds$ to obtain:

$$\mathbb{P}_{n1}(y_n^*) = \int_{t=0}^{\infty} \prod_{k}^{K_n} \left[1 - e^{-t\cdot e^{-\frac{V_{nk}-V_{n0}}{\sigma}}}\right] \int_{s=t\cdot e^{\left(\frac{V_{n0}+LS_n}{\sigma}\right)}}^{\infty} \prod_{z=1}^{Z_n} \left[1 - e^{-s\cdot e^{-\frac{V_{nz}+LS_n}{\sigma}}}\right] \cdot e^{-s} \cdot ds \cdot e^{-t} \cdot dt \tag{31}$$

Next, use the substitution $v = e^{-t} \Leftrightarrow dt = -v^{-1} \cdot dv$ and $\omega = e^{-s} \Leftrightarrow ds = -\omega^{-1} \cdot d\omega$:

$$\mathbb{P}_{n1}(y_n^*) = \int_{v=0}^{1} \prod_{k}^{K_n} \left[1 - v^{e^{-\frac{V_{nk}-V_{n0}}{\sigma}}}\right] \int_{\omega=0}^{v^{\sum_m^{M_n} e^{-\frac{V_{nm}-V_{n0}}{\sigma}}}} \prod_{z=1}^{Z_n} \left[1 - \omega^{e^{-\frac{V_{nz}+LS_n}{\sigma}}}\right] \cdot d\omega \cdot dv \tag{32}$$

We now introduce some matrix notation to make the next steps more accessible. Let $\mathbf{1}_{M_n}$ describe a M_n by 1 vector of ones and A_n a vector of similar size containing $e^{-\frac{V_{nm}-V_{n0}}{\sigma}}$ for each $m \in M_n$ such that $v^{\sum_m^{M_n} e^{-\frac{V_{nm}-V_{n0}}{\sigma}}} = v^{\mathbf{1}'_{M_n} \cdot A_n}$. Define $\mathbf{W_n}$ as a matrix of size 2^{Z_n} by Z_n describing all possible combinations of non-chosen but unaffordable projects included in Z_n, including the empty set. That is, $\mathbf{W_n}$ represents a matrix containing binary indicators describing a two-level full factorial design with Z_n factors. Let W_{nc} describe a given row c of $\mathbf{W_n}$ and $|W_{nc}|$ the rowsum of W_{nc}, i.e. $|W_{nc}| = \sum_{z\in Z_n} W_{ncz}$. Let B_n be a vector of size Z_n by 1 containing $e^{-\frac{V_{nz}+LS_n}{\sigma}}$ for each $z \in Z_n$. We can then define:

$$\begin{aligned}\int_{\omega=0}^{v^{\sum_m^{M_n} e^{-\frac{V_{nm}-V_{n0}}{\sigma}}}} \prod_{z=1}^{Z_n} \left[1 - \omega^{e^{-\frac{V_{nz}+LS_n}{\sigma}}}\right] \cdot d\omega &= \int_{\omega=0}^{v^{\mathbf{1}'_{M_n} \cdot A_n}} \sum_{c}^{2^{Z_n}} (-1)^{|W_{nc}|} \cdot \omega^{W_{nc}\cdot B_n} d\omega \\ &= \left[\sum_{c}^{2^{Z_n}} (-1)^{|W_{nc}|} \cdot \frac{\omega^{1+W_{nc}\cdot B_n}}{1 + W_{nc} \cdot B_n}\right]_{\omega=0}^{v^{\mathbf{1}'_{M_n} \cdot A_n}} \\ &= \sum_{c}^{2^{Z_n}} (-1)^{|W_{nc}|} \cdot \frac{v^{\left(\mathbf{1}'_{M_n} \cdot A_n\right)\cdot(1+W_{nc}\cdot B_n)}}{1 + W_{nc} \cdot B_n}\end{aligned} \tag{33}$$

In similar vein, define $\mathbf{Q_n}$ as a matrix of size 2^{K_n} by K_n describing all possible combinations of non-chosen but affordable projects included in K_n, including the empty set. That is, $\mathbf{Q_n}$ represents a matrix containing binary indicators describing a two-level full factorial design with K_n factors. Let Q_{nq} describe a given row q of Q_n and $|Q_{nq}|$ the rowsum of Q_{nq}, i.e. $|Q_{nq}| = \sum_{k\in K_n} Q_{nqk}$. Let C_n be a vector of size K_n by 1 containing $e^{-\frac{V_{nk}-V_{n0}}{\sigma}}$ for each $k \in K_n$. We can then define:

$$\prod_{k}^{K_n}\left[1 - \nu^{e^{-\frac{V_{nk}-V_{n0}}{\sigma}}}\right] = \sum_{q}^{2^{K_n}}(-1)^{|Q_{nq}|}\cdot \nu^{Q_{nq}\cdot C_n} \tag{34}$$

Combining these results in the probability expression provides the following closed form choice probability:

$$\begin{aligned}\mathbb{P}_{n1}(y_n^*) &= \int_{\nu=0}^{1}\sum_{q}^{2^{K_n}}\sum_{c}^{2^{Z_n}}(-1)^{|Q_{nq}|}\cdot(-1)^{|W_{nc}|}\cdot \nu^{Q_{nq}\cdot C_n}\cdot \frac{\nu^{\left(\mathbf{1}'_{M_n}\cdot A_n\right)\cdot(1+W_{nc}\cdot B_n)}}{1+W_{nc}\cdot B_n}d\nu \\ &= \sum_{q}^{2^{K_n}}\sum_{c}^{2^{Z_n}}(-1)^{|Q_{nq}|}\cdot(-1)^{|W_{nc}|}\cdot\frac{1}{1+Q_{nq}\cdot C_n+\left(\mathbf{1}'_{M_n}\cdot A_n\right)\cdot\left(1+W_{nc}\cdot B_n\right)}\cdot\frac{1}{1+W_{nc}\cdot B_n}\end{aligned} \tag{35}$$

We can distinguish four specific cases:

1. The set Z_n is empty (all non-chosen alternatives are affordable)
   $\mathbb{P}_{n1}(y_n^*) = \sum_q^{2^{K_n}}(-1)^{|Q_{nq}|}\cdot\frac{1}{1+Q_{nq}\cdot C_n+\mathbf{1}'_{M_n}\cdot A_n}$.
2. The set K_n (all non-chosen alternatives are not affordable) is empty
   $\mathbb{P}_{n1}(y_n^*) = \sum_c^{2^{Z_n+1}}(-1)^{|W_{nc}|}\cdot\frac{1}{1+W_{nc}\cdot B_n}$
3. When all projects are chosen then:
   $\mathbb{P}_{n1}(y_n^*) = \frac{e^{-\frac{LS_n+V_{n0}}{\sigma}}}{1+e^{-\frac{LS_n+V_{n0}}{\sigma}}}$
4. When no projects are chosen then:
   $\mathbb{P}_{n1}(y_n^*) = \sum_q^{2^J}(-1)^{|Q_{nq}|}\cdot\frac{1}{1+Q_{nq}\cdot C_n}$.

Appendix B. Derivation of choice probabilities — Case 2

The choice probability for case 2 is given by:

$$\begin{aligned}\mathbb{P}_{n2}(y_n^*) = \left||G|\right| \int_{\epsilon_{n,J+1}=-\infty}^{\infty}\prod_{k=1}^{K_n}\left(1-F\left[V_{nk}-V_{n,J+1}+\epsilon_{n,J+1}\right]\right)\prod_{m=1}^{M_n}F\left[V_{nm}-V_{n,J+1}+\epsilon_{n,J+1}\right] \\ \cdot f\left[V_{n0}-V_{n,J+1}+\epsilon_{n,J+1}\right]\cdot f\left[\epsilon_{n,J+1}\right]d\epsilon_{n,J+1}\end{aligned} \tag{36}$$

where $\left||G|\right| = \left|\frac{\partial\epsilon_{n0}}{\partial y_{n0}^*}\right| = \left|\frac{\partial(V_{n0}-V_{n,J+1}+\epsilon_{n,J+1})}{\partial y_{n0}} = (\alpha_0-1)\frac{1}{y_{n0}+\gamma_0} + (\alpha_{J+1}-1)\frac{1}{y_{n,J+1}}\frac{1}{Q}\right|$ is the absolute value of the Jacobian determinant. The latter is required because of the change of variable for ϵ_{n0}. Namely, in equilibrium it holds that $V_{n0}-\epsilon_{n0} = V_{n,J+1}-\epsilon_{n,J+1}$, such that for every realisation of $\epsilon_{n,J+1}$ we get:

$$\epsilon_{n0} = (\alpha_0-1)\cdot\ln\left(\frac{y_{n0}^*}{\gamma_0}\right)+\ln\left(\Psi_{n0}\right)-\left(\alpha_{J+1}-1\right)\cdot\ln\left(y_{n,J+1}^*\right)-\ln\left(\Psi_{n,J+1}\right)+\ln(Q)+\epsilon_{n,J+1} \tag{37}$$

$$\frac{\partial\epsilon_{n0}}{\partial y_{n0}^*} = \frac{(\alpha_0-1)}{y_{n0}^*+\gamma_0}-\frac{\left(\alpha_{J+1}-1\right)}{y_{n,J+1}^*}\cdot\frac{\partial y_{n,J+1}^*}{\partial y_{n0}^*} \tag{38}$$

In equilibrium we also know from the private and public budget constraint that:

$$y_{n,J+1}^* = Y_n\cdot(1-t_n)-\left(\frac{y_{n0}^*+\sum_{j=1}^{J}y_{nj}^*\cdot c_{nj}-B}{Q}\right) \tag{39}$$

$$\frac{\partial y_{n,J+1}^*}{\partial y_{n0}^*} = -\frac{1}{Q} \tag{40}$$

$$\frac{\partial\epsilon_{n0}}{\partial y_{n0}^*} = \frac{(\alpha_0-1)}{y_{n0}^*+\gamma_0}+\frac{\left(\alpha_{J+1}-1\right)}{y_{n,J+1}^*}\cdot\frac{1}{Q} \tag{41}$$

The absolute value of the latter term is the Jacobian. Substituting the density functions gives:

$$\begin{aligned}\mathbb{P}_{n2}(y_n^*) = \frac{1}{\sigma^2}\left||G|\right|\int_{\epsilon_{n,J+1}=-\infty}^{\infty}\prod_{k=1}^{K_n}\left(1-e^{-e^{-\frac{V_{nk}-V_{n,J+1}+\epsilon_{n,J+1}}{\sigma}}}\right)\prod_{m=1}^{M_n}e^{-e^{\frac{V_{nm}-V_{n,J+1}+\epsilon_{n,J+1}}{\sigma}}} \\ \cdot e^{-\frac{V_{n0}-V_{n,J+1}+\epsilon_{n,J+1}}{\sigma}}e^{-e^{-\frac{V_{n0}-V_{n,J+1}+\epsilon_{n,J+1}}{\sigma}}}\cdot e^{-\frac{\epsilon_{n,J+1}}{\sigma}}e^{-e^{-\frac{\epsilon_{n,J+1}}{\sigma}}}d\epsilon_{n,J+1}\end{aligned} \tag{42}$$

Using the substitution of variable $t = e^{-\frac{\epsilon_{n,J+1}}{\sigma}} \Leftrightarrow d\epsilon_{n,J+1} = -\sigma \frac{1}{t} dt$ we obtain:

$$\begin{aligned}\mathbb{P}_{n2}(y_n^*) = \frac{1}{\sigma}\Big||G|\Big| e^{-\frac{V_{n0}-V_{n,J+1}}{\sigma}} \int_{t=0}^{\infty} \prod_{k=1}^{K} \left(1 - e^{-t\cdot e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}}\right) \prod_{m=1}^{M_n} e^{-t\cdot e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}} \\ \cdot e^{-t\cdot e^{-\frac{V_{n0}-V_{n,J+1}}{\sigma}}} \cdot e^{-t} \cdot t \cdot dt\end{aligned} \tag{43}$$

Next, use the substitution $v = e^{-t} \Leftrightarrow dt = -v^{-1} dv$ to obtain:

$$\begin{aligned}\mathbb{P}_{n2}(y_n^*) &= \frac{1}{\sigma}\Big||G|\Big| e^{-\frac{V_{n0}-V_{n,J+1}}{\sigma}} \int_{v=0}^{1} \prod_{k=1}^{K_n} \left(1 - v^{e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}}\right) \prod_{m=1}^{M_n} v^{e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}} \cdot v^{e^{-\frac{V_{n0}-V_{n,J+1}}{\sigma}}} (-\ln[v])\, dv \\ &= \frac{1}{\sigma}\Big||G|\Big| e^{-\frac{V_{n0}-V_{n,J+1}}{\sigma}} \int_{v=0}^{1} \prod_{k=1}^{K_n} \left(1 - v^{e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}}\right) v^{\sum_{m=0}^{M_n} e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}} (-\ln[v])\, dv \\ &= \frac{1}{\sigma}\Big||G|\Big| e^{-\frac{V_{n0}-V_{n,J+1}}{\sigma}} \int_{v=0}^{1} \sum_{s=1}^{2^{K_n}} (-1)^{|S_{ns}|} v^{S_{ns}\cdot D_n + I'_{M_n+1}\cdot E_n} \cdot (-\ln[v])\, dv \\ &= \frac{1}{\sigma}\Big||G|\Big| e^{-\left(\frac{V_{n0}-V_{n,J+1}}{\sigma}\right)} \sum_{s}^{2^{K_n}} (-1)^{|S_{ns}|} \frac{1}{\left(1 + S_{ns}\cdot D_n + I'_{M_n+1}\cdot E_n\right)^2}\end{aligned} \tag{44}$$

In the above, define $\mathbf{S_n}$ as a matrix of size 2^{K_n} by K_n describing all possible combinations of non-chosen but affordable projects included in K_n, including the empty set. That is, $\mathbf{S_n}$ represents a matrix containing binary indicators describing a two-level full factorial design with K_n factors. Let S_{ns} describe a given row s of S_n and $|S_{ns}|$ the rowsum of S_{ns}, i.e. $|S_{ns}| = \sum_{k\in K_n} S_{nsk}$. Let D_n be a vector of size K_n by 1 containing $e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}$ for each $k \in K_n$. Additionally, the set of chosen goods M_n is extended with good 0 such that $\sum_{m=0}^{M_n} e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}} = I'_{M_n+1} \cdot E_n$, where I_{M_n+1} is a M_n+1 by 1 vector of ones and E_n is a M_n+1 by 1 vector containing the elements $e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}$, for $m = 0, \ldots, M_n$.

Appendix C. Derivation of choice probabilities — Case 3

The choice probability for case 3 is given by:

$$\begin{aligned}\mathbb{P}_{n3}(y_n^*) = \int_{\epsilon_{n,J+1}=-\infty}^{\infty} \prod_{k=0}^{K_n} \left(1 - F\left[V_{nk} - V_{n,J+1} + \epsilon_{n,J+1}\right]\right) \prod_{m=1}^{M_n} F\left[V_{nm} - V_{n,J+1} + \epsilon_{n,J+1}\right] \\ \cdot f\left[\epsilon_{n,J+1}\right] d\epsilon_{n,J+1}\end{aligned} \tag{45}$$

Substituting the density functions gives:

$$\begin{aligned}\mathbb{P}_{n3}(y_n^*) = \frac{1}{\sigma} \int_{\epsilon_{n,J+1}=-\infty}^{\infty} \prod_{k=0}^{K_n} \left(1 - e^{-e^{-\frac{V_{nk}-V_{n,J+1}+\epsilon_{n,J+1}}{\sigma}}}\right) \prod_{m=1}^{M_n} e^{-e^{-\frac{V_{nm}-V_{n,J+1}+\epsilon_{n,J+1}}{\sigma}}} \\ \cdot e^{-\frac{\epsilon_{n,J+1}}{\sigma}} e^{-e^{-\frac{\epsilon_{n,J+1}}{\sigma}}} d\epsilon_{n,J+1}\end{aligned} \tag{46}$$

Using the substitution of variable $t = e^{-\frac{\epsilon_{n,J+1}}{\sigma}} \Leftrightarrow d\epsilon_{n,J+1} = -\sigma \frac{1}{t} dt$ we obtain:

$$\mathbb{P}_{n3}(y_n^*) = \int_{t=0}^{\infty} \prod_{k=0}^{K_n} \left(1 - e^{-t\cdot e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}}\right) \prod_{m=1}^{M_n} e^{-t\cdot e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}} \cdot e^{-t} dt \tag{47}$$

Next, use the substitution $v = e^{-t} \Leftrightarrow dt = -v^{-1} dv$ to obtain:

$$\begin{aligned}\mathbb{P}_{n3}(y_n^*) &= \int_{v=0}^{1} \prod_{k=0}^{K_n} \left(1 - v^{e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}}\right) v^{\sum_{m=1}^{M_n} e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}} dv \\ &= \int_{v=0}^{1} \sum_{s}^{2^{K_n+1}} (-1)^{|S_{ns}|} \cdot v^{S_{ns}\cdot D_n + I'_{M_n}\cdot E_n} dv \\ &= \sum_{s}^{2^{K_n+1}} (-1)^{|S_{ns}|} \cdot \frac{1}{1 + S_{ns}\cdot D_n + I'_{M_n}\cdot E_n}\end{aligned} \tag{48}$$

In the above, define $\mathbf{S_n}$ as a matrix of size 2^{K_n+1} by K_n+1 describing all possible combinations of non-chosen but affordable projects included in K_n, including the empty set.[12] In other words, $\mathbf{S_n}$ represents a matrix containing binary indicators describing a two-level

[12] K_n includes good y_{n0}, i.e. the remaining public budget.

full factorial design with $K_n + 1$ factors. Let S_{ns} describe a given row s of S_n and $|S_{ns}|$ the rowsum of S_{ns}, i.e. $|S_{ns}| = \sum_{k \in K_n+1} S_{nsk}$. Let D_n be a vector of size $K_n + 1$ by 1 containing $e^{-\frac{V_{nk}-V_{n,J+1}}{\sigma}}$ for each $k = 0, \ldots, K_n$. Here, the set of chosen goods M_n is not extended with good 0 such that $\sum_{m=1}^{M_n} e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}} = I'_{M_n} \cdot E_n$, where I_{M_n} is a M_n by 1 vector of ones and E_n is a M_n by 1 vector containing the elements $e^{-\frac{V_{nm}-V_{n,J+1}}{\sigma}}$, for $m = 0, \ldots, M_n$.

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