Package 'rdborrow'

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Type Package

Title External Control Borrowing for Rare Disease Trials

Description Implements causal inference methods for incorporating external control data into randomized controlled trials (RCTs) with longitudinal outcomes. Provides an analysis module supporting weighting-based methods such as inverse probability weighting (IPW) and augmented inverse probability weighting (AIPW), difference-in-differences (DID), and synthetic control approaches for borrowing external control information, as well as a simulation module for generating trial and external control data, evaluating estimator performance via Monte Carlo studies, and conducting power analyses for sample size determination. Methods are based on Zhou et al. (2024) <doi:10.1093/biostatistics/kxae012> and Zhou et al. (2024) <doi:10.1080/01621459.2024.2395586>.

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`rdborrow-package` *The rdborrow package*

Description

rdborrow is a package that implements causal inference methods for analyzing and designing clinical trials with external controls.

Authors

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See Also

Useful links:

- GitHub Repo for rdborrow: `https://github.com/Genentech/rdborrow`

- Estimating treatment effect in randomized trial after control to treatment crossover using external controls: doi:10.1080/10543406.2024.2330209

- Shi L, Pang H, Chen C, Zhu J. rdborrow: an R package for causal inference incorporating external controls in randomized controlled trials with longitudinal outcomes. J Biopharm Stat. 2025 Oct; 35(6):1043-1066. doi:10.1080/10543406.2025.2489283

`did_ec_aipw` *DID-EC-AIPW method*

Description

Creates a method object for difference-in-differences augmented inverse probability weighting (DID-EC-AIPW) estimation with external control borrowing for the open-label extension phase (Zhou et al., 2024, Eq. 5). Doubly robust: consistent if either the propensity score model or the outcome model is correct.

Usage

```
did_ec_aipw(
  ps_formula,
  trt_formula = NULL,
  outcome_formula,
  bootstrap = 500L,
  bootstrap_ci_type = NULL
)
```

Arguments

`ps_formula`	Formula string for the propensity score model predicting trial participation.
`trt_formula`	Formula string for the treatment assignment model, or `NULL` (default) for marginal probability.
`outcome_formula`	Character vector of outcome model formulas, one per time point.
`bootstrap`	Number of bootstrap replicates. Defaults to 500.
`bootstrap_ci_type`	Bootstrap CI type. Defaults to `"perc"`.

Value

An S4 object of class `did_ec_aipw_method`.

References

Zhou et al. (2024). Estimating treatment effect in randomized trial after control to treatment crossover using external controls. *Journal of Biopharmaceutical Statistics*. doi:10.1080/10543406.2024.2444222

Examples

```
did_ec_aipw(
  ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
  trt_formula = "A ~ x1 + x2 + x3 + x4 + x5",
  outcome_formula = c(
    "y1 ~ x1 + x2 + x3 + x4 + x5",
    "y2 ~ x1 + x2 + x3 + x4 + x5",
    "y3 ~ x1 + x2 + x3 + x4 + x5",
    "y4 ~ x1 + x2 + x3 + x4 + x5"
  ),
  bootstrap = 500
)
```

`did_ec_ipw` *DID-EC-IPW method*

Description

Creates a method object for difference-in-differences inverse probability weighting (DID-EC-IPW) estimation with external control borrowing for the open-label extension phase (Zhou et al., 2024, Eq. 4).

Usage

```
did_ec_ipw(
  ps_formula,
  trt_formula = NULL,
  bootstrap = 500L,
  bootstrap_ci_type = NULL
)
```

Arguments

`ps_formula`	Formula string for the propensity score model predicting trial participation.
`trt_formula`	Formula string for the treatment assignment model, or `NULL` (default) for marginal probability.
`bootstrap`	Number of bootstrap replicates (required for DID methods). Defaults to 500.
`bootstrap_ci_type`	Bootstrap CI type. Defaults to `"perc"`.

Value

An S4 object of class `did_ec_ipw_method`.

References

Zhou et al. (2024). Estimating treatment effect in randomized trial after control to treatment crossover using external controls. *Journal of Biopharmaceutical Statistics*. doi:10.1080/10543406.2024.2444222

Examples

```
did_ec_ipw(
  ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
  trt_formula = "A ~ x1 + x2 + x3 + x4 + x5",
  bootstrap = 500
)
```

`did_ec_or` *DID-EC-OR method constructor*

Description

Creates a method object for difference-in-differences outcome regression (DID-EC-OR) estimation with external control borrowing for the open-label extension phase (Zhou et al., 2024, Eq. 3). Uses outcome models only (no propensity score model).

Usage

```
did_ec_or(
  outcome_formula_ext,
  outcome_formula_rct_ctrl,
  outcome_formula_rct_trt,
  bootstrap = 500L,
  bootstrap_ci_type = NULL
)
```

Arguments

`outcome_formula_ext`
: Character vector of outcome model formulas for external controls, one per time point.

`outcome_formula_rct_ctrl`
: Character vector of outcome model formulas for RCT control subjects, one per time point.

`outcome_formula_rct_trt`
: Character vector of outcome model formulas for RCT treated subjects, one per time point.

`bootstrap`
: Number of bootstrap replicates. Defaults to 500.

`bootstrap_ci_type`
: Bootstrap CI type. Defaults to `"perc"`.

Value

An S4 object of class `did_ec_or_method`.

References

Zhou et al. (2024). Estimating treatment effect in randomized trial after control to treatment crossover using external controls. *Journal of Biopharmaceutical Statistics*. doi:10.1080/10543406.2024.2444222

Examples

```
model_forms <- c(
  "y1 ~ x1 + x2 + x3 + x4 + x5",
  "y2 ~ x1 + x2 + x3 + x4 + x5",
  "y3 ~ x1 + x2 + x3 + x4 + x5",
  "y4 ~ x1 + x2 + x3 + x4 + x5"
)
did_ec_or(
  outcome_formula_ext = model_forms,
  outcome_formula_rct_ctrl = model_forms,
  outcome_formula_rct_trt = model_forms,
  bootstrap = 500
)
```

---

ec_aipw *EC-AIPW method*

Description

Creates a method object for augmented IPW estimation with external control borrowing (Zhou et al., 2024). Augments the IPW estimator with an outcome regression model for improved efficiency. Pass to `setup_analysis_primary` and `run_analysis`.

Usage

```
ec_aipw(
  ps_formula,
  outcome_formula,
  weight = NULL,
  bootstrap = NULL,
  bootstrap_ci_type = NULL
)
```

Arguments

`ps_formula`	Formula string for the propensity score model predicting trial participation.
`outcome_formula`	Character vector of outcome model formulas, one per time point (e.g., `c("y1 ~ x1 + x2", "y2 ~ x1 + x2")`).
`weight`	Borrowing weight. `NULL` (default) for data-adaptive optimal weight, `0` for RCT-only, or a value in (0, 1].
`bootstrap`	Number of bootstrap replicates, or `NULL` (default) for sandwich variance with normal CIs.
`bootstrap_ci_type`	Bootstrap CI type. Defaults to `"perc"`.

Value

An S4 object of class `ec_aipw_method`.

References

Zhou et al. (2024). Causal estimators for incorporating external controls in randomized trials with longitudinal outcomes. *JRSS-A*. doi:10.1093/jrsssa/qnae075

Examples

```
# optimal weight, sandwich SE
ec_aipw(
  ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
  outcome_formula = c(
    "y1 ~ x1 + x2 + x3 + x4 + x5",
    "y2 ~ x1 + x2 + x3 + x4 + x5"
  )
)

# no borrowing
ec_aipw(
  ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
  outcome_formula = c(
    "y1 ~ x1 + x2 + x3 + x4 + x5",
    "y2 ~ x1 + x2 + x3 + x4 + x5"
  ),
  weight = 0
)

# fixed weight with bootstrap
ec_aipw(
  ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
  outcome_formula = c(
    "y1 ~ x1 + x2 + x3 + x4 + x5",
    "y2 ~ x1 + x2 + x3 + x4 + x5"
  ),
  weight = 0.3,
  bootstrap = 500
)
```

`ec_ipw` *EC-IPW method constructor*

Description

Creates a method object for IPW estimation with external control borrowing (Zhou et al., 2024). Pass to `setup_analysis_primary` and `run_analysis`.

Usage

```
ec_ipw(ps_formula, weight = NULL, bootstrap = NULL, bootstrap_ci_type = NULL)
```

Arguments

ps_formula	Formula string for the propensity score model predicting trial participation. The left-hand side is replaced internally (e.g., "S ~ x1 + x2 + x3").
weight	Borrowing weight. NULL (default) for data-adaptive optimal weight, 0 for RCT-only, or a value in (0, 1].
bootstrap	Number of bootstrap replicates, or NULL (default) for sandwich variance with normal CIs.
bootstrap_ci_type	Bootstrap CI type, or NULL (default) which resolves to "perc" when bootstrap is set. One of "perc", "bca", "norm", "basic", or "stud".

Value

An S4 object of class ec_ipw_method.

References

Zhou et al. (2024). Causal estimators for incorporating external controls in randomized trials with longitudinal outcomes. *JRSS-A*. doi:10.1093/jrsssa/qnae075

Examples

```
# optimal weight, sandwich SE
ec_ipw(ps_formula = "S ~ x1 + x2 + x3 + x4 + x5")

# no borrowing
ec_ipw(ps_formula = "S ~ x1 + x2 + x3 + x4 + x5", weight = 0)

# optimal weight with bootstrap
ec_ipw(
  ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
  bootstrap = 500
)

# fixed weight with bootstrap
ec_ipw(
  ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
  weight = 0.3,
  bootstrap = 500
)
```

`estimate` *Run estimation for a method object*

Description

S4 generic that dispatches to the appropriate estimation logic based on the method class. Each method subclass (e.g., `ec_ipw_method`, `did_ec_ipw_method`) implements its own `estimate()` method containing the full estimation pipeline.

Usage

```
estimate(method, ...)

## S4 method for signature 'ec_ipw_method'
estimate(
  method,
  data,
  outcomes,
  treatment,
  trial_status,
  covariates,
  alpha = 0.05,
  quiet = TRUE
)

## S4 method for signature 'did_ec_ipw_method'
estimate(
  method,
  data,
  outcomes,
  treatment,
  trial_status,
  covariates,
  alpha = 0.05,
  quiet = TRUE,
  T_cross
)

## S4 method for signature 'did_ec_aipw_method'
estimate(
  method,
  data,
  outcomes,
  treatment,
  trial_status,
  covariates,
  alpha = 0.05,
```

```
  quiet = TRUE,
  T_cross
)

## S4 method for signature 'did_ec_or_method'
estimate(
  method,
  data,
  outcomes,
  treatment,
  trial_status,
  covariates,
  alpha = 0.05,
  quiet = TRUE,
  T_cross
)

## S4 method for signature 'ec_aipw_method'
estimate(
  method,
  data,
  outcomes,
  treatment,
  trial_status,
  covariates,
  alpha = 0.05,
  quiet = TRUE
)

## S4 method for signature 'scm_method'
estimate(
  method,
  data,
  outcomes,
  treatment,
  trial_status,
  covariates,
  alpha = 0.05,
  quiet = TRUE,
  T_cross
)
```

Arguments

method	An S4 method object (e.g., from ec_ipw).
...	Additional method-specific arguments.
data	Data frame with all subjects (RCT + external controls).
outcomes	Character vector of outcome column names.

treatment	Name of the treatment column.
trial_status	Name of the trial participation column.
covariates	Character vector of covariate column names.
alpha	Significance level (default 0.05).
quiet	Logical. Suppress output (default TRUE).
T_cross	Integer crossover time point (OLE methods only).

Value

A list with estimation results.

Examples

```
method <- ec_ipw(ps_formula = "S ~ x1 + x2 + x3 + x4 + x5")
estimate(
  method,
  data = SyntheticData,
  outcomes = c("y1", "y2"),
  treatment = "A",
  trial_status = "S",
  covariates = c("x1", "x2", "x3", "x4", "x5")
)
```

---

run_analysis *Run an analysis with external control borrowing*

Description

Estimates treatment effects by combining randomized trial data with external controls. Choose a method, wrap it in an analysis object, and pass it here.

Usage

```
run_analysis(analysis_obj, quiet = TRUE)
```

Arguments

analysis_obj	An analysis object created by setup_analysis_primary or setup_analysis_OLE.
quiet	Logical. If TRUE, suppress printed output.

Details

Six borrowing methods are available:

`ec_ipw` Inverse probability weighting (primary analysis).

`ec_aipw` Augmented inverse probability weighting (primary analysis).

`did_ec_ipw` Difference-in-differences with IPW (open-label extension).

`did_ec_aipw` Difference-in-differences with AIPW (open-label extension).

`did_ec_or` Difference-in-differences with outcome regression (open-label extension).

`scm` Synthetic control method (open-label extension).

Value

For primary methods, a list with `results` (data frame of point estimates, standard errors, and confidence intervals) and `borrow_weight`. For OLE methods, a data frame of point estimates and bootstrap confidence intervals.

See Also

`run_simulation` for evaluating operating characteristics via Monte Carlo simulation.

Examples

```
method <- ec_ipw(ps_formula = "S ~ x1 + x2 + x3 + x4 + x5")
analysis <- setup_analysis_primary(
  data = SyntheticData,
  trial_status_col_name = "S",
  treatment_col_name = "A",
  outcome_col_name = c("y1", "y2"),
  covariates_col_name = c("x1", "x2", "x3", "x4", "x5"),
  method_weighting_obj = method
)
run_analysis(analysis)
```

---

run_simulation *Evaluate operating characteristics via Monte Carlo simulation*

Description

Runs repeated simulations under user-specified data-generating scenarios to estimate power, type I error rate, bias, and coverage for one or more borrowing methods.

Usage

```
run_simulation(simulation_obj, quiet = TRUE)
```

Arguments

simulation_obj	A simulation object created by setup_simulation_primary or setup_simulation_OLE.
quiet	Logical. If TRUE, suppress iteration output.

Details

Six borrowing methods are available:

ec_ipw Inverse probability weighting (primary analysis).

ec_aipw Augmented inverse probability weighting (primary analysis).

did_ec_ipw Difference-in-differences with IPW (open-label extension).

did_ec_aipw Difference-in-differences with AIPW (open-label extension).

did_ec_or Difference-in-differences with outcome regression (open-label extension).

scm Synthetic control method (open-label extension).

Value

A simulation report object containing estimated power, type I error rate, and related operating characteristics for each method.

See Also

run_analysis for analyzing a single dataset.

Examples

```
method <- ec_ipw(ps_formula = "S ~ x1 + x2 + x3 + x4 + x5")
sim <- setup_simulation_primary(
  data_matrix_list_null = list(SyntheticData, SyntheticData),
  trial_status_col_name = "S",
  treatment_col_name = "A",
  outcome_col_name = c("y1", "y2"),
  covariates_col_name = c("x1", "x2", "x3", "x4", "x5"),
  method_obj_list = list(method),
  true_effect = c(0, 0),
  method_description = "IPW"
)
run_simulation(sim)
```

`scm` *SCM method constructor*

Description

Creates a method object for synthetic control estimation with external control borrowing for the open-label extension phase (Zhou et al., 2024). Constructs a weighted combination of external controls matching each RCT control subject on covariates and pre-crossover outcomes.

Usage

```
scm(
  lambda_min = 0,
  lambda_max = 0.1,
  nlambda = 2L,
  parallel = "no",
  ncpus = 1L,
  bootstrap = 200L,
  bootstrap_ci_type = NULL
)
```

Arguments

`lambda_min`	Minimum penalty parameter for LOOCV.
`lambda_max`	Maximum penalty parameter for LOOCV.
`nlambda`	Number of lambda values to evaluate in LOOCV.
`parallel`	Parallelization type for bootstrap (`"no"`, `"multicore"`, or `"snow"`).
`ncpus`	Number of CPUs for parallel bootstrap.
`bootstrap`	Number of bootstrap replicates. Defaults to 200.
`bootstrap_ci_type`	Bootstrap CI type. Defaults to `"perc"`.

Value

An S4 object of class `scm_method`.

References

Zhou et al. (2024). Estimating treatment effect in randomized trial after control to treatment crossover using external controls. *Journal of Biopharmaceutical Statistics*. doi:10.1080/10543406.2024.2444222

Examples

```
scm(lambda_min = 0, lambda_max = 0.001, nlambda = 2, bootstrap = 50)
```

`setup_analysis_OLE` *Set up an open-label extension (OLE) analysis*

Description

Bundles data, column mappings, crossover time, and a method object into an analysis object ready to be passed to `run_analysis`.

Usage

```
setup_analysis_OLE(
  data,
  trial_status_col_name,
  treatment_col_name,
  outcome_col_name,
  covariates_col_name,
  method_OLE_obj,
  T_cross,
  alpha = 0.05
)
```

Arguments

`data`	A data frame containing all subject-level data.
`trial_status_col_name`	Name of the trial status column.
`treatment_col_name`	Name of the treatment column.
`outcome_col_name`	Character vector of outcome column names covering both placebo-controlled and OLE periods.
`covariates_col_name`	Character vector of covariate column names.
`method_OLE_obj`	A method object created by `did_ec_ipw`, `did_ec_aipw`, `did_ec_or`, or `scm`.
`T_cross`	Integer crossover time point (column index boundary). The first `T_cross` outcome columns are from the placebo-controlled phase and are used as negative controls for bias correction. The remaining `length(outcome_col_name) -T_cross` columns are from the open-label extension phase and are used to estimate the treatment effect. Must be a positive integer strictly less than `length(outcome_col_name)`.
`alpha`	Significance level (default 0.05).

Details

Available OLE methods:

`did_ec_ipw` Difference-in-differences with IPW.

`did_ec_aipw` DID with augmented IPW.

`did_ec_or` DID with outcome regression.

`scm` Synthetic control method.

Value

An object of class `analysis_OLE_obj`, to be passed to `run_analysis`.

See Also

`run_analysis`, `setup_analysis_primary`

Examples

```
method <- did_ec_ipw(
  ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
  trt_formula = "A ~ x1 + x2 + x3 + x4 + x5",
  bootstrap = 50
)
setup_analysis_OLE(
  data = SyntheticData,
  trial_status_col_name = "S",
  treatment_col_name = "A",
  outcome_col_name = c("y1", "y2", "y3", "y4"),
  covariates_col_name = c("x1", "x2", "x3", "x4", "x5"),
  method_OLE_obj = method,
  T_cross = 2
)
```

---

setup_analysis_primary

Set up a primary analysis with external control borrowing

Description

Bundles data, column mappings, and a method object into an analysis object ready to be passed to `run_analysis`.

Usage

```
setup_analysis_primary(
  data,
  trial_status_col_name,
  treatment_col_name,
  outcome_col_name,
  covariates_col_name,
  method_weighting_obj,
  alpha = 0.05
)
```

Arguments

`data`	A data frame containing all subject-level data.
`trial_status_col_name`	Name of the trial status column.
`treatment_col_name`	Name of the treatment column.
`outcome_col_name`	Character vector of outcome column names.
`covariates_col_name`	Character vector of covariate column names.
`method_weighting_obj`	A method object created by `ec_ipw` or `ec_aipw`.
`alpha`	Significance level (default 0.05).

Details

Available primary methods:

`ec_ipw` Inverse probability weighting.

`ec_aipw` Augmented inverse probability weighting (doubly robust).

Value

An object of class `analysis_primary_obj`, to be passed to `run_analysis`.

See Also

`run_analysis`, `setup_analysis_OLE`

Examples

```
method <- ec_ipw(ps_formula = "S ~ x1 + x2 + x3 + x4 + x5")
setup_analysis_primary(
  data = SyntheticData,
  trial_status_col_name = "S",
  treatment_col_name = "A",
  outcome_col_name = c("y1", "y2"),
  covariates_col_name = c("x1", "x2", "x3", "x4", "x5"),
  method_weighting_obj = method
)
```

setup_bootstrap *Setup bootstrap (Deprecated)*

Description

‘r lifecycle::badge("deprecated")‘

Bootstrap settings are now specified directly in each method constructor (e.g., [ec_ipw()], [did_ec_ipw()]). The separate bootstrap object is no longer needed.

Usage

```
setup_bootstrap(...)
```

Arguments

...	Ignored.

Value

This function is defunct and always signals an error; it does not return a value.

Examples

```
try(setup_bootstrap())
```

setup_method_DID *Setup method DID (Deprecated)*

Description

‘r lifecycle::badge("deprecated")‘

This function has been removed. Use [did_ec_ipw()] for inverse probability weighting, [did_ec_aipw()] for augmented inverse probability weighting, or [did_ec_or()] for outcome regression.

Usage

```
setup_method_DID(...)
```

Arguments

...	Ignored.

Value

This function is defunct and always signals an error; it does not return a value.

Examples

```
try(setup_method_DID())
```

`setup_method_SCM` *Setup method SCM (Deprecated)*

Description

‘r lifecycle::badge("deprecated")‘

This function has been removed. Use [scm()] instead.

Usage

```
setup_method_SCM(...)
```

Arguments

...	Ignored.

Value

This function is defunct and always signals an error; it does not return a value.

Examples

```
try(setup_method_SCM())
```

`setup_method_weighting`
Setup method weighting (Deprecated)

Description

‘r lifecycle::badge("deprecated")‘

This function has been removed. Use [ec_ipw()] for inverse probability weighting or [ec_aipw()] for augmented inverse probability weighting.

Usage

```
setup_method_weighting(...)
```

Arguments

...	Ignored.

Value

This function is defunct and always signals an error; it does not return a value.

Examples

```
try(setup_method_weighting())
```

`setup_simulation_OLE` *Construct a simulation object for OLE analysis*

Description

Construct a simulation object for OLE analysis

Usage

```
setup_simulation_OLE(
  data_matrix_list,
  trial_status_col_name,
  treatment_col_name,
  outcome_col_name,
  covariates_col_name,
  method_obj_list,
  T_cross,
  true_effect,
  method_description,
  alpha = 0.05
)
```

Arguments

`data_matrix_list`	List of simulated data frames.
`trial_status_col_name`	Name of the trial status column.
`treatment_col_name`	Name of the treatment column.
`outcome_col_name`	Character vector of outcome column names.
`covariates_col_name`	Character vector of covariate column names.
`method_obj_list`	List of method objects to evaluate.
`T_cross`	Numeric crossover time point.
`true_effect`	Numeric vector of true treatment effects.
`method_description`	Character vector of method labels, one per method in ‘method_obj_list‘.
`alpha`	Significance level.

Value

An object of class 'simulation_OLE_obj'.

Examples

```
setup_simulation_OLE(
  data_matrix_list = list(SyntheticData),
  trial_status_col_name = "S",
  treatment_col_name = "A",
  outcome_col_name = c("y1", "y2", "y3", "y4"),
  covariates_col_name = c("x1", "x2", "x3", "x4", "x5"),
  method_obj_list = list(
    did_ec_ipw(
      ps_formula = "S ~ x1 + x2 + x3 + x4 + x5",
      trt_formula = "A ~ x1 + x2 + x3 + x4 + x5",
      bootstrap = 50
    )
  ),
  T_cross = 2,
  true_effect = c(0, 0),
  method_description = "IPW, DID"
)
```

---

setup_simulation_primary

Construct a simulation object for primary analysis

Description

Construct a simulation object for primary analysis

Usage

```
setup_simulation_primary(
  data_matrix_list_null,
  trial_status_col_name,
  treatment_col_name,
  outcome_col_name,
  covariates_col_name,
  method_obj_list,
  true_effect,
  method_description,
  data_matrix_list_alt = list(),
  alt_effect = numeric(0),
  alpha = 0.05
)
```

Arguments

`data_matrix_list_null`
: List of data frames simulated under the null.

`trial_status_col_name`
: Name of the trial status column.

`treatment_col_name`
: Name of the treatment column.

`outcome_col_name`
: Character vector of outcome column names.

`covariates_col_name`
: Character vector of covariate column names.

`method_obj_list`
: List of method objects to evaluate.

`true_effect`
: Numeric vector of true treatment effects.

`method_description`
: Character vector of method labels, one per method in ‘method_obj_list‘.

`data_matrix_list_alt`
: List of data frames simulated under the alternative.

`alt_effect`
: Numeric vector of alternative treatment effects.

`alpha`
: Significance level.

Value

An object of class ‘simulation_primary_obj‘.

Examples

```
setup_simulation_primary(
  data_matrix_list_null = list(SyntheticData),
  trial_status_col_name = "S",
  treatment_col_name = "A",
  outcome_col_name = c("y1", "y2"),
  covariates_col_name = c("x1", "x2", "x3", "x4", "x5"),
  method_obj_list = list(
    ec_ipw(ps_formula = "S ~ x1 + x2 + x3 + x4 + x5")
  ),
  true_effect = c(0, 0),
  method_description = "IPW"
)
```

simulate_outcome_from_model *Simulate outcomes from additive linear models*

Description

Generates longitudinal outcomes from a structural causal model of the form 'Y_t = A * effect + X phase ('t <= T_cross'), treatment assignment 'A' is used directly. In the OLE phase ('t > T_cross'), all RCT patients are assumed to receive treatment (effect multiplied by 1 instead of 'A').

Usage

```
simulate_outcome_from_model(X, A, outcome_model_specs, OLE_flag, T_cross)
```

Arguments

X	Data frame of covariates.
A	Numeric vector of treatment indicators (same length as 'nrow(X)').
outcome_model_specs	List of lists, one per time point. See Details above.
OLE_flag	Logical. If 'TRUE', time points after 'T_cross' use the OLE model (all patients treated).
T_cross	Positive integer. The crossover time point separating the primary and OLE phases. Only used when 'OLE_flag = TRUE'.

Details

Each element of 'outcome_model_specs' is a list with:

'effect' Numeric scalar. Treatment effect for this time point.

'model_form_x' Named numeric vector of covariate coefficients. Names must include '"1"' (intercept) and match column names in 'X'.

'noise_mean' Numeric scalar. Mean of the normal noise.

'noise_sd' Numeric scalar. SD of the normal noise.

Value

A data frame with 'n' rows and one column per time point ('y1', 'y2', ...).

Examples

```
X <- data.frame(x1 = rnorm(20), x2 = rnorm(20))
A <- rbinom(20, 1, 0.5)
specs <- list(
  list(
    effect = 1.5,
```

```
    model_form_x = c("1" = 2.0, "x1" = 0.5, "x2" = -0.3),
    noise_mean = 0, noise_sd = 1
  ),
  list(
    effect = 0,
    model_form_x = c("1" = 1.0, "x1" = 0.2, "x2" = 0.1),
    noise_mean = 0, noise_sd = 1
  )
)
Y <- simulate_outcome_from_model(X, A, specs, OLE_flag = FALSE, T_cross = 2)
```

`simulate_trial` *Simulate trials*

Description

Simulate trials

Usage

```
simulate_trial(
  X_int,
  X_ext,
  num_treated,
  OLE_flag,
  T_cross,
  outcome_model_specs
)
```

Arguments

`X_int`	Data frame of internal (RCT) covariates.
`X_ext`	Data frame of external control covariates.
`num_treated`	Number of treated subjects.
`OLE_flag`	Logical. Whether this is an OLE simulation.
`T_cross`	Integer crossover time point.
`outcome_model_specs`	List of outcome model specifications.

Value

a data frame for the simulated data

Examples

```
X_int <- data.frame(x1 = rnorm(20), x2 = rnorm(20))
X_ext <- data.frame(x1 = rnorm(30), x2 = rnorm(30))
specs <- list(
  list(
    effect = 1.5,
    model_form_x = c("1" = 2.0, "x1" = 0.5, "x2" = -0.3),
    noise_mean = 0, noise_sd = 1
  ),
  list(
    effect = 0,
    model_form_x = c("1" = 1.0, "x1" = 0.2, "x2" = 0.1),
    noise_mean = 0, noise_sd = 1
  )
)
Data <- simulate_trial(X_int,
  X_ext,
  num_treated = 10,
  OLE_flag = FALSE,
  T_cross = 2,
  outcome_model_specs = specs
)
```

`simulate_trial_status` *Simulate trial participation status*

Description

Simulates a binary trial participation indicator using a logistic model. The probability of participation is ‘inv.logit(X_intercept covariate matrix with an intercept column prepended.

Usage

```
simulate_trial_status(X, model_specs)
```

Arguments

`X`	Data frame of covariates. The number of columns must equal ‘length(model_specs$coef) - 1‘ (the intercept is added automatically).
`model_specs`	List with:
	‘family‘ Character string. Currently only ‘"binomial"‘ is supported.
	‘coef‘ Numeric vector of length ‘ncol(X) + 1‘. Logistic regression coefficients (intercept first).

Value

A single-column data frame with column ‘S‘ (1 = RCT participant, 0 = external control).

Examples

```
X <- data.frame(x1 = rnorm(20), x2 = rnorm(20))
S <- simulate_trial_status(X, model_specs = list(
  family = "binomial",
  coef = c(0, 0.5, -0.5)
))
```

`simulate_trt_assign` *Simulate treatment assignment*

Description

Randomly assigns treatment to RCT patients ('S = 1') with a given probability. External control patients ('S = 0') always receive control ('A = 0').

Usage

```
simulate_trt_assign(X, S, prob)
```

Arguments

`X`	Data frame of covariates. Must have the same number of rows as 'S'.
`S`	Data frame with a column 'S' indicating trial status (1 = RCT, 0 = external control).
`prob`	Numeric scalar between 0 and 1. Probability of treatment assignment for RCT patients.

Value

A single-column data frame with column 'A' indicating treatment status (1 = treated, 0 = control).

Examples

```
X <- SyntheticData[c("x1", "x2")]
S <- SyntheticData["S"]
A <- simulate_trt_assign(X, S, prob = 1 / 2)
```

`simulate_X_copula` *Simulate covariates using a copula*

Description

Couples several marginal distributions using a copula to generate correlated multivariate covariates.

Usage

```
simulate_X_copula(n, p, cp, margins, paramMargins)
```

Arguments

`n`	Positive integer. Number of units to simulate.
`p`	Positive integer. Number of covariates. Must equal the dimension of ‘cp‘.
`cp`	A copula object (from the ‘copula‘ package).
`margins`	Character vector of length ‘p‘. Names of marginal distributions (e.g. ‘"norm"‘, ‘"binom"‘).
`paramMargins`	List of length ‘p‘. Each element is a named list of parameters for the corresponding marginal distribution.

Value

A data frame with ‘n‘ rows and ‘p‘ columns named ‘x1‘, ..., ‘xp‘.

Examples

```
normal <- copula::normalCopula(param = c(0.8), dim = 4, dispstr = "ar1")
X <- simulate_X_copula(1000, 4, normal,
  margins = c("norm", "t", "norm", "binom"),
  paramMargins = list(
    list(mean = 2, sd = 3),
    list(df = 2),
    list(mean = 0, sd = 1),
    list(size = 10, prob = 0.5)
  )
)
cor(X, method = "spearman")
```

simulate_X_dct_mvnorm *Simulate covariates by discretizing a multivariate normal*

Description

Draws from a multivariate normal distribution and optionally discretizes selected columns into categorical variables based on specified probability cutpoints.

Usage

```
simulate_X_dct_mvnorm(
  n,
  p,
  mu = rep(0, p),
  sig = diag(p),
  cat_cols = c(),
  cat_prob = list()
)
```

Arguments

n	Positive integer. Number of units to simulate.
p	Positive integer. Number of covariates.
mu	Numeric vector of length ‘p‘. Mean of the multivariate normal. Defaults to a zero vector.
sig	Numeric matrix of dimension ‘p x p‘. Covariance matrix. Defaults to the identity matrix.
cat_cols	Integer vector. Column indices to discretize into categorical variables. Each index must be between 1 and ‘p‘.
cat_prob	List of numeric vectors, one per element of ‘cat_cols‘. Each vector gives the category probabilities (must sum to 1). The number of categories equals the length of the vector, and the resulting values are 0-indexed (0, 1, ..., K-1).

Value

A data frame with ‘n‘ rows and ‘p‘ columns named ‘x1‘, ..., ‘xp‘.

Examples

```
simulate_X_dct_mvnorm(
  20, 3,
  mu = rep(0, 3), sig = diag(3),
  cat_cols = c(1),
  cat_prob = list(c(0.3, 0.7))
)
simulate_X_dct_mvnorm(
```

```
  20, 3,
  mu = rep(0, 3), sig = diag(3),
  cat_cols = c(1, 3),
  cat_prob = list(c(0.2, 0.6, 0.2), c(0.3, 0.7))
)
```

`simulate_X_mixture` *Simulate covariates from a Gaussian mixture model*

Description

Generates covariates where categorical variables define mixture components and continuous variables are drawn from component-specific multivariate normal distributions. Each combination of categorical levels has its own probability and its own distribution for the continuous covariates.

Usage

```
simulate_X_mixture(
  n,
  p_cat,
  p_cont,
  cat_level_list,
  cat_comb_prob,
  cont_para_list
)
```

Arguments

`n`	Positive integer. Number of units to simulate.
`p_cat`	Non-negative integer. Number of categorical covariates.
`p_cont`	Non-negative integer. Number of continuous covariates. At least one of ‘p_cat‘ or ‘p_cont‘ must be positive.
`cat_level_list`	List of length ‘p_cat‘. Each element is a vector of possible levels for that categorical variable. The total number of combinations is ‘prod(lengths(cat_level_list))‘.
`cat_comb_prob`	Numeric vector of probabilities, one per combination of categorical levels (in the order produced by [expand.grid()]). Must sum to 1.
`cont_para_list`	List of parameter lists for the continuous covariates. When ‘p_cat > 0‘, must have one element per combination of categorical levels; each element is a list with ‘mean‘ (length ‘p_cont‘) and ‘sigma‘ (‘p_cont x p_cont‘ matrix). When ‘p_cat == 0‘, a single-element list.

Value

A data frame with ‘n‘ rows and ‘p_cat + p_cont‘ columns named ‘x1‘, ..., ‘xp‘.

Examples

```
# Continuous only
X <- simulate_X_mixture(
  n = 100, p_cat = 0, p_cont = 2,
  cat_level_list = list(),
  cat_comb_prob = c(),
  cont_para_list = list(list(mean = c(0, 0), sigma = diag(2)))
)

# Mixed categorical and continuous
X <- simulate_X_mixture(
  n = 100, p_cat = 1, p_cont = 2,
  cat_level_list = list(c(0, 1)),
  cat_comb_prob = c(0.4, 0.6),
  cont_para_list = list(
    list(mean = c(0, 0), sigma = diag(2)),
    list(mean = c(2, 2), sigma = diag(2))
  )
)
```

SyntheticData *Synthetic example dataset for rdborrow*

Description

A simulated dataset containing covariates, treatment, trial status, and longitudinal outcomes for demonstrating external control borrowing methods.

Usage

```
data(SyntheticData)
```

Format

A data frame.

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