

Distributed-lag linear structural equation models in R: the `dlsem` package

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1 Introduction

Structural causal models (SCMs, Pearl, 2000) are a mathematical framework describing the behaviour of a multivariate system, and represent one of the prevalent methodologies for causal inference in contemporary applied sciences. Markovian SCMs are a special case where the joint probability distribution of the considered variables can be factored according to a directed acyclic graph. Distributed-lag linear structural equation models (DLSEMs) are Markovian SCMs, where each factor of the joint probability distribution is a distributed-lag linear regression. They were firstly introduced in the context of lag exposure assessment (Magrini, 2018), then applied to an economic impact assessment problem (Magrini *et al.*, 2019). DLSEMs account for temporal delays in the dependence relationships among the considered variables and allow to perform dynamic causal inference by assessing causal effects at different time lags. As such, they are suitable to investigate the effect of an external impulse on a multivariate system through time. Econometrics and epidemiology are two of the main fields of application for DLSEMs.

Package `dlsem` implements inference functionalities for DLSEMs with several types of constrained lag shapes. This vignette is structured as follows. In Section 2, theory on the DLSEM is presented. In Section 3, instructions for the installation of the `dlsem` package are provided. In Section 4, the practical use of `dlsem` is illustrated through a simple impact assessment problem. Section 5 includes final remarks and considerations on future development of the package.

2 Theory

Distributed-lag linear regression Lagged instances of one or more covariates may be included in the linear regression model to account for temporal delays in their influence on the response:

$$y_t = \beta_0 + \sum_{j=1}^J \sum_{l=0}^{L_j} \beta_{j,l} x_{j,t-l} + \epsilon_t \quad (1)$$

where y_t is the value of the response variable at time t , $x_{j,t-l}$ is the value of the j -th covariate at l time lags before t , and ϵ_t is the random error at time t uncorrelated with the covariates and with ϵ_k , $\forall k \neq t$. The set $(\beta_{j,0}, \beta_{j,1}, \dots, \beta_{j,L_j})$ is denoted as the *lag shape* of the j -th covariate and represents its regression coefficient (in the remainder, simply ‘coefficient’) at different time lags.

The model in Formula 1 has the disadvantage that a parameter is required for each lagged instance of a covariate, and lagged instances of the same covariate tend to be highly correlated. The Almon’s polynomial lag shape (Almon, 1965) overcomes these limitations by forcing the coefficients for lagged instances of the same covariate to follow a polynomial of order Q :

$$\beta_{j,l} = \begin{cases} \phi_{j,0} & l = 0 \\ \sum_{q=0}^Q \phi_{j,q} l^q & \text{otherwise} \end{cases} \quad (2)$$

For instance, for $q = 2$ we have that $\beta_{j,l} = \phi_{j,0} + \phi_{j,1}l + \phi_{j,2}l^2$. Unfortunately, the Almon’s polynomial lag shape may show multiple modes and coefficients with different signs, thus entailing problems of interpretation. Constrained lag shapes (see, for example, (Magrini, 2018)) overcome this issue. Package `dlsem` includes the *endpoint-constrained quadratic* lag shape:

$$\beta_{j,l} = \begin{cases} \theta_j \left[-\frac{4}{(b_j - a_j + 2)^2} l^2 + \frac{4(a_j + b_j)}{(b_j - a_j + 2)^2} l - \frac{4(a_j - 1)(b_j + 1)}{(b_j - a_j + 2)^2} \right] & a_j \leq l \leq b_j \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

the *quadratic decreasing* lag shape:

$$\beta_{j,l} = \begin{cases} \theta_j \frac{l^2 - 2(b_j + 1)l + (b_j + 1)^2}{(b_j - a_j + 1)^2} & a_j \leq l \leq b_j \\ 0 & \text{otherwise} \end{cases} \quad (4)$$

and the *gamma* lag shape:

$$\beta_{j,l} = \theta_j (l + 1)^{\frac{\delta_j}{1 - \delta_j}} \lambda_j^l \left[\left(\frac{\delta_j}{(\delta_j - 1) \log \lambda_j} \right)^{\frac{\delta_j}{1 - \delta_j}} \lambda_j^{\frac{\delta_j}{(\delta_j - 1) \log \lambda_j} - 1} - 1 \right]^{-1} \quad (5)$$

$$0 < \delta_j < 1 \quad 0 < \lambda_j < 1$$

The endpoint-constrained quadratic lag shape is zero for a time lag $l < a_j$ or $l > b_j$, and symmetric with mode equal to θ_j at lag $(a_j + b_j)/2$. The quadratic decreasing lag shape decreases from value θ_j at lag a_j to value 0 at lag $b_j + 1$ according to a quadratic function. The gamma lag shape is positively skewed with mode equal to θ_j at lag $\frac{\delta_j}{(\delta_j - 1) \log \lambda_j}$. Value a_j is denoted as the *gestation lag*, value b_j as the *lead lag*, and value $b_j - a_j$ as the *lag width*. A static lag shape is obtained if $a_j = b_j = 0$. The gamma lag shape is not expressed as a function of a_i and b_i , thus it cannot reduce exactly to a static lag shape, but numerical approximation can be used to find the couples of values of δ_i and λ_i satisfying given values of a_i and b_i . For these three lag shapes it holds:

$$\begin{aligned} \beta_{j,l} > 0 &\iff \theta_j > 0 \\ \beta_{j,l} < 0 &\iff \theta_j < 0 \end{aligned} \quad \forall l : a_j \leq l \leq b_j \quad (6)$$

and we refer to the *lag sign* as the sign of parameter θ_j .

A linear regression with constrained lag shapes is linear in parameters $\beta_0, \theta_1, \dots, \theta_J$, provided that the values of $a_1, \dots, a_J, b_1, \dots, b_J$ are known. Thus, one may fit several regressions with different values of $a_1, \dots, a_J, b_1, \dots, b_J$, and select the one with the minimum residual sum of squares¹.

¹ Note that neither the response variable nor the covariates must contain a unit root in order to obtain unbiased estimates with ordinary least squares (Granger and Newbold, 1974). A reasonable procedure is to sequentially apply differentiation to all variables until the Augmented Dickey-Fuller test (Dickey and Fuller, 1981) rejects the hypothesis of unit root for all of them.

Structural causal models Structural causal models (SCMs) were developed by Pearl (2000) in the context of causal inference. They are rooted to path analysis (Wright, 1934) and simultaneous equation models (Haavelmo, 1943; Koopmans *et al.*, 1950). A SCM consists of a tuple $\{\mathbf{V}, \mathbf{U}, \Omega_{\mathbf{V}}, \Omega_{\mathbf{U}}, \mathbf{f}, \mathbb{P}_{\mathbf{U}}\}$, where:

- $\mathbf{V} = \{V_1, \dots, V_J\}$ is a set of endogenous variables;
- $\Omega_{\mathbf{V}} = \Omega_{V_1} \times \dots \times \Omega_{V_J}$ is the cartesian product of the domains of variables in \mathbf{V} ;
- $\mathbf{U} = \{U_1, \dots, U_K\}$ is a set of unobserved variables;
- $\Omega_{\mathbf{U}} = \Omega_{U_1} \times \dots \times \Omega_{U_K}$ is the cartesian product of the domains of variables in \mathbf{U} ;
- $\mathbf{f} : \Omega_{\mathbf{V}} \times \Omega_{\mathbf{U}} \rightarrow \Omega_{\mathbf{V}}$ is a measurable function;
- $\mathbb{P}_{\mathbf{U}}$ is a probability measure on $\Omega_{\mathbf{U}}$.

Markovian SCMs (Pearl, 2000, Chapter 3) are a special case where \mathbf{f} is acyclic and variables in \mathbf{U} are each other independent. In a Markovian SCM, the following factorization of the joint probability distribution of variables in \mathbf{V} holds:

$$p(v_1, \dots, v_J) = \prod_{j=1}^J p(v_j \mid \Pi_j = \pi_j) \quad (7)$$

where Π_j is the set of variables in \mathbf{V} such that, for $j > 1$, V_j is independent of variables in $\{V_1, \dots, V_{j-1}\} \setminus \Pi_j$, given variables in Π_j . This means that the joint probability distribution of variables in \mathbf{V} can be factored according to conditional independence relationships holding among them disregarding variables in \mathbf{U} . Pearl (2000, pages 12 and following) shows that these conditional independence relationships are encoded into a directed acyclic graph (DAG) such that Π_j is the parent set of V_j , $\forall j = 1, \dots, J$. For example, in the Markovian SCM associated to the DAG in Figure 1, it holds:

$$p(v_1, v_2, v_3, v_4) = p(v_1) p(v_2 \mid v_1) p(v_3 \mid v_1) p(v_4 \mid v_2, v_3) \quad (8)$$

and, for example, V_4 is independent of V_1 given V_2 and V_3 .

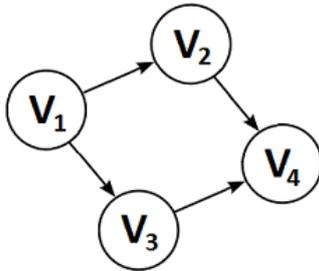


Figure 1: An example of directed acyclic graph.

Let $\text{do}(V_i = v_i)$ denote an intervention setting the value of V_i to v_i . Then, in a Markovian SCM it holds:

$$p(v_1, \dots, v_J \mid \text{do}(V_i = v_i)) = \prod_{j \neq i} p(v_j \mid \pi_j) \Big|_{V_i = v_i} \quad (9)$$

where $\Big|_{V_i = v_i}$ indicates that $p(v_i \mid \pi_i)$ is replaced by value v_i . This formula, called *truncated factorization* (Pearl, 2000, Section 3.2), allows to compute the effect of an intervention from the (pre-intervention) distribution in Formula 7, that is to predict such effect from non-experimental (observational) data. In a Markovian SCM, the effect of $\text{do}(V_i = v_i)$ on V_j , called *causal effect* of V_i on V_j , is given by the following expression (see Pearl, 2000, page 70 and following):

$$p(V_j = v_j \mid \text{do}(V_i = v_i)) = \sum_{\pi_i} p(V_j = v_j \mid V_i = v_i, \Pi_i = \pi_i) p(\Pi_i = \pi_i) \quad (10)$$

where Π_i is the parent set of V_i .

In a linear parametric formulation of SCMs (linear Markovian SCMs), each factor $p(v_j | \pi_j)$ of the joint probability distribution in Formula 7 is the linear regression where V_j is the response variable and variables in Π_j are the covariates. For example, in the linear Markovian SCM associated to the DAG in Figure 1, $p(v_4 | v_2, v_3)$ is the linear regression where V_4 is the response variable and V_2 and V_3 are the covariates.

As shown by Magrini, 2018, the computation of causal effects in a linear Markovian SCM involves the coefficients of the regressions only, without the need of Formula 10. Let $\text{do}(\Delta V_i = 1)$ be an intervention changing the value of V_i by a unit. Under such intervention:

- if V_i is parent of V_j , the *direct* causal effect of V_i on V_j is equal to the coefficient of V_i in the regression of V_j ;
- the causal effect of V_i on V_j through a multi-edge directed path $\langle V_i, \dots, V_j \rangle$ connecting V_i to V_j , called *indirect* causal effect of V_i on V_j through $\langle V_i, \dots, V_j \rangle$, is equal to (see, for example, Wright, 1934):

$$e(\langle V_i, \dots, V_j \rangle) = \prod_{k: V_k \in \langle V_i, \dots, V_j \rangle \wedge k \neq i} \beta_{k|k-1} \quad (11)$$

where $\beta_{k|k-1}$ is the coefficient of V_{k-1} in the regression of V_k . The direct causal effect of V_i on V_j and all the indirect causal effects of V_i on V_j are denoted as *pathwise* causal effects of V_i on V_j ;

- the *overall* causal effect of V_i on V_j is equal to the sum of all the pathwise causal effects of V_i on V_j .

For example, in the linear Markovian SCM associated to the DAG in Figure 1, there are two directed paths connecting V_1 to V_4 : $\langle V_1, V_2, V_4 \rangle$ with pathwise causal effect $\beta_{2|1} \cdot \beta_{4|2}$, and $\langle V_1, V_3, V_4 \rangle$ with pathwise causal effect $\beta_{3|1} \cdot \beta_{4|3}$. Thus, the overall causal effect of V_1 on V_4 is equal to $\beta_{2|1} \cdot \beta_{4|2} + \beta_{3|1} \cdot \beta_{4|3}$.

Distributed-lag linear structural equation models Distributed-lag linear structural equation models (DLSEMs) are Markovian SCMs where each factor of the joint probability distribution in Formula 7 is a distributed-lag linear regression. They were firstly introduced in the context of lag exposure assessment (Magrini, 2018), then applied to an economic impact assessment problem (Magrini *et al.*, 2019). The DAG of a DLSEM would involve all the possible temporal instances of each variable in \mathbf{V} . Here, for simplicity, a static DAG is still used for a DLSEM, where the edge $\langle V_i, V_j \rangle$ exists if and only if there exists at least one time lag where the coefficient of variable V_i in the regression of variable V_j is non-zero. Causal effects at different time lags in a DLSEM are defined as follows:

- if V_i is parent of V_j , the *direct* causal effect of V_i on V_j at lag l is equal to the coefficient of V_i at lag l in the regression of V_j ;
- Let $\langle V_{d_0}, \dots, V_{d_m} \rangle$, $d_0 = i$ and $d_m = j$, be a directed path composed of m edges connecting V_i to V_j , and $Q_m^{(l)}$ be the set of all the possible ordered m -uples of time lags such that their sum is equal to l . The *indirect* causal effect of V_i on V_j through such path at lag l is equal to:

$$e(\langle V_{d_0}, \dots, V_{d_m} \rangle; d_0 = i, d_m = j) = \sum_{(q_1, \dots, q_m) \in Q_m^{(l)}} \prod_{k=1}^m b_{d_k|d_{k-1}, q_k} \quad (12)$$

where $b_{d_k|d_{k-1}, q_k}$ is the coefficient of $V_{d_{k-1}}$ at lag q_k in the regression of V_{d_k} ;

- the *overall* causal effect of V_i on V_j at lag l is equal to the sum of all the pathwise causal effects of V_i on V_j at lag l .

A *pathwise causal lag shape* is the set of causal effects associated to a path at different time lags. An *overall causal lag shape* is the set of the overall causal effects of a variable on another one at different time lags.

3 Installation

Before installing `dlsem`, you must have installed R version 2.1.0 or higher, which is freely available at <http://www.r-project.org/>.

To install the `dlsem` package, type the following in the R command prompt:

```
> install.packages("dlsem")
```

and R will automatically install the package to your system from CRAN. In order to keep your copy of `dlsem` up to date, use the command:

```
> update.packages("dlsem")
```

The latest version of `dlsem` is 2.4.4.

4 Illustrative example

The practical use of package `dlsem` is illustrated through a simple impact assessment problem denoted as “industrial development problem”. The objective is to test whether the influence through time of the number job positions in industry (proxy of the industrial development) on the amount of greenhouse gas emissions (proxy of pollution) is direct and/or mediated by the amount of private consumption. The DAG for the industrial development problem is shown in Figure 2. The analysis will be conducted on the dataset `industry`, containing simulated data for 10 imaginary regions in the period 1983-2015.

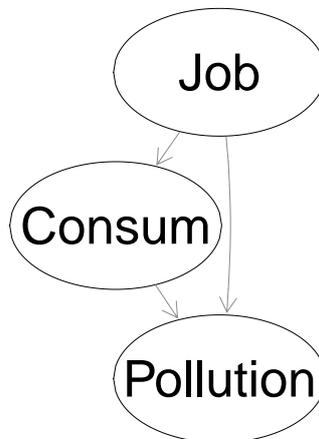


Figure 2: The DAG for the industrial development problem. ‘Job’: number of job positions in industry. ‘Consum’: private consumption index. ‘Pollution’: amount of greenhouse gas emissions.

```
> data(industry)
> summary(industry)
```

Region	Year	Population	GDP
1	: 32 Min. :1983	Min. : 4771649	Min. : 97119
2	: 32 1st Qu.:1991	1st Qu.: 8310737	1st Qu.: 186783
3	: 32 Median :1998	Median :25381874	Median : 463942
4	: 32 Mean :1998	Mean :32368547	Mean : 727735
5	: 32 3rd Qu.:2006	3rd Qu.:56273337	3rd Qu.:1307044
6	: 32 Max. :2014	Max. :78308254	Max. :1883702
(Other):128			
Job	Consum	Pollution	
Min. : 34.77	Min. : 37.35	Min. : 3161	

1st Qu.:105.07	1st Qu.: 87.88	1st Qu.: 7536
Median :137.03	Median :108.47	Median : 25320
Mean :127.61	Mean :108.17	Mean : 32202
3rd Qu.:152.68	3rd Qu.:124.85	3rd Qu.: 47109
Max. :200.83	Max. :211.16	Max. :101441

4.1 Specification of the model code

The first step to build a DLSEM with the `dlsem` package is the definition of the model code, which includes the formal specification of the regressions. The variables for which a regression is specified are called *endogenous* variables. The other variables are referred as *exogenous* variables (not to be confused with the unobserved disturbances).

The model code must be a list of formulas, one for each regression. In each formula, the response and the covariates must be quantitative variables², and operators `qu.ec.lag()`, `qdec.lag()` and `gamm.lag()`³ may be employed to specify, respectively, an endpoint-constrained quadratic, a quadratic decreasing or a gamma lag shape. Operators `qu.ec.lag()` and `qdec.lag()` have three arguments: the name of the covariate to which the lag shape is applied, the gestation lag (a_j) and the lead lag (b_j). Operator `gamm.lag()` has three arguments: the name of the covariate to which the lag shape is applied, parameter δ_j and parameter λ_j . If none of these two operators is applied to a covariate, it is assumed that its coefficient is equal to 0 for time lags greater than 0 (no lag shape). The group factor and exogenous variables must not appear in the model code (see Subsection 4.3 for the way to include them). The specification of regressions with no endogenous covariates may be omitted from the model code (for example, one could avoid to specify the regression for the number of job positions). In this problem, all lag shapes are assumed to be endpoint-constrained quadratic lag shapes between 0 and 15 time lags:

```
> indus.code <- list(
+   Job ~ 1,
+   Consum~qu.ec.lag(Job,0,15),
+   Pollution~qu.ec.lag(Job,0,15)+qu.ec.lag(Consum,0,15)
+ )
```

4.2 Specification of control options

The second step to build a DLSEM with the `dlsem` package is the specification of control options. Control options are distinguished into global (applied to all the regressions) and local (regression-specific) options. Global control options must be a named list with one or more of the following components:

- **adapt**: a logical value indicating if adaptation of lag shapes must be performed, that is parameters of lag shapes must be chosen on the basis of fit to data. Default is **FALSE**, meaning no adaptation;
- **min.gestation**: the minimum gestation lag for all lag shapes. If not provided, it is taken as equal to 0;
- **max.gestation**: the maximum gestation lag for all lag shapes. If not provided, it is taken as equal to **max.lead** (see below);
- **max.lead**: the maximum lead lag for all lag shapes. If not provided, it is computed accordingly to the sample size;
- **min.width**: the minimum lag width for all lag shapes. It cannot be greater than **max.lead**. If not provided, it is taken as 0;
- **sign**: the lag sign for all lag shapes, that may be either '+' for positive or '-' for negative. If not provided, adaptation will disregard the lag sign.

Local control options must be a named list containing one or more among the following components:

² Qualitative variables may be included only as exogenous variables, as described in Subsection 4.3.

³ The operator `gamm.lag()` replaces the old operator `gamma.lag()`. If the latter is employed, it is automatically replaced by the former and a warning is returned.

- **adapt**: a named vector of logical values, where each component must have the name of one endogenous variable and indicate if adaptation of lag shapes must be performed for the regression of that variable;
- **min.gestation**: a named list. Each component of the list must have the name of one endogenous variable and be a named vector. Each component of the named vector must have the name of one covariate in the regression of the endogenous variable above and include the minimum gestation lag for its lag shape;
- **max.gestation**: the same as **min.gestation**, with the exception that the named vector must include the maximum gestation lag;
- **max.lead**: the same as **min.gestation**, with the exception that the named vector must include the maximum lead lag;
- **min.width**: the same as **min.gestation**, with the exception that the named vector must include the minimum lag width;
- **sign**: the same as **min.gestation**, with the exception that the named vector must include the lag sign (either '+' for positive or '-' for negative).

Local control options have no default values, and global ones are applied in their absence. If some local control options conflict with global ones, only the former are applied.

Suppose that one wants to perform adaptation with the following constraints for all lag shapes: (i) maximum gestation lag of 3 years, (ii) maximum lead lag of 15 years, (iii) minimum lag width of 5 years, (iv) positive lag sign. Control options for these constraints may be expressed in several ways. The most simple solution is to specify only global control options, as the constraints hold for all the regressions:

```
> indus.global <- list(adapt=T,max.gestation=3,max.lead=15,min.width=5,sign="+")
> indus.local <- list()
```

In alternative, one may specify only local control options, by repeating them for each regression:

```
> indus.global <- list()
> indus.local <- list(
+   adapt=c(Consum=T,Pollution=T),
+   max.gestation=list(Consum=c(Job=3),Pollution=c(Job=3,Consum=3)),
+   max.lead=list(Consum=c(Job=15),Pollution=c(Job=15,Consum=15)),
+   min.width=list(Consum=c(Job=5),Pollution=c(Job=5,Consum=5)),
+   sign=list(Consum=c(Job="+"),Pollution=c(Job="+",Consum="+"))
+ )
```

or both local and global control options:

```
> indus.global <- list(adapt=T,min.width=5)
> indus.local <- list(
+   max.gestation=list(Consum=c(Job=3),Pollution=c(Job=3,Consum=3)),
+   max.lead=list(Consum=c(Job=15),Pollution=c(Job=15,Consum=15)),
+   sign=list(Consum=c(Job="+"),Pollution=c(Job="+",Consum="+"))
+ )
```

4.3 Parameter estimation

Once the model code and control options are specified, parameter estimation can be performed using the command `dlsem(.)`. The user may indicate a single group factor (just one) to argument **group** and one or more exogenous variables to argument **exogenous**. By indicating the group factor, one intercept for each level of the group factor will be estimated in each regression, in order to explain the variability due to differences between groups. By indicating exogenous variables, they will be included as non-lagged

covariates in each regression, in order to eliminate cross-sectional spurious effects. Each exogenous variable may be either qualitative or quantitative and its coefficient in each regression is 0 for time lags greater than 0 (no lag shape). The user may decide to apply the logarithmic transformation to all strictly positive quantitative variables by setting argument `log` to `TRUE`, in order to interpret each coefficient as an elasticity (percentage increase in the value of the response variable for 1% increase in the value of a covariate). Before parameter estimation, differentiation is performed until the hypothesis of unit root is rejected by the Augmented Dickey-Fuller test for all quantitative variables⁴, and each missing value is replaced by its conditional mean computed through the Expectation-Maximization algorithm (Dempster *et al.*, 1977)⁵. In this problem, the region is indicated as the group factor, while population and gross domestic product are indicated as exogenous variables. Also, the logarithmic transformation is requested, and global and local control options are provided to arguments `global.control` and `local.control`, respectively:

```
> indus.mod <- dlsem(indus.code,group="Region",exogenous=c("Population","GDP"),
+ data=industry,global.control=indus.global,local.control=indus.local,log=T)
```

```
Checking unit roots ...
Order 2 differentiation performed
Starting estimation ...
Estimating regression 1/3 (Job)
Estimating regression 2/3 (Consum) ... 5%
Estimating regression 2/3 (Consum) ... 45%
Estimating regression 2/3 (Consum) ... 50%
Estimating regression 2/3 (Consum) ... 55%
Estimating regression 2/3 (Consum) ... 95%
Estimating regression 2/3 (Consum) ... 100%
Estimating regression 3/3 (Pollution) ... 5%
Estimating regression 3/3 (Pollution) ... 10%
Estimating regression 3/3 (Pollution) ... 15%
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Estimating regression 3/3 (Pollution) ... 80%
Estimating regression 3/3 (Pollution) ... 85%
Estimating regression 3/3 (Pollution) ... 90%
Estimating regression 3/3 (Pollution) ... 95%
Estimating regression 3/3 (Pollution) ... 100%
Estimation completed
```

The results of command `dlsem(.)` is an object of class `dlsem`. Among the components of `dlsem` objects, we found:

- `estimate`: a list of objects of class `lm`, one for each regression;
- `call`: a list containing the call for each regression after eventual adaptation of lag shapes;

⁴ If the group factor is specified, the panel version of the Augmented Dickey-Fuller test proposed by Levin *et al.* (2002) is used instead.

⁵ Qualitative variables cannot contain missing values. Each quantitative variable must have at least 3 observed values if the group factor is not specified, otherwise it must have at least 3 observed values per group.

- `model.code`: the model code after eventual adaptation of lag shapes;
- `data`: data after eventual logarithmic transformation and differentiation, which were used in the estimation.

The `summary` method for class `dlsem` returns the summary of the estimation:

```
> summary(indus.mod)
```

ENDOGENOUS PART

Response: Job

-

Response: Consum

	Estimate	Std. Error	t value	Pr(> t)
quec.lag(Job, 0, 5, Region)	0.08402506	0.03541094	2.372856	0.01845011 *

Response: Pollution

	Estimate	Std. Error	t value	Pr(> t)
quec.lag(Job, 2, 9, Region)	0.1653309	0.05421167	3.049729	2.607124e-03 **
quec.lag(Consum, 1, 7, Region)	0.2761310	0.06612504	4.175892	4.463789e-05 ***

EXOGENOUS PART

Response: Job

	Estimate	Std. Error	t value	Pr(> t)
Population	-2.736238	0.23492976	-11.64705	6.011303e-26 ***
GDP	-1.288838	0.04651619	-27.70729	3.188049e-83 ***

Response: Consum

	Estimate	Std. Error	t value	Pr(> t)
Population	0.8684730	0.21857798	3.973287	9.410625e-05 ***
GDP	-0.7978187	0.02946955	-27.072650	1.792218e-74 ***

Response: Pollution

	Estimate	Std. Error	t value	Pr(> t)
Population	-0.1699546	0.4631706	-0.3669374	7.140615e-01
GDP	0.1483852	0.0274912	5.3975538	1.938848e-07 ***

INTERCEPTS

Response: Job

	Estimate	Std. Error	t value	Pr(> t)
Region1	-0.0007181623	0.001584229	-0.45331977	0.6506599
Region2	-0.0002918816	0.001498658	-0.19476195	0.8457166
Region3	-0.0001845842	0.002708807	-0.06814224	0.9457197
Region4	-0.0010649837	0.001934211	-0.55060362	0.5823323
Region5	-0.0002115054	0.001271257	-0.16637509	0.8679785
Region6	0.0006350961	0.001426435	0.44523318	0.6564857
Region7	-0.0012157448	0.001979673	-0.61411409	0.5396247
Region8	0.0009839196	0.001967937	0.49997520	0.6174743
Region9	0.0004066387	0.001242299	0.32732749	0.7436580
Region10	0.0004527381	0.001309831	0.34564623	0.7298609

Response: Consum

	Estimate	Std. Error	t value	Pr(> t)
Region1	0.0009737983	0.0020635513	0.4719041	0.6374294
Region2	0.0001731643	0.0014820774	0.1168389	0.9070866
Region3	-0.0014935029	0.0020643222	-0.7234834	0.4700964
Region4	0.0006231951	0.0011688879	0.5331522	0.5944278
Region5	0.0016930324	0.0029976513	0.5647863	0.5727533

```

Region6  0.0005740860 0.0014307041  0.4012612 0.6885894
Region7  0.0010632512 0.0017084610  0.6223444 0.5343137
Region8 -0.0003392722 0.0009730119 -0.3486825 0.7276373
Region9 -0.0006974118 0.0017003595 -0.4101555 0.6820624
Region10 -0.0015422918 0.0023231782 -0.6638715 0.5074179

```

Response: Pollution

```

      Estimate Std. Error   t value Pr(>|t|)
Region1 -0.0013961766 0.002133362 -0.65444885 0.5135899
Region2 -0.0006181500 0.001684527 -0.36695770 0.7140464
Region3  0.0012771221 0.002426209  0.52638592 0.5992152
Region4 -0.0016716218 0.001497670 -1.11614842 0.2657251
Region5  0.0004357724 0.001047990  0.41581748 0.6779985
Region6 -0.0003959463 0.003556120 -0.11134224 0.9114589
Region7 -0.0007565788 0.001822874 -0.41504727 0.6785613
Region8  0.0005295859 0.002232830  0.23718152 0.8127637
Region9 -0.0005338554 0.001486462 -0.35914490 0.7198733
Region10 0.0001337096 0.001659112  0.08059108 0.9358494

```

ERRORS

```

      Std. Dev.  df
Job          0.01869265 288
Consum       0.01525950 237
Pollution   0.01392880 196

```

R-SQUARED

```

      Job      Consum Pollution (global)
0.8683767 0.8173357 0.3719263 0.7166416

```

We see that the number of job positions in industry (*Job*) significantly influences, on one hand, the amount of private consumption (*Consum*) from 0 to 4 time lags and, on the other hand, the amount of greenhouse gas emissions (*Pollution*) from 2 to 6 time lags, while the amount of private consumption (*Consum*) significantly influences the amount of greenhouse gas emissions (*Pollution*) from 1 to 5 time lags. This result provides evidence that the influence of industrial development on pollution is both direct and mediated by private consumption.

The `plot` method for class `dlsem` displays the DAG of the model where each edge is coloured with respect to the sign of the estimated causal effect (green: positive, red: negative, light gray: not statistically significant):

```
> plot(indus.mod)
```

The result is shown in Figure 3. Note that the DAG includes only the endogenous variables.

4.4 Assessment of causal effects

After parameter estimation is performed by means of command `dlsem()`, the command `causalEff()` can be used on the resulting object of class `dlsem` to compute all the pathwise causal lag shapes and the overall one connecting two variables. The main arguments of command `causalEff()` include the name of one or more variables generating the causal effect (argument `from`), and the name of the variable receiving the causal effect (argument `to`). Optionally, specific time to which computation should be focused may be provided to argument `lag`, otherwise the whole lag shapes will be considered. Cumulative causal effects may be returned by setting the argument `cumul` to `TRUE`. Only exogenous variables can be indicated as starting or ending variables. Note that, due to the properties of the multiple linear regression model, causal effects are net of the influence of the group factor and exogenous variables.

The cumulative causal effect of the number of job positions on the amount of greenhouse gas emissions may be obtained by means of the following code:

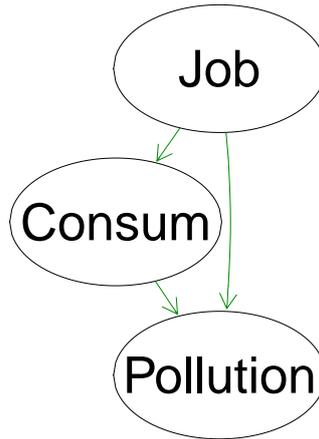


Figure 3: The DAG where each edge is coloured with respect to the sign of the estimated causal effect. Green: positive causal effect. Red: negative causal effect. Grey: not statistically significant causal effect (no such edges here).

```
> causalEff(indus.mod,from="Job",to="Pollution",cumul=T)
```

```
$`Job*Consum*Pollution`
      estimate  std. err.  lower 95%  upper 95%
0  0.000000000  0.000000000  0.000000000  0.000000000
1  0.004971841  0.002461622  0.000147151  0.009796532
2  0.021781400  0.006379617  0.009277581  0.034285219
3  0.056584289  0.011925956  0.033209845  0.079958734
4  0.112695070  0.018618448  0.076203583  0.149186557
5  0.188929970  0.025724937  0.138510021  0.239349920
6  0.278423114  0.032408759  0.214903114  0.341943114
7  0.367916258  0.037932610  0.293569708  0.442262808
8  0.444151159  0.041880887  0.362066129  0.526236189
9  0.500261939  0.044254117  0.413525464  0.586998414
10 0.535064829  0.045386736  0.446108461  0.624021196
11 0.551874387  0.045766753  0.462173199  0.641575575
12 0.556846229  0.045832906  0.467015383  0.646677074
13 0.556846229  0.045832906  0.467015383  0.646677074
```

```
$`Job*Pollution`
      estimate  std. err.  lower 95%  upper 95%
0  0.000000000  0.000000000  0.000000000  0.000000000
1  0.000000000  0.000000000  0.000000000  0.000000000
2  0.06531591  0.02141695  0.02333945  0.1072924
3  0.17961876  0.04316725  0.09501250  0.2642250
4  0.32657956  0.06469551  0.19977869  0.4533804
5  0.48986934  0.08397795  0.32527558  0.6544631
6  0.65315912  0.09959460  0.45795730  0.8483609
7  0.80011993  0.11063987  0.58326976  1.0169701
8  0.91442277  0.11681570  0.68546821  1.1433773
9  0.97973869  0.11876276  0.74696795  1.2125094
10 0.97973869  0.11876276  0.74696795  1.2125094
11 0.97973869  0.11876276  0.74696795  1.2125094
12 0.97973869  0.11876276  0.74696795  1.2125094
13 0.97973869  0.11876276  0.74696795  1.2125094
```

```
$overall
      estimate  std. err.  lower 95%  upper 95%
0  0.000000000  0.000000000  0.000000000  0.000000000
1  0.004971841  0.002461622  0.000147151  0.009796532
2  0.087097312  0.027413271  0.033368289  0.140826336
```

```

3  0.236203048 0.054891202 0.128618269 0.343787828
4  0.439274632 0.083171503 0.276261482 0.602287782
5  0.678799313 0.109546143 0.464092818 0.893505808
6  0.931582238 0.131782147 0.673293977 1.189870499
7  1.168036185 0.148246207 0.877478958 1.458593412
8  1.358573932 0.158200668 1.048506321 1.668641543
9  1.480000625 0.162181913 1.162129918 1.797871333
10 1.514803514 0.162494620 1.196319911 1.833287118
11 1.531613073 0.162601173 1.212920629 1.850305517
12 1.536584914 0.162619806 1.217855952 1.855313877
13 1.536584914 0.162619806 1.217855952 1.855313877

```

The output of command `causalEff(.)` is a list of matrices including point estimates and asymptotic confidence intervals for all the pathwise causal lag shapes and the overall one connecting the starting variables to the ending variable. Since the logarithmic transformation was applied to all quantitative variables, the resulting causal effects are interpreted as elasticities, that is, for a 1% of job positions more, greenhouse gas emissions are expected to grow by 0.61% after 5 years and by 1.11% after 10 years. The influence ends after 11 years, as the cumulative causal effects at 11 and 12 years are equal.

A pathwise or an overall causal lag shape can be displayed using the command `lagPlot(.)`. For instance, one may display the causal lag shape associated to each path connecting the number of job positions to the amount of greenhouse gas emissions:

```

> lagPlot(indus.mod,path="Job*Pollution")
> lagPlot(indus.mod,path="Job*Consum*Pollution")

```

or the overall causal lag shape of the number of job positions on the amount of greenhouse gas emissions:

```

> lagPlot(indus.mod,from="Job",to="Pollution")

```

The resulting graphics are shown in Figure 4. Note that a multi-edge pathwise causal lag shape is a mixture of different lag shapes, thus it may show an irregular aspect, like it is the case of the overall causal lag shape displayed in the lower panel of Figure 4.

4.5 Comparison among alternative models

We now fit two alternative models for the industrial development problem, such that all lag shapes are quadratic decreasing and gamma lag shapes, respectively.

```

> # model 2: quadratic decreasing lag shapes
> indus.code_2 <- list(
+   Job ~ 1,
+   Consum~qdec.lag(Job,0,15),
+   Pollution~qdec.lag(Job,0,15)+qdec.lag(Consum,0,15)
+ )
> indus.mod_2 <- dlsem(indus.code_2,group="Region",exogenous=c("Population","GDP"),
+   data=industry,global.control=indus.global,local.control=indus.local,log=T,quiet=T)
> summary(indus.mod_2)$endogenous

```

```

$Job
NULL

```

```

$Consum
              Estimate Std. Error  t value Pr(>|t|)
qdec.lag(Job, 0, 6, Region) 0.0672567 0.04076228 1.649974 0.1003313

```

```

$Pollution
              Estimate Std. Error  t value Pr(>|t|)
qdec.lag(Job, 2, 15, Region) 0.09367527 0.04805766 1.949227 0.05332646 .
qdec.lag(Consum, 1, 15, Region) 0.14377054 0.07513024 1.913617 0.05777026 .

```

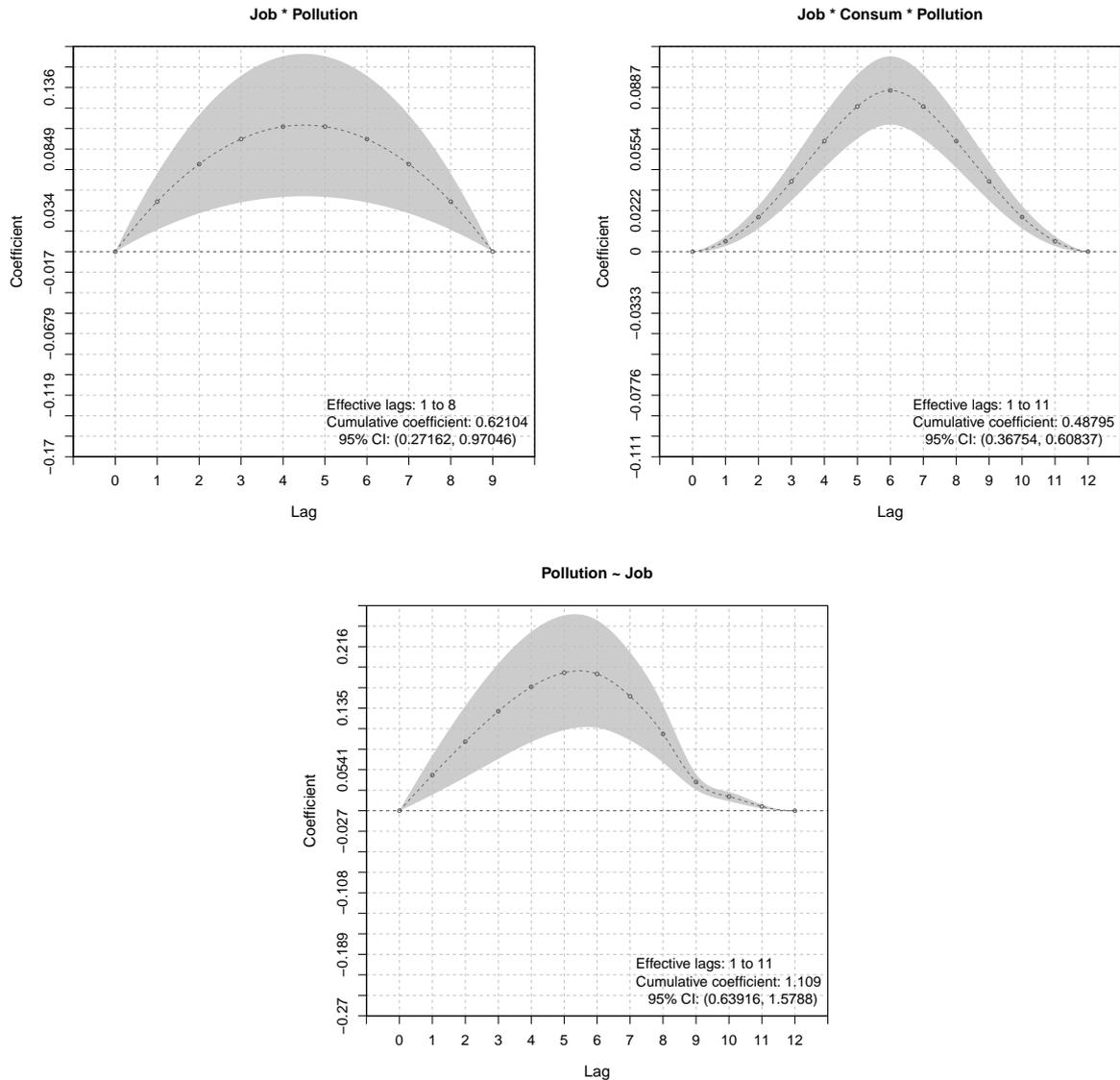


Figure 4: The pathwise causal lag shapes (upper panels) and the overall one (lower panel) connecting the number of job positions to the amount of greenhouse gas emissions. 95% asymptotic confidence intervals are shown in grey.

```
> # model 3: gamma lag shapes
> indus.code_3 <- list(
+   Job ~ 1,
+   Consum ~ gamm.lag(Job, 0.5, 0.5),
+   Pollution ~ gamm.lag(Job, 0.5, 0.5) + gamm.lag(Consum, 0.5, 0.5)
+ )
> indus.mod_3 <- dlsem(indus.code_3, group="Region", exogenous=c("Population", "GDP"),
+   data=industry, global.control=indus.global, local.control=indus.local, log=T, quiet=T)
> summary(indus.mod_3)$endogenous

$Job
NULL

$Consum
              Estimate Std. Error t value Pr(>|t|)
gamm.lag(Job, 0.7, 0.05, Region) 0.1203123 0.05434118 2.214017 0.02778018 *

$Pollution
```

	Estimate	Std. Error	t value	Pr(> t)
<code>gamm.lag(Job, 0.95, 0.05, Region)</code>	0.1172286	0.05290258	2.215934	2.835837e-02
<code>gamm.lag(Consum, 0.9, 0.15, Region)</code>	0.3460273	0.08228652	4.205152	4.703199e-05


```

gamm.lag(Job, 0.95, 0.05, Region)      *
gamm.lag(Consum, 0.9, 0.15, Region) ***

```

Here the option `quiet` was set to `TRUE` to suppress messages on the estimation progress. We see that the three models provide different results. Method `compareModels` can be used to compare them according to information criteria:

```

> compareModels(list(indus.mod, indus.mod_2, indus.mod_3))

```

	logLik	p	AIC	AICc	BIC
1	1628.355	39	-4881.437	-4874.562	-4755.705
2	1617.976	39	-4860.679	-4853.804	-4734.946
3	1625.748	39	-4876.222	-4869.348	-4750.490

The model with endpoint-constrained quadratic lag shapes has the lowest value of each information criterion, and thus the best fit to data. Note that information criteria for variable `Job` are the same in each model because it has no endogenous covariates.

5 Final remarks

Lag shapes included in the package may represent a large number of real-world lag structures, nevertheless new lag shapes with further specific features may be added in the future. Also, further functionalities for linear models for time series data are going to be implemented in the next releases.

Please, do not hesitate to contact me for suggestions, questions, feedbacks or bug reports.

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