

# Package ‘netSEM’

February 24, 2026

**Type** Package

**Title** Network Structural Equation Modeling

**Description** The network structural equation modeling conducts a network statistical analysis on a data frame of coincident observations of multiple continuous variables [1].

It builds a pathway model by exploring a pool of domain knowledge guided candidate statistical relationships between each of the variable pairs, selecting the 'best fit' on the basis of a specific criteria such as adjusted r-squared value.

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[1] Bruckman, Laura S., Nicholas R. Wheeler, Junheng Ma, Ethan Wang, Carl K. Wang, Ivan Chou, Jiayang Sun, and Roger H. French. (2013)

[doi:10.1109/ACCESS.2013.2267611](https://doi.org/10.1109/ACCESS.2013.2267611).

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acrylic	<i>A data frame of an acrylic polymer degradation experiment</i>
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### Description

This data set is from a study of photodegradation of acrylic polymer. In this work, polymeric samples were exposed to different levels of light exposures and resulting optical changes were determined through optical spectroscopy. \*IrradTot\* (total applied irradiance) is the main exogenous variable and \*YI\* (yellowness index) is the endogenous variable (response). The other columns in the data set (\*IAD1\*, \*IAD2\*, \*IAD2p\*, and \*IAD3\*) are induced absorbance to dose values extracted from optical absorbance spectra as single metrics and used as intermediate unit level endogenous (response) variables in the netSEM analysis. Photodegradation in a stress and response framework: poly(methyl methacrylate) for solar mirrors and lens. Doi: 10.1117/1.JPE.2.022004

### Usage

```
data(acrylic)
```

### Format

A 357 by 6 data frame of continuous variables

**YI** Yellowness index of acrylic sample

**IrradTot** Total applied solar irradiance

**IAD1** Induced Absorbance to Dose of the Fundamental Absorption Edge - Optical absorbance at 275 nm

**IAD2** Induced Absorbance to Dose of the Tinuvin light stabilizer doublet peak at 298 nm

**IAD2p** Induced Absorbance to Dose of the Tinuvin light stabilizer doublet peak at 339 nm

**IAD3** Induced Absorbance to Dose in the yellowing region, at 440 nm

### Author(s)

Myles P. Murray, Laura S. Bruckman, Roger H. French

### Source

Solar Durability and Lifetime Extension (SDLE) Research Center, Case Western Reserve University

## Description

A backsheet is a multi-layer polymer laminate used as the back surface of a crystalline silicon photovoltaic (PV) module that is designed to protect the inner components of the PV module. Typical backsheets consist of three layers of polymers to control diffusion of water and oxygen, as well as to protect human beings from electrical shock. It is critical that your PV module solar panel has a backsheet that is of high quality and can withstand various environmental elements for its 25 year expected product lifetime. Poly(ethylene-terephthalate) (PET) is an important material, and it is mainly used as the core (middle) layer of a backsheet to provide mechanical stability and electrical isolation. It is sometimes also used as the outer, or air side, layer of a backsheet. However, Backsheets using PET air side layers are highly susceptible to moisture and ultraviolet (UV) irradiance. Degradation of PV module backsheets can cause severe safety issues and economic losses. Indoor accelerated exposures are used to study backsheets degradation using higher irradiance and shorter exposure times so as to predict the performance of backsheets exposed to the real world conditions.

## Usage

data(backsheet)

## Format

A data frame with 110 rows and 5 variables:

**YI** Yellowness index of PET outer layer measured at every exposure step

**Hours** Exposure time of PET in Damp Heat condition

**oxidation** Formation of conjugated structures in the polymer during oxidation (FTIR peak at 1552 cm<sup>-1</sup>)

**hydrolysis** Formation of acid and alcohol structures during hydrolysis (FTIR peak 2900 - 3300 cm<sup>-1</sup>)

**crystallization** Crystallinity calculated as the ratio of FTIR peak at 1340 cm<sup>-1</sup> to 1370 cm<sup>-1</sup>

## Details

PV module backsheet degradation can be characterized by changes in the yellowness index (YI), which represents the color change of polymer and is associated with chemical change due to irradiance, high temperature and other process. The YI value of a PV backsheet also relates to the module efficiency. In addition, the Fourier-transform infrared spectroscopy (FTIR) is an effective method to study the chemical change of polymers. This non-destructive FTIR measurement enables researchers to obtain qualitative information about polymer functional groups and the relative contribution of each group in the sample to degradation.

In this example, a dataset containing the YI of PET based backsheets (PET/PET/EVA) exposed to 1,500 hours of Damp Heat with no irradiance and a relative humidity (RH) of 85% and a chamber temperature of 85 degree celsius. The PET samples were removed from the exposure chamber

every 500 hours and the YI measurement was conducted at every time step. The stress variable is exposure time with unit of hours. Mechanistic variables from FTIR are included to track chemical changes in the materials related to polymer chain scission due to hydrolysis, crystallinity change and oxidation.

**Author(s)**

Yu Wang, Wei-heng Huang, Laura S. Bruckman, Roger H. French

**Source**

Solar Durability and Lifetime Extension (SDLE) Research Center, Case Western Reserve University

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crack

*Crack Quantification for Photovoltaic Backsheets*

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**Description**

A dataset containing the average normalized crack depth for photovoltaic backsheets with inner layers of either ethylene-vinyl acetate or polyethylene exposed to 4,000 hours of continuous UVA irradiance with an intensity of 1.55 w/m<sup>2</sup> at 340 nm and a chamber temperature of 70 deg C. Mechanistic variables from Fourier transform infrared spectroscopy are included to track chemical changes in the materials related to cracking. See the journal article titled 'A Non-Destructive Method for Crack Quantification in Photovoltaic Backsheets Under Accelerated and Real-World Exposures' in Polymer Degradation and Stability for more details. Doi: 10.1016/j.polymdegradstab.2018.05.008

**Usage**

data(crack)

**Format**

A data frame with 97 rows and 5 variables:

**dAvgNorm** Average crack depth normalized by the backsheet's inner layer thickness

**uva360dose** Integrated, cumulative photodose for all wavelengths less than 360 nm

**crys730** Percent crystallinity calculated from the ratio of CH<sub>2</sub> rocking peaks at 731 and 720 cm<sup>-1</sup>

**carb1715** Ketone carbonyl index calculated as the ratio of intensities at 1715 and 2851 cm<sup>-1</sup>

**carbPC1** 1st principal component score from the carbonyl region (1500-1800 cm<sup>-1</sup>)

**Author(s)**

Addison G. Klinke, Abdulkerim Gok, Laura S. Bruckman, Roger H. French

**Source**

Solar Durability and Lifetime Extension (SDLE) Research Center, Case Western Reserve University

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IVfeature

*IV features data*

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### Description

The dataset contains current-voltage (I-V) curve scans and the I-V features data obtained by the I-V features extraction algorithm of the ddiv R package. These extracted I-V features are for the brand A photovoltaic (PV) modules exposed to damp heat indoor accelerated test conditions of 85 degrees C and 85 The measurement step-wise through time at 500 hour time intervals. The raw data is provided by the SunEdison company. The I-V features include max power (Pmp), short circuit current (Isc), current at max power(Imp), fill factor (FF), series resistance (Rs), shunt resistance (Rsh), open circuit voltage (Voc), and voltage at max power (Vmp). The shunt resistance (Rsh) is too noisy to use for netSEM modeling. After checking the correlation between Isc, Imp, Voc, Vmp, FF, Rs. FF, Rs, Vmp are highly correlated, so we randomly select one to be contained in the model. Here we choose Isc, Imp, Rs and Voc to be contained in the model and these four I-V features show no indication of high correlation. The trend of the I-V features are related to the mechanisms of PV degradation. The variable 'dy' is time that has been converted into decimal year in which 1 means 1 year. We would use this dataet to buit <SIMIR> models with time as the stressor, and four I-V features as tracking variables of the degradation mechanisms and max power as the reponse.

### Usage

```
data(IVfeature)
```

### Format

A data frame with 20 rows and 9 variables:

**Pmp** max power at the measurement step

**dy** the exposure time after been converted into decimal year

**Isc** short circuit current

**Imp** current at max power

**Rs** series resistance

**Voc** open circuit voltage

### Author(s)

Jiqi Liu, Alan Curran, Justin S. Fada, Xuan Ma, Wei-Heng Huang, Jennifer L. Braid, Roger H. French

### Source

Solar Durability and Lifetime Extension (SDLE) Research Center, Case Western Reserve University

**Description**

Functional graded materials (FGM) are a class of materials with engineered continuous compositional gradients through the plate thickness. This work applies the netSEM approach on an aluminum FGM, produced via sequential alloy casting using planar solidification, to quantify the < Processing | Microstructure | Performance > relationships. The material has a continuous gradient in zinc (Zn) and magnesium (Mg) concentrations through the plate thickness. This subsequently produces a gradient in strengthening mechanisms from a dominant precipitate-strengthened aluminum alloy (AA) (Zn-based AA-7055) to a dominant strain-hardenable aluminum alloy (Mg-based AA-5456). Therefore, the material is simultaneously strengthened via solid solution strengthening and precipitation strengthening.

**Usage**

```
data(metal)
```

**Format**

A data frame with 72 rows and 6 variables:

**Hardness** Vickers hardness

**Z** the compositional gradient (z-direction)

**Mg** the element Zinc

**Zn** the element Magnesium

**MgZn2** the alloy

**Mgexcess** Mg-excess

**Author(s)**

Amit K. Verma, Roger H. French, Jennifer L. W. Carter

**Source**

Solar Durability and Lifetime Extension (SDLE) Research Center, Case Western Reserve University

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netSEMp1                      *network Structural Equation Modeling (netSEM)*

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### Description

This function carries out netSEM using markovian principle.

### Usage

```
netSEMp1(x, exogenous, endogenous)
```

### Arguments

x	A dataframe. By default it considers all columns as exogenous variables, except the first column which stores the system's endogenous variable.
exogenous	by default it considers all columns as exogenous variables except column number 1, which is the main endogenous response.
endogenous	A character string of the column name of the main endogenous OR a numeric number indexing the column of the main endogenous.

### Details

netSEMp1 determines the univariate relationships in the spirit of the Markovian process and builds a network model. In this case, the relationship between each pair of system variables, including predictors and the system level response is determined with the Markovian property that assumes the value of the current predictor is sufficient in relating to the next level variable, i.e., the relationship is independent of the specific value of the preceding-level variable to the current predictor, given the current value. Each pair of variables is tested for sensible (in the domain knowledge sense) paring relation chosen from pre-selected common functional forms in linear regression settings. Adjusted R-squared is used for model selection for every pair.

P-values reported in the "res.print" field of the return list contains the P-values of estimators of linear regression coefficients. The P-values are ordered in the common order of coefficients, i.e. in the order of increasing exponents. For example, in the quadratic functional form  $y \sim b_0 + b_1x + b_2x^2$ , the three P-values correspond to those of  $\hat{b}_0$ ,  $\hat{b}_1$  and  $\hat{b}_2$ , respectively. If there are less than 3 coefficients to estimate, the extra P-value field is filled with NA's.

### Value

An object of class netSEM, which is a list of the following items:

- "data": data frame used in netSEMp1 analysis.
- "exogenous": Main stressor variable.
- "endogenous": Main response variable.
- "bestModels": A dataframe.
- "allModels": A list of model objects.

**Examples**

```
## Not run:
## Load the sample acrylic data set
data(acrylic)

## Run netSEM_markovian
ans <- netSEMp1(acrylic, "IrradTot", "YI")

## End(Not run)
```

---

netSEMp2

*network Structural Equation Modelling (netSEM) - Principle 2*


---

**Description**

This function builds an netSEM model using principle 2.

**Usage**

```
netSEMp2(x, exogenous, endogenous, str = FALSE, criterion = "AIC")
```

**Arguments**

x	A dataframe. By default it considers all columns as exogenous variables, except the first column which stores the system endogenous variable.
exogenous	by default it considers all columns as exogenous variables except column number 1, which is the main endogenous response.
endogenous	A character string of the column name of the main endogenous OR a numeric number indexing the column of the main endogenous.
str	A boolean, whether or not this is a 'strength' type problem.
criterion	By default uses AIC to identify best model. Alternative choice is BIC.

**Details**

Principle 2 resembles the multiple regression principle in the way multiple predictors are considered simultaneously. Specifically, the first-level predictors to the system level variable, such as, Time and unit level variables, acted on the system level variable collectively by an additive model. This collective additive model can be found with a generalized stepwise variable selection (using the stepAIC() function in R, which performs variable selection on the basis of AIC or BIC) and this proceeds iteratively.

Data is analysed first using Principle 1 to find the best models. If needed, transformations based on the best models are applied to the predictors. Starting from the system response variable, each variable is regressed on all other variables except for the system response in an additive multiple regression model, which is reduced by a stepwise selection using stepAIC(). Then, for each selected variable, fitted regression for 6 selected functional forms (8 if strength type problem) and pick the best.

**Value**

A list of the following items:

- "data":
- "res.print": A dataframe.
- "res.model": A model object.

**See Also**

[netSEMp1](#)

**Examples**

```
## Not run:
## Load the sample acrylic data set
data(acrylic)

## Using AIC criterion
ans <- netSEMp2(acrylic, "IrradTot", "YI")

## Using BIC criterion
ans <- netSEMp2(acrylic, "IrradTot", "YI", criterion = "BIC")

## End(Not run)
```

---

paths

*paths data frame*

---

**Description**

The function finds the best paths through netSEM modeling.

**Usage**

```
paths(a, top_n = 3, p_val = 0.05)
```

**Arguments**

a	a netSEM object containing every variable
top_n	an integer. How many paths from each variable should the function look at. Default value is 3.
p_val	a numeric. The threshold below which a p-value is considered significant, and thus the path is considered valid. The default is 0.05, meaning that paths with p-values greater than 0.05 will not be considered significant. This parameter can be adjusted based on the specifics of your analysis.

## Details

`paths_analysis` uses a recursive algorithm to rank all different paths through a netSEM model by the lowest R2adj in the pathway (the weakest link). Function returns the best paths in a data frame.

## Value

a data frame with two columns: `Paths`, containing the best paths through the netSEM as a string and `min_R2` containing the smallest R2adj value between two variables in the path.

## Examples

```
## Not run:
## Load the sample acrylic data set
data(acrylic)

## Run netSEM
ans <- netSEMp1(acrylic, "IrradTot", "YI")

path_data <- paths(ans, 3, 0.05)

## End(Not run)
```

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pet

*A data frame of an degradation experiment of poly(ethylene-terephthalate) films*

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## Description

The data set is a study of photolysis and hydrolysis of poly(ethylene-terephthalate) films that contain an ultraviolet stabilizer additive. In this work, polymeric samples were exposed to UV light and moisture according to ASTM G-154 Cycle 4 standard accelerated weathering conditions. Resulting optical chemical changes were determined through optical and infrared (IR) spectroscopy. `*Time*` is the main exogenous variable and `*YI*` (yellowness index) is the endogenous variable (response). The other columns in the data set (`*AbsEdge*`, `*UV.Stab.Bleaching*`, `*Crystallization*`, and `*ChainScission*`) are values extracted from optical and IR absorbance spectra as single metrics and used as intermediate unit level endogenous (response) variables in the netSEM analysis.

## Usage

```
data(pet)
```

## Format

A 37 by 6 data frame of continuous variables:

**YI** Yellowness index of PET film

**Time** Time exposed to ASTM G-154 Cycle 4 conditions

**AbsEdge** Fundamental Absorption Edge - Optical absorbance at 312 nm

**UVStabBleaching** Ultraviolet Stabilizer Bleaching - Optical absorbance at 340 nm

**Crystallization** IR spectroscopy peak of relative crystallinity - IR absorbance at 975 wavenumber

**ChainScission** IR carbonyl peak - IR absorbance at 1711 wavenumber

#### Author(s)

Devin A. Gordon, Wei-Heng Huang, Roger H. French, Laura S. Bruckman

#### Source

Solar Durability and Lifetime Extension (SDLE) Research Center, Case Western Reserve University

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plot.netSEMp1	<i>Plotting of netSEM diagram</i>
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#### Description

Plot netSEMp1 result plot.netSEMp1 plots a network structural equation network model diagram, fitted under principle 1, based on best functional form for each selected pairwise variable.

#### Usage

```
## S3 method for class 'netSEMp1'
plot(
  x,
  cutoff = NULL,
  latent = NULL,
  plot.save = FALSE,
  title = "netSEM_markovian",
  path = NULL,
  filename = NULL,
  style = TRUE,
  ...
)
```

#### Arguments

x	An object of class "netSEMp1", the returned list from netSEMp1. Plotting uses the first element of this list (table) in which the first column of it is endogenous variable, second column is variable and other columns are corresponding best functional form, r-squared, adj-r-squared, P-value1, P-value2 and P-value3.
cutoff	A threshold value for adjusted R-squared. The maximum number of cutoff is 3.
latent	The latent variable that corresponds to the mechanic variable. The default is NULL.
plot.save	True/False, it saves the network diagram plot as a png file. The default is false.
title	The title. The default is 'netSEMp1.'

path	The pathways to highlight with a certain color. The default is NULL.
filename	A character string naming a file to save as a png file.
style	True/False, it plots the first interval in the network diagram with dotted weak line. The default is True.
...	A S3 generic/method consistency.

### Value

An html style plot of pairwise relationship pathway diagram between exogenous variables and an endogenous variable. Arrows show relationships between each variable with given statistical relations along the connection lines.

### See Also

[netSEMp1](#)

### Examples

```
## Not run:
# Load acrylic data set
data(acrylic)

# Build a netSEM model
ans <- netSEMp1(acrylic, "IrradTot", "YI")

# Plot the network model
plot(ans, cutoff = c(0.3,0.6,0.8))

# Plot the network model without a cutoff
plot(ans)

plot(ans, cutoff = c(0.3,0.6,0.8), title = "Acrylic")

\donttest{
# Plot the network diagram with latent argument labels
plot(ans, cutoff = c(0.3, 0.6, 0.8),
      latent = c('IAD1' = 'FundAbsEdge',
                'IAD2' = 'UVStab',
                'IAD2p' = 'UVStab',
                'IAD3' = 'Ye1Met'))

# Drop relationships lower than minimum cutoff value
plot(ans, cutoff = c(0.3,0.6,0.8), style = FALSE)

# Change color of pathways
plot(ans, cutoff = c(0.3,0.6,0.8),
      title = "Acrylic", path = c('red', 'IAD1->IAD2p'),
      latent = c('IAD1' = 'FundAbsEdge'), style = FALSE)

# Save plot
plot.netSEMp1(ans, acrylic,
```

```

        cutoff = c(0.3, 0.6, 0.8),
        plot.save = TRUE,
        filename = 'acrylic-netSEMp1')
}

## End(Not run)

```

---

plot.netSEMp2

*Plotting of netSEM diagram*


---

### Description

Plot netSEMp2 result plot.netSEMp2 plots a structural equation network model diagram, fitted under principle 2, based on best functional form for each selected pairwise variable.

### Usage

```

## S3 method for class 'netSEMp2'
plot(
  x,
  cutoff = NULL,
  latent = NULL,
  title = "netSEMp2",
  plot.save = FALSE,
  filename = NULL,
  style = TRUE,
  ...
)

```

### Arguments

x	An object of class "netSEMp2", the returned list from netSEMp2.
cutoff	A threshold value for adjusted R-squared. The maximum number of cutoff is 3.
latent	The latent variable that corresponds to the mechanic variable. The default is NULL.
title	The title of the plot. Default value is "netSEMp2".
plot.save	True/False, it saves the network diagram plot as png file. The default is false.
filename	A character string naming a file to save as a png file.
style	True/False, it plots the first interval in the network diagram with dotted weak line. The default is True.
...	A S3 generic/method consistency.

### Value

An html style plot of pairwise relationship pathway diagram between exogenous variables and an endogenous variable. Arrows show relationships between each variable with given statistical relations along the connection lines.

**See Also**[netSEMp2](#)**Examples**

```
## Not run:
# Load acrylic data set
data(acrylic)

# Build a netSEMp2 model
ans <- netSEMp2(acrylic, "IrradTot", "YI")

# Plot the network model with a title
plot(ans, cutoff = c(0.3,0.6,0.8), title = "Acrylic")

\donttest{
# plot the network diagram and save file
plot(ans, cutoff = c(0.3,0.6,0.8),
      plot.save = TRUE,
      filename = "acrylic-netSEMp2")
}

## End(Not run)
```

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 PVmodule

*Dataframe for PV module degradation under Damp Heat Exposure*


---

**Description**

In this example, full size PV modules were exposed to damp heat conditions (relative humidity of 85% and a chamber temperature of 85 deg C) for 4000 hours and the degradation in PV power output was measured at specific time intervals, or time steps. In addition, some modules were withdrawn from the study at these time steps, to produce a retained sample library with samples available for each time step. These retained samples were dismantled destructively in order to determine the changes occurred in the module materials. In the resulting netSEM model, time was used as a proxy for damp heat exposure stress ( $S$ ) variable and  $P_{max}$  (maximum power generated by the modules) was used as the performance level response ( $R$ ) variable, several mechanistic variables ( $M$ ) were obtained through chemical evaluation methods, including FTIR and TGA on EVA encapsulant. This example also demonstrate how to add latent variables.

**Usage**

```
data(PVmodule)
```

**Format**

A 16 by 4 data frame of continuous variables

**Pmax** Maximum power generated by PV modules

**Time** Time in decimal years for exposure of PV modules to damp heat conditions

**IREVA** Infrared signal measurement that tracks hydrolysis of EVA encapsulant

**TGA** Thermogravimetric analysis of PV module to track formation of acetic acid

### Author(s)

Menghong Wang, Abdulkerim Gok, Roger H. French

### Source

Solar Durability and Lifetime Extension (SDLE) Research Center, Case Western Reserve University

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var_selection	<i>network Structural Equation Modeling (netSEM)</i>
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### Description

This function selects the variable that best represents a specific degradation mechanism with the greatest adjusted R<sup>2</sup> of <SIML.

### Usage

```
var_selection(a, exogenous, endogenous)
```

### Arguments

a	A dataframe. By default it considers all columns as exogenous variables, except the first column which stores the system's endogenous variable.
exogenous	by default it considers all columns as exogenous variables except column number 1, which is the main endogenous response.
endogenous	A character string of the column name of the main endogenous OR a numeric number indexing the column of the main endogenous.

### Value

A character string of the variable that best represents a specific degradation mechanism.

### Examples

```
## Not run:
## Load the sample acrylic data set
data(acrylic)

## Run netSEMp1_predict
ans <- var_selection(a = acrylic, exogenous = "IrradTot", endogenous = "YI")

## End(Not run)
```

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