

# An introduction to Synthetic Control Methods and their applications to climate change analysis

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## Abstract

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# 1 Introduction

**Lorem ipsum** SCM termed by Athey and Imbens (2017) as “arguably the most important innovation in the policy evaluation literature in the last 15 years”.

## 2 Synthetic Control Methods

Synthetic Control Methods (SCM) have been originally proposed in Abadie and Gardeazabal (2003) and by Abadie et al. (2010) to estimate the effects of aggregate interventions. The key idea behind the method is that, when units are a few aggregate entities, a better counterfactual than using any single unit can be derived by computing a combination of the untreated units that closely resembles the treated one, i.e. a “synthetic control”. The selection of the “donor units” is formalized with a data driven procedure. Although the method was originally intended for samples with few units, it has been successfully applied in contexts with large samples, for instance in Acemoglu et al. (2016). Such a synthetic control unit is computed as a weighted average of all potential comparison units that best resemble the treated units. In this section, I will introduce the method and explore feasibility, data requirements and methodological issues. The main references are Abadie and Gardeazabal (2003) and Abadie, Diamond and Hainmueller (2010), which introduced the method in the literature, and Abadie (2021), which provides a useful guide to the application of SCM.

### 2.1 Setting the method

Suppose to have data for  $j = 1, \dots, J + 1$  units, and suppose that unit  $j = 1$  is the treated unit. The “donor pool” of untreated units which will contribute to the construction of a synthetic control for unit  $j = 1$  is then constituted by the remaining  $j = 2, \dots, J + 1$  units. Assume that data covers  $T$  periods, with periods up to  $T_0$  being the pre-intervention observations.

For each unit  $j$  at time  $t$  data is available for the outcome of interest  $Y_{jt}$ , and for a number  $k$  of predictors  $X_{1j}, \dots, X_{kj}$ . Define the  $k \times 1$  vectors  $\mathbf{X}_1, \dots, \mathbf{X}_{J+1}$  which contain values of the predictors for units  $j = 1, \dots, J + 1$ . Define the  $k \times J$  matrix  $\mathbf{X}_0 = \mathbf{X}_2, \dots, \mathbf{X}_{J+1}$  which collects values of the predictors of the untreated units. For each unit  $j$ , define the potential outcome without treatment as  $Y_{jt}^N$ . For the treated unit  $j = 1$ , define the potential response under the treatment as  $Y_{jt}^I$  in the post treatment period  $t > T_0$ .

The effect of the intervention for the affected unit  $j = 1$  for  $t > T_0$  is:

$$\tau_{1t} = Y_{1t}^I - Y_{1t}^N$$

For the treated unit,  $Y_{1t}^I$  is observed so that  $Y_{1t} = Y_{1t}^I$ , but  $Y_{1t}^N$  is not. SCM provides a way to estimate  $Y_{1t}^N$  for  $t > T_0$ , that is, how the outcome of interest would have been in the absence of treatment. Notice that  $\tau_{1t}$  is allowed to change over time.

## 2.2 Estimation

A downside of comparative case studies lies in the attempt to select the control units by informally arguing for an affinity between the treated and the untreated before the intervention. However, when using data from aggregate units such as countries or regions, it can be difficult to find a proper counterfactual. SCM offers a formal procedure to select and combine the comparison units in order to create a scenario where unit  $j = 1$  was unaffected by treatment.

Define  $\mathbf{W} = w_2, \dots, w_{J+1}'$  as a  $J \times 1$  vector of nonnegative weights that sum to one. The  $\mathbf{W}$  vector attributes a weight to each unit in the donor pool  $j = 2, \dots, J + 1$  and characterizes its contribution to the synthetic unit.

For a set of weights,  $\mathbf{W}$ , the estimators of  $Y_{1t}^N$  and  $\tau_{1t}$  are:

$$\hat{Y}_{1t}^N = \sum_{j=2}^{J+1} w_j Y_{jt}$$

$$\hat{\tau}_{1t} = Y_{1t} - \hat{Y}_{1t}^N$$

Nonnegative weights ensure a convex combination of the donor units, so that the resulting control can be interpreted as a weighted average of the control units with typically sparse weights. Furthermore, it ensures comparability of the outcome variable by giving the synthetic control outcome the same scale of the intervention unit. Abadie (2021) notes that, when using weights that sum to one, variables in the data should be rescaled to correct for differences in size between the units, for instance by using per capita GDP instead of level GDP. This correction is not needed if variables are already comparable, for instance in the case of prices. Allowing for weights outside of the  $[0, 1]$  interval may provide a more accurate synthetic control by placing negative emphasis on some donor units that are dissimilar to the treated one. However, negative unbounded weights may introduce extrapolation, where the assigned weights are used to extrapolate beyond the observed

range of data to estimate the effect of treatment. This can lead to biased estimates and reduced precision, and makes the interpretation of weights less straightforward.

The core of the SCM estimation lies in the definition of the weights. The approach in Abadie et al. (2021) is to optimize the weights with the aim of minimizing the distance between the treatment and control group in the pre-treatment period. Given the nonnegative constant vector  $\mathbf{V} = (v_1, \dots, v_k)$  that represent the relative importance of the  $k$  predictors, the optimal weight vector  $\mathbf{W}^*$  is the one that minimizes:

$$\|\mathbf{X}_1 - \mathbf{X}_0 \mathbf{W}\| = \left( \sum_{h=1}^k v_h (X_{h1} - w_2 X_{h2} - \dots - w_{J+1} X_{hJ+1})^2 \right)^{1/2}$$

Subject to  $\sum_{j=2}^{J+1} w_j$  and  $w_j \geq 0$ . That is, minimizing the distance between the treated unit  $\mathbf{X}_1$  and the weighted combination of the control units  $\mathbf{X}_0 \mathbf{W}$ . The output  $\mathbf{W}^* = (w_2^*, \dots, w_{J+1}^*)'$  is used in the estimation of the treatment effect for the treated unit across  $t = T_0 + 1, \dots, T$  as:

$$\hat{\tau}_{1t} = Y_{1t} - \sum_{j=2}^{J+1} w_j^* Y_{jt}$$

Any possible choice of weights in  $\mathbf{V}$  produces a different set of optimal weights, which is effectively a different synthetic control  $\mathbf{W}(\mathbf{V}) = (w_2(\mathbf{V}), \dots, w_{J+1}(\mathbf{V}))'$ . For this reason the choice of  $\mathbf{V}$  is a key issue. An initial approach could be to divide the predictor weights equally across the  $k$  predictors included in the model. However, two more elegant solutions are proposed by the authors.

A first proposed solution is to choose  $\mathbf{V}$  such that the synthetic control  $\mathbf{W}(\mathbf{V})$  minimizes the mean squared prediction error (MSPE) of the synthetic control with respect to  $Y_{1t}^N$  over the pre treatment period  $\mathcal{T}_0 = 1, \dots, T_0$ :

$$\sum_{t \in \mathcal{T}} (Y_{1t} - w_2(\mathbf{V}) Y_{2t} - \dots - w_{J+1}(\mathbf{V}) Y_{J+1t})^2$$

Another solution is out-of-sample validation, which requires substantial pre treatment observations. This path exploits the observed pre treatment  $Y_{1t}^N$  to gauge the predictive power of the variables  $X_{1j}, \dots, X_{kj}$  and assign coherent weights  $\mathbf{V}$ . To use out-of-sample validation start by dividing the  $\mathcal{T}_0$  period in a *training* period and a *validation* period. The lengths of the two periods may depend on data availability and frequency of measurement of outputs and variables. Then, for every value  $\mathbf{V}$ , compute the synthetic

control weights on the training period and call them  $\tilde{w}_2(V), \dots, \tilde{w}_{J+1}(V)$ . The MSPE over the validation period will be:

$$\sum_{t=t_1+1}^{T_0} (Y_{1t} - \tilde{w}_2(V)Y_{2t} - \dots - \tilde{w}_{J+1}(V)Y_{J+1t})^2$$

Then, compute  $\mathbf{V}^* \in \mathcal{V}$  such that MSPE is minimized, with  $\mathcal{V}$  being the set of all potential  $\mathbf{V}$ . Then, check the synthetic control's ability to emulate the treated unit behavior on the remaining validation period observations by using  $\mathcal{V}^*$  to compute  $\mathcal{W}^* = \mathcal{W}(\mathbf{V})^*$ .

For an analysis of the shortcomings of cross-validation as defined in this section, see subsection 2.3.

### 2.2.1 Bias properties of SCM

Appendix B of Abadie et al. (2010) provides an analysis of the bias properties of synthetic control estimators in the case of a linear factor model and a vector autoregressive (VAR) model. According to their findings, the estimator's bias in a factor model scenario can be constrained by a function that goes to zero as the amount of pre-treatment periods increases. In an VAR scenario, the synthetic control estimator is unbiased.

maybe add something more detailed if you have time

### 2.2.2 Inference in SCM

Complete!!!

## 2.3 A detour on methodological advantages

SCM come with advantages relative to other competing methods. In this subsection, these features are emphasized with respect to linear regression estimators.

*Transparency and goodness of fit.* While both synthetic control estimation and regression estimators are applied to panel data, SCM are transparent relative to the discrepancy between the treated unit and the synthetic unit. Furthermore, the goodness of fit of the synthetic control unit can be easily evaluated through analysis of the pre treatment period. SCM should not be used if the fit in the pre treatment period is not satisfactory.

*Extrapolation prevention.* Another advantage of synthetic controls comes from the restrictions placed on the weights, which prevent extrapolation.

Instead, regression weights may lie outside of the  $[0, 1]$  interval (for a comparison of the outcomes of SCM and regression see Abadie, Diamond and Hainmueller (2015)).

*No need for post-treatment outcomes.* Synthetic control weights can be computed before the observation of post-treatment outcomes. **EXPAND**

*Weight sparsity.* When estimating weights for the control group, regression estimators typically provide non zero weights to all control units. Instead, sythetic control weights are sparse. The contribution of each donor unit is straightforward and allows for a geometric interpretation of the sparse weights: the sythetic unit represents a point that lies in the convex hull generated by the donor units with non zero weights. Note that with many treated units the weights are not necessarily unique nor that sparse. Abadie and L'Hour (2019) offers a penalized version of SCM that provides unique and sparse weights under some conditions.

## 2.4 Contextual and data requirements for a credible application

Most of the data and contextual requirements for successfull application of SCM are applicable to any other comparative case study. Following Abadie (2021), I will start from contextual requirements, and eventually move on to data requirements.

### 2.4.1 Contextual requirements

The first observation is on the volatility of outcomes. Excessive random noise in the outcome variable increases the likelihood of over-fitting, therefore it is advised to filter out such noise before implementation, otherwise the effect of treatment may be drowned out. This concern does not come from common volatility between the units, but from unit specific volatility.

The second observation pertains to the donor pool. For a unit to be a suitable candidate of the donor units, it should not be affected by or subject to the treatment provided to the unit of interest, and it should have common features with the treated unit (typically, units in a similar region and/or context). This entails the elimination from the donor pool of any unit which may have suffered a shock to the outcome that would not have happened in the absence of treatment in unit of interest.

**add reflection on climate change shocks usually being common shocks**

Third, a typical concern is anticipatory behavior by the units which would introduce bias in the SCM estimates. Depending on data availability, a solution would be to backdate the period that marks the start of treatment.



Since SCM allow for differential exposure to treatment across time, the initial periods that are barely affected by treatment may show very small effects, whereas the subsequent periods will show larger effects.

Spillover effects are another point of concern that stems from the selection of an ideal donor unit. Usually, a donor unit is valid if it has common features with the treated one, while also being unaffected by the shock. As a consequence, donor units tend to come from the same regions or be exposed to the same context. Spillover effects are especially an issue if units come from the same geographical area. In order to understand the bias introduced by interference, the researcher may carry out and compare the estimates with and without the affected donor units. Moreover, due to the transparency of the synthetic counterfactual and the sparsity of weights, the researcher may reason as to the potential direction of the bias and account for that in their analysis.

#### **2.4.2 Data requirements**

For the method to accurately and credibly track the treated unit there must be availability of a window of pre-treatment observations from all units. Using large periods of time may present the issue of structural breaks in the pre-treatment window, affecting the structural stability of the model. Accuracy of prediction may suffer if we add enough observations, thus the predictive ability of the synthetic control fails.

Extensive post-treatment information is crucial for the evaluation of the effects, especially if they are expected to intensify or dissipate over time.

### **2.5 Issues and solutions for successful application**

Similar to any other technique, the application of synthetic controls demands careful consideration of the proper data and contextual prerequisites that must be fulfilled, along with fulfilling the required conditions for its use to claim a causal explanation of outcomes. Various features are currently being debated and enhanced in the literature, while some areas remain unexplored. For instance, such an area is the investigation of computational aspects, which is still relatively under-researched and holds significant potential for improvement.

An important note must be made about the validation weights, as noted by Klößner et al. (2018). Predictor weights are not necessarily uniquely defined, so that when replicating Abadie et al. (2015), the authors find different yet equivalent solutions for the weights depending on the software

package used (STATA versus R) and on the specific donor units ordering (alphabetical versus custom) when using out-of-sample validation.

- numerical instability - see Kuosmanen 2021:1 and 2021:2 in OSE JDX mafia project

### **3 Applying SCM to climate change analysis**

inizia con riflessione sulle implicazioni della parte DATA E CONTEXT REQUIREMENTS per le applicazioni allo studio del cambiamento climatico

### **4 Literature review and general applications in macro**

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### **5 Potential applications to Fleurbeay project**

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### **6 Data sourcing and explanations**

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### **7 Conclusion**

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