The Impact of the Accident on Sayano-Shushenskaya Dam: an Application of Synthetic Control Method

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Abstract

The aim of this paper is to investigate an economic impact of the technological accident happened in 2009 on Sayano-Shushenskaya hydroelectric power station on Khakassia, the region where this dam is located. In order to conduct it, the synthetic control method, first introduced by Abadie and Gadeazabal (2003), was applied. The disaster on Sayano-Shushenskaya dam is the most significant disaster that happened recently on hydroelectric station in Russia and caused deaths of the workers, economic and energetic losses, and ecological consequences. However, in this research, it was discovered that this catastrophe had a positive non-significant influence on Gross Regional Product (GRP) per capita of Khakassia. Such economic effect could be explained by a specific of this technological disaster, an inflow of investments and a good coordination of emergency operations.

Keywords: Sayano-Shushenskaya Dam, Synthetic Control Method, Khakassia, Economic Effect.

JEL: C20, O13, Q40.

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1. Introduction

Technological disaster is known as an accident, which emerges because of a breakage in technology system or a human error in its control. Such type of a disaster can be considered as one of the most dangerous and destructive accidents in a modern world, which can lead to social, economic and ecological consequences. Therefore, there is an assumption that technological catastrophes have negative effect on the economy. In many cases, such accidents are largescale and happen suddenly, so they can cause great losses quickly.

Because of the all stated above, technological disasters should receive a substantial attention from the government and researchers. However, much greater number of investigations were made about an economic impact of the other type of the disasters, in particular, natural disasters. Technological disasters, in their turn, and their influence on the economy were not studied sufficiently.

This research studies the economic effect of a technological disaster, particularly, the accident that happened on Sayano-Shushenskaya hydroelectric power station in 2009 and its influence on the economic growth of Khakassia, one of the Russian regions, where the dam is located. It is especially worth to study because Sayano-Shushenskaya dam is the most powerful hydroelectric power station in Russian Federation and one of the most powerful hydroelectric power stations in the world[1]. Moreover, the catastrophe on Sayano-Shushenskaya dam is the largest disaster that happened on hydroelectric station in modern Russia (Ismagilov, 2010). The facts mentioned above can be considered as the reasons to choose this technological accident for the work.

Consequently, the purpose of this study is to evaluate an impact of the accident on Sayano-Shushenskaya dam on the economic growth of Khakassia. The analysis is performed by observing the economy of Khakassia in a situation, when this technological disaster did not happen. In order to conduct it, the synthetic control method, which was applied in many recent researches that studied events on aggregate level, is used. In addition, the Gross Regional Product (GRP) per capita was chosen as an indicator that measures the regional economic growth. In this way, an economic effect of this accident can be estimated by the difference in the GRP per capita outcomes of the "real" Khakassia and the "synthetic" Khakassia, represented by the constructed synthetic control.

This study contributes to the literature by evaluation of economic consequences of the technological disaster because an influence on the economy of such type of disasters was not investigated enough. Moreover, this research is the first application of the synthetic control method to estimate an impact of the accident happened on Sayano-Shushenskaya hydroelectric power station on the regional economy.

[1] See JSC "Rushydro", Sayano-Shushenskiy branch, "General information".

The research is organized in a following way. The next section introduces a general review on the literature about technological disasters and its influence on economy. Section 3 provides an information about Sayano-Shushenskaya dam characteristics and a comprehensive description of the technological disaster happened on there in 2009 and its consequences. Section 4 presents an overview of the literature about the synthetic control method that forms the theoretical background of this paper. Section 5 represents an empirical strategy and the results of the investigation obtained. Finally, the findings are discussed and the conclusions are made.

2. Technological disasters

There does not exist any general definition of “disaster” because a form and a content of the definition depends on the sphere, where it should be used. One of the definitions was provided by Turner and Pedgeon (1997). According to these researchers, an accident is considered as a disaster in such case, when one or several of the criteria are met: an accident should be extremely unpredicted, large, public or costly (Turner, Pedgeon, 1997).

There is a classification of disasters on natural and man-made (Ibrahim, et al., 2003, p. 305). It is well known that natural processes on Earth, for instance, earthquakes, floods, hurricanes and wildfires are natural disasters. On the contrast, man-made disasters are caused by the activity of people.

Man-made disasters, in turn, are divided on socio-technical and warfare (Ibrahim, et al., 2003, p. 305). Socio-technical disasters occur on a base of plant, factory, transport and other production accidents. Major accidents that happen on major hazard installations and are considered as technological disasters (Ibrahim, et al., 2003, p. 305). In most of the cases, such disasters happen due to human errors in managing of technological systems or its breakdown. Apparently, an impact of technological disasters is not limited by installations; it can easily spread to surroundings and environment.

Technological disaster should receive a considerable attention from different authorities and researchers because nowadays many significant disasters of such type happen all around the world. For instance, according to the statistics provided by the report of European Environment Agency, in Europe, in a period from 1998 to 2009, occurred 10 major oil spills in coastal areas, 4 toxic spills from mining activity and happened 339 major industrial accidents that were registered under the MARS (Major Accident Reporting System)[2].

According to the all stated above, the accident happened on Sayano-Shushenskaya hydroelectric power station can be denoted as a technological disaster. The reason for it is that the catastrophe on the dam is a major accident that occurred on an electric power station, a human-made installation.

[2] See European Environmental Agency, Mapping the impacts of natural hazards and technological accidents in Europe, EEA Technical report 13, 2010.

An accomplishment of sustainable economic growth is a goal for most of the countries in a modern world. According to Solow (1999) neo-classical growth model, by analyzing shift from a steady state of the economy, it is possible to foresee that the economic growth is influenced by a destruction of capital. It is common that a quite significant destruction of physical and human capital is caused by a unexpected shock situation. For instance, natural or man-made disaster can be considered as a shock for the economy that leads to a capital destruction and probably has an influence on the economy.

Many researchers have already conducted investigations about an impact of natural disasters on economic growth. However, not many researches were made about the consequences of technological disasters on the economy. Furthermore, most of the researches consider an influence of certain technological disaster on the economy but the minority of them analyzes an economic effect of technological disasters in general.

The work that examined a general impact of different types of disasters on economic growth is the research of Sawada, Bhattcharyay and Tomoaki (2011). The authors used a cross-country panel data for 189 countries for the period from 1968 to 2001 to evaluate an influence of various natural and man-made disasters on per capita GDP growth rate and per capita consumption growth rate in a short-term and a long-term separately (Sawada et al., 2011). By this separation, it was feasible to take into account direct costs of the disaster and indirect losses that the economy could have in the future. The authors obtained an empirical evidence that technological disasters have short-term significant negative welfare influence (a decrease in per capita GDP growth rate) and do not have a long-term welfare influence. Moreover, on the grounds of Noy (2009), the authors investigated the differentiated effect of disasters with a regard to diverse size of economies, particularly, large or small economies. The significant negative effect of technological disasters on economic growth was obtained for large economies but not for small economies. Probably, this result is connected with a higher concentration of technology and industrial installations in large economies, as well as its stronger involvement in the economy.

In addition, it is necessary to mention the study of Halkos, Manadi and Tzeremes (2015) that investigated the effect of disasters (both natural and mad-made) on production efficiency in number of countries. Moreover, the authors evaluated an influence of disasters on low-income and high-income countries separately. The sample of 137 countries, including countries with different levels of income, was examined in a period from 1980 to 2011. The authors attained the result that the low number of disasters had a positive effect on countries' production efficiency because of potential investments that it could promote. However, after a specific number of disasters, there appeared a negative impact of disasters. Moreover, low-income countries were influenced by disasters more rapidly than high-income countries. Finally, the authors found that a negative influence of disasters arose first in an efficiency and after in a level of technological change (Halkos et al., 2015).

The other more specific study of Ando (2013) investigated, how recent disasters in Japan affected changes in its export. Among other disasters, the author analyzed the consequences of the most well-known recent technological disaster in Japan, Fukushima nuclear accident happened in 2011. In order to perform the investigation, the decomposition approach was applied. Moreover, the study recorded short-term changes in a trade, particularly, it was focused on monthly changes. The results obtained by the researcher showed quite significant negative impact of the nuclear accident on the number of exported products, which affected a trade (Ando, 2013). This effect could be explained by the safety trade regulations, which were established by several countries, the partners of Japan.

The other work that examined an influence of nuclear accident on the economy is the research of Konovalchuk (2006). In particular, the author investigated the long-term economic impacts of Chernobyl nuclear accident that happened in 1986 on Ukrainian economy. For example, changes in consumption, supply, prices, investments, import and other economic indicators were analyzed. In order to evaluate these effects, Computable General Equilibrium (CGE) modeling was applied. According to the results obtained by the author, the disaster had a negative influence on sectoral production and increased prices. The effect of Chernobyl accident had impacts of different extent with regards to the sector and its sensibility (Konovalchuk, 2006). These results can be explained by a peculiar economic patterns and the way how each sector utilized capital and labor that was damaged by the disaster.

There is no doubt that researchers analyzed not only an impact of nuclear technological disasters on economy. For instance, the study of Garza-Gil et al. (2006) evaluated economic losses from Prestige oil spill. This oil spill emerged because tanker "Prestige" sank off near the coast of Galicia in 2002. The authors of this article examined short-term economic effects of the spill on Galician fishing sector. The results, obtained by the authors, showed that there was a quite significant negative short-term economic effect of the oil spill disaster on fishing production, income and added value (Garza-Gil et al., 2006).

It can be assumed that the reason for the existence of not many studies that investigate technological disasters is that technological disasters happen less frequently in the world than natural disasters. For instance, Table 1 presents an overview of natural and technological disasters occurred in Europe in 1998-2009 according to European Environmental Agency and the losses caused by these disasters.

It could be noticed that, during this period, there happened two times more natural disasters than technological disasters that entailed not comparably greater number of fatalities. In addition, as it can be noticed from the Table, it is complicated to estimate the losses from technological disasters. For instance, losses from oil spills or toxic blowouts in the air are less evident than losses from a storm or flood.

Table 1. Overview of disasters in Europe from 1998 to 2009.

Hazard type	Recorded events	Number of fatalities	Overall losses (EUR billion)
Storm	155	729	44.338
Extreme temperature events	101	77 551	9.962
Forest fires	35	191	6.917
Drought	8	0	4.940
Flood	213	1 126	52.173
Snow avalanche	8	130	0.742
Landslide	9	212	0.551
Earthquake	46	18 864	29.205
Volcano	1	0	0.004
Oil spills	9	n/a	No comprehensive data available (a)
Industrial accidents	339	169	No comprehensive data available (b)
Toxic spills	4	n/a	No comprehensive data available (c)
Total	**928**	**98 972**	**148.831**

Source: European Environmental Agency, Mapping the impacts of natural hazards and technological accidents in Europe, EEA Technical report 13, 2010.

Moreover, many natural disasters are caused by certain climate and geographical characteristics of a place of origin and can reiterate in this place more times. On the contrary, technological disasters are extremely diversified, have different origins and are not connected with specific conditions of a place. Therefore, in many studies, technological disasters were investigated with many details that should be taken into account.

Furthermore, a lack of studies about an impact of technological disasters on economy of a country or region can be connected with a difficulty to find an appropriate comparison unit to estimate the actual difference, which is considered as a loss caused by the disaster. This issue is connected with numerous unique characteristics of a region or a country, which are not reproduced by an only one comparison unit. However, a suitable comparison unit can facilitate to observe the economic development of a country or a region without an effect of the disaster. The synthetic control method, which is applied in this research, contributes to solve the problem of a suitable comparison unit. In Section 4 of this paper, this method and its theoretical background are described in a more comprehensive way.

3. The accident on Sayano-Shushenskaya hydroelectric power station

Sayano-Shushenskaya dam is considered as the most powerful hydroelectric power station in Russian Federation and one of the most powerful hydroelectric power stations in the world[3]. In

[3] See JSC “Rushydro”, Sayano-Shushenskiy branch, “General information.”

particular, it has a total installed capacity of 6400 Megawatts. Table 2 presents the characteristics of the world's most powerful hydroelectric stations, including Sayano-Shushenskaya dam.

Table 2. The most powerful hydroelectric power stations in the world and their capacity.

Hydroelectric power station	Country	River	Capacity, Megawatts
Three Gorges	China	Yangtze	18 200
Itaipu	Brazil	Parana	12 600
Guri 2	Venezuela	Caroni	10 300
Tukirui	Brazil	Tocantins	8 000
Grand Coulee	USA	Colombia	10 830
Sayano-Shushenskaya	Russian Federation	Enisey	6 400
Krasnoyarskaya	Russian Federation	Enisey	6 000

Source: Fortov et al. (2011)

Sayano-Shushenskaya station complex consists of Sayano-Shushenskaya dam, counter regulating Maynskaya dam, located downstream on the river Enisey, and the shore spillway. Sayano-Shushenskaya dam consists of 10 hydraulic units with capacity of 640 Megawatts each respectively.

Sayano-Shushenskaya hydroelectric power station is placed on river Enisey in Siberia, specifically, in the southeast of Khakassia, on its border with the other region, Krasnoyarskiy Krai. Figure 1 shows an exact location of Sayano-Shushenskaya dam on the map of Russian Federation.

Figure 1. Location of Sayano-Shushenskaya dam on the map of Russia.

Source: Safety at risk, "The accident that destroyed the largest Russian hydroelectric power station caused more than 70 deaths -17.08.2009".

It should be noted that Sayano-Shushenskaya dam is the most powerful source of peak load coverage in the energy system of Siberia. The main consumers of electricity from the station are various plants in Khakassia and nearby regions, such as aluminum plants in Sayanogorsk, Krasnoyarsk and Novokuznetsk, and Kuznetsk ferroalloy plant[4].

It took several years to build Sayano-Shushenskaya dam. The suitable place for building Sayano-Shushenskaya hydroelectric power station was chosen in 1961[5]. In 1975, Enisey was overlapped. The dam was put into operation in 1978, when the first hydraulic unit was launched. The last tenth hydraulic unit was launched only after 7 years, in 1985.

Sayano-Shushenskaya station is owned by JSC "Rushydro". The government of Russian Federation holds the majority of shares of this company. It should be noted that "Rushydro"is a company that owns several hydroelectric power stations in the other Russian regions.

The technological disaster on Sayano-Shushenskaya hydroelectric power station happened on August 17, 2009. It is considered as the largest hydroelectric power station catastrophe in the history of modern Russia (Ismagilov, 2010).

Before the accident, the dam worked in automatic control mode. The disaster happened in the second hydraulic unit, which was put into operation in automatic control the day before, on August 16. During several hours before the accident, the hydraulic unit experienced an increased level of dynamic loads and vibrations. At the time of the catastrophe, there was an avalanche-like enhancement in vibrations that led to weakening of a turbine cover fixation (Fortov et al., 2011). Thereafter, the hydraulic unit pulled away and was pushed out from its shaft by the water pressure. A column of water broke out from the shaft and led to destruction of the engine room roof, flood in the room with electro-technical equipment and electrical short in the other units (Fortov et al., 2011).

Numerous expert judgments and several commissions propounded and analyzed different potential reasons of the catastrophe. Many versions that substantiated the reason of this accident were formulated. Ultimately, the main technical reasons of the disaster on Sayano-Shushenskaya station were (Fortov et al., 2011):

- The work of hydraulic unit with frequent transitions thought zones with not recommended loads;
- Continuous exploitation of the hydraulic unit with unacceptably high vibrations;

[4] See JSC "Rushydro", Sayano-Shushenskiy branch, "General information."

[5] See JSC "Rushydro", Sayano-Shushenskiy branch, "History of building of Sayano-Shushenskaya hydroelectric power station."

- High pressure on the cover of turbine that surpassed bearing capacity of the turbine cover fixation.

In order to conduct the emergency operations, around 2700 people were involved and more than 200 units of equipment were used (including 11 planes and 15 boats)[6]. During the first hours of the accident liquidation, with the participation of the station workers and contracted workers, emergency gates of hydraulic units were closed and an entry of water to the engine room was stopped. Thereafter, the gates of the spillway dam were opened. Before it was finished, the regulation of the river was conducted by Maynskaya dam.

Considering economic and energetic losses, and a harm inflicted to national interests, the technological disaster on Sayano-Shushenskaya hydroelectric power station can be compared to the catastrophe on Chernobyl nuclear power plant (Ismagilov, 2010).

Because of the catastrophe on Sayano-Shushenskaya dam 75 workers, who were there at the time of the accident, were dead and 13 workers were injured (Ismagilov, 2010). Moreover, a large amount of electro energy was lost during the time of the accident and its liquidation, specifically, 6,4 Gigawatts of energy capacity were forfeited. Likewise, a work of the dam was stopped during the reconstruction, so a considerable quantity of electro energy was wasted. Particularly, the estimated value of non-produced and non-realized electro energy was 50 billion of rubbles (Ismagilov, 2010).

According to Novak A., a vice Minister of Finance in Russia, it was estimated that several years and 40 billion of rubbles were required to conduct a reconstruction of Sayano-Shushenskaya dam.[7] However, the reconstruction of Sayano-Shushenskaya station was not financed by federal budget; it was subsidized by an investment program of JSC “Rushydro”.[8] Therefore, the proprietor of the dam, JSC “Rushydro”, incurred most of the economic losses.

An only part of Sayano-Shushenskaya hydroelectric power station that was financed from the federal budget was the shore spillway, which was built from 2005 to 2011 and was not affected by the accident[9]. After the catastrophe, the building of shore spillway was speeded up, in order to mitigate the risk of extreme spring flood in the conditions of limited throughput capacity of the dam.

It is necessary to mention the ecological consequences of the accident on Sayano-Shushenskaya hydroelectric power station. Because of the disaster, a large amount of technical oil from the engine room of the station got into the river Enisey and formed oil spills on its surface (Kretov, 2009). Commonly, the oil was used in Sayano-Shushenskaya dam in order to cool the hydraulic units. The river

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[6] See JSC “Rushydro”, Sayano-Shushenskiy branch, “The accident.”

[7] See Ministry of Finance of Russian Federation, Press center, “Comments of Novak A. to news agencies on the meeting about a liquidation of consequences of the accident on Sayano-Shushenskaya hydroelectric power station.”

[8] See JSC “Rushydro”, Sayano-Shushenskiy branch, “Questions and answers.”

[9] See JSC “Rushydro”, Sayano-Shushenskiy branch, “Questions and answers.”

and an industrial area of the station were cleaned from technical oil and its spills by the work of a specific division of JSC "Transneft", the company that specializes on oil transportation. As a result, the workers collected 324 tons of oil liquids[10] and finished the work on August 28th.

It took five years to carry out the reconstruction of Sayano-Shushenskaya station. In 2010, the first stage of the reconstruction was finished. As a result, the four less affected hydraulic units were repaired and launched. The accelerated repair of several hydraulic units facilitated a resumption of electro energy generation in a quite short time. During the second stage of the reconstruction, which lasted from 2011 to 2013, the new five hydraulic units were put into operation. Finally, at the time of the third stage of the reconstruction from 2013 to 2014, the four hydraulic units, which were repaired during the first stage, were replaced on the new ones[11]. Moreover, the second hydraulic unit, which was the most affected unit by the accident, was replaced on the new one. Besides the replacement of the hydraulic units, the other equipment (including equipment that was not affected by the accident but that was old and worn out) was also renewed[12].

4. Synthetic control method

4.1 Related literature

Generally, the synthetic control method is applied to investigate a potential effect of the considered treatment on units in aggregate form, like countries, regions or cities. As it was already discussed above, for units in such form, it is complicated to determine a suitable single comparison unit. In order to solve this issue, synthetic control method proposes to compare the change in the outcome of the aggregate treated unit to the change in the outcome of the best suitable combination of several comparison units within the control group. Comparing to traditional methods of regression, the synthetic control method is transparent and safeguard against extrapolation because it is a weighted average of the control units with positive weights, which are sum to one (Abadie et al., 2010, p. 494). Moreover, selection of control units that can form a synthetic control does not involve researchers to examine post-intervention result and its influence on the conclusions, this work is performed by a computer algorithm. In this case, the researches are made in a more conscientious manner.

Abadie and Gadeazabal (2003) were first, who introduced this method. In their article, the synthetic control method was used to estimate an impact of conflict caused by terrorists on the economy of Basque Country. In this case, the synthetic control method was applied because the characteristics that were related to economic growth in the Basque Country were different from other Spanish regions

[10] See JSC "Rushydro", Sayano-Shushenskiy branch, "The accident."

[11] See JSC "Rushydro", Sayano-Shushenskiy branch, "Reconstruction of the station."

[12] See JSC "Rushydro", Sayano-Shushenskiy branch, "Reconstruction of the station."

characteristics (Abadie, Gadeazabal, 2003). Hence, there was no any Spanish region that could be considered as a suitable comparison unit for the Basque Country. Therefore, the two Spanish regions, Catalonia and Madrid were selected as the most suitable combination to form the synthetic control because of their pre-terrorism characteristics that were quite comparable to the Basque Country. The discovered influence was verified by placebo test. In order to perform this test, the authors chose Catalonia, the region that had the largest weight in the synthetic control.

Based on the previous research, Abadie et al. (2010) studied an implementation of the synthetic control method to comparative case studies, particularly, to the effects of Proposition 99, a tobacco control program in California. Despite the fact that the analysis of comparative case studies is complicated because of inferential challenges and uncertainty connected with the selection of suitable control groups, the applicability of the synthetic control method to comparative case studies was proved (Abadie et al., 2010, p. 503). Moreover, by the application of new inferential methods, the authors showed that the obtained estimates were significant. Specifically, the authors performed several placebo studies by implementation of the synthetic control method to the other states in USA. Furthermore, the authors rendered the software, which was used in their research, in order to conduct the evaluation. In addition, it needs to be noticed that the articles of Abadie and Gadeazabal (2003) and Abadie et al. (2010) show that it is possible to perform unbiased estimations by an application of the synthetic control method on a data with not many pre-intervention observations.

The work of Abadie et al. (2015) studies an application of the synthetic control method as a connector of quantitative and qualitative approaches to empirical research in political science (Abadie et al., 2015, p. 495). The authors considered how this method could be implemented, in order to simplify and complement comparative case studies (Abadie et al. 2015, p. 508). Specifically, the authors used the synthetic control method to conduct evaluation of an influence of the German reunification that happened in 1990 on the economy. The authors made a conclusion that this method provided systematization, which enabled to make accurate quantitative conclusions in comparative researches conducted in small samples. Moreover, the method made it easier to conduct comprehensive qualitative analysis and compare treated unit with the comparison units because the units, which were utilized in a synthetic control, were clearly indicated.

More recently published works confirmed that synthetic control method is one of the few methods, which can be used in numerous applications on aggregate (national or regional) level. In particular, Munasib and Rickman (2015) used the method to investigate the effects of atypical oil and gas production in several states and Grier and Maynard (2016) estimated an impact of national leader on the economy of Venezuela. Likewise, Gharehgozli (2017) applied the synthetic control method to analyze an influence of international sanctions on the economic development of Iran. In addition, Albalate and Bel (2020) used synthetic control method to evaluate, how government formation deadlock affected the economy of Belgium.

Therefore, the same method could be applied to estimate the effect of the technological disaster happened on Sayano-Shushenskaya hydroelectric power station in 2009 on the economic development of Khakassia, the region, where the dam is located. In order to analyze an economic impact of the accident on Khakassia, the "synthetic" Khakassia could be constructed and compared with the "real" Khakassia. In the next part of this section, a methodology of the synthetic control will be described in a more formal way.

4.2 Methodology

On the grounds of Abadie et al. (2015) article, the methodology is formulated for only one unit treated by the event. Let us consider the sample of J +1 units (in this case, Russian regions), where each unit of the sample is assigned an index j. Suppose that the unit j =1 is the treated unit or Khakassia and units from j =2 to j = J +1 are selected potential comparison units (the donor pool) or the other Russian regions. These units should fit the counterfactual of the treated unit without intervention, so the regions in the donor pool should have the same outcomes (Abadie et al., 2015). Moreover, the regions that were affected by the similar event, in this case, any significant accident with the similar losses, should be eliminated from the donor pool. Therefore, in this application of the synthetic control method, the treated unit will be Khakassia whose economic development was probably influenced by the technological accident on Sayano-Shushenskaya dam in 2009 and the donor pool will be the sample of the other Russian regions, where no any similar significant accident occurred from 1998 to 2009. The outcome that is considered in this paper is Gross Regional Product (GRP) per capita.

The sample is a balanced panel with longitudinal data, in which all selected regions are recorded at the stated periods of time, t =1, ..., T. Likewise, it includes positive numbers of pre-intervention periods, T_0, and post-intervention periods, T_1, where $T=T_0+T_1$. In this instance, pre-intervention period is from 1998 to 2009 and post-intervention period is from 2009 to 2017. Therefore, Khakassia was exposed to the treatment (the accident on Sayano-Shushenskaya station), during the period $T_0 + 1, ..., T$, and the accident, respectively, did not have any effect during the period $1, ..., T_0$, which is a pre-treatment period. An objective of this research is to evaluate an influence of the treatment on the post-intervention outcome. Thereby, the goal is to estimate an impact of the technological disaster on Sayano-Shushenskaya dam that happened in 2009 on economic development of Khakassia, particularly, the Gross Regional Product (GRP) per capita of this region.

It was already mentioned above that by using several untreated units, the pre-intervention features of the treated unit might be more precisely approximated than by using only one untreated unit. Thus, a synthetic control is a weighted average of the potential comparison units and it could be denoted by vector ($J \times 1$) of non-negative weights $W = (w_2, ..., w_{J+1})'$, with $0 \leq w_j \leq 1$ for j =2, ... J and $w_2 + \cdots + w_{J+1} = 1$ (Abadie et al. 2015, p. 497). Different synthetic controls are represented by diverse values of

W, so selecting the values of weights W corresponds to selecting a synthetic control. Weights should match with a selected synthetic control that most precisely represents features of the treated unit. Suppose that X_1 is a (k×1) vector, which contains the treated unit's values of the pre-intervention characteristics, in this case, the features of Khakassia before 2009, and X_0 is the k×J matrix, which includes the values of the same characteristics for the potential comparison units or other Russian regions that were selected.

The vector $X_1 - X_0W$ reflects the difference among the pre-intervention characteristics of Khakassia and a synthetic control. W* is the chosen synthetic control that makes the difference size minimal. Assume that for m = 1,...,k, X_{1m} is a value of the m-th variable for Khakassia and X_{0m} is a 1× J vector, which includes values of the m–th variable for the potential comparison units or other regions in Russia (Abadie et al. 2015). In line with Abadie and Gardeazabal (2003) and Abadie, et al. (2010), (2015) W* is the value of W that makes minimal the following expression:

$$\sum_{m=1}^{k} v_m \,(X_{1m} - X_{0m}W)^2$$

Where v_m is a weight, which represents a comparative importance that is assigned to the m-th variable, when the difference between X_1 and X_{0W} is estimated. The synthetic control should precisely replicate values of the treated unit variables, which have a great power of prediction on the considered outcome. Thus, variables with larger predictive power should have larger v_m.

Let's consider that Y_{jt} is the outcome of unit j at time t and Y_1 is a (T_1 ×1) vector, which contains the post-intervention values of the treated unit outcome. Hence, $Y_1 = (Y_{1\ T0+1}, ..., Y_{1\ T})'$. Likewise, suppose that Y_0 is a matrix (T_1 × J), where column j comprises the post-intervention values of the outcome of unit j +1 (unit from the donor pool). The synthetic control estimator of the treatment effect for a post-intervention period t (when t ≥ T_0) is obtained from a comparison of the post-intervention outcomes of the treated unit and synthetic control at the stated period, which can be expressed like:

$$Y_{1\,t} - \sum_{j=2}^{J+1} w_j * Y_{jt}.$$

In this case, the synthetic control estimator is an impact of the accident happened on Sayano-Shushenskaya dam on the economic development of Khakassia for a period from 2009 to 2017, which is derived as a difference in Gross Regional Product (GRP) per capita in Khakassia after 2009 and synthetic control values at the same period.

Predictors of post-intervention outcomes are represented by variables in X_0 and X_1 and are not influenced by the treatment. There is a criticism of the synthetic control method that its application can be bounded because of unmeasured factors that may have an influence on the value of outcome variable and heterogeneity in the impacts of measured and unmeasured factors. However, in the article of Abadie, et al. (2010), it was stated that the great amount of pre-intervention periods that corresponds to pre-intervention outcomes (Y_0 and Y_1) facilitated to supervise unmeasured factors and the impacts of measured and unmeasured factors. The intuition is that only units, which are similar in the impact of measured and unmeasured factors on the selected outcome variable, will have the same behavior of the selected outcome variable in enhanced periods. Thus, when the treated unit and the synthetic control unit have the same manner during pre-intervention period, it is considered that a difference in the outcomes in the post-intervention period occurred only because of the intervention.

The synthetic control calculations are made by using software scripts written for R, MATLAB and Stata, which are available for free. For instance, in Stata, the appropriate software scripts are downloaded by entering “ssc install synth, replace”. By this action, it is possible to load the software from the archive of Statistical Software Components.

As it was already stated above, the synthetic control method simplifies evaluations in the situations, when there are no any single untreated unit that can be considered as a suitable comparison for the treated unit. Despite the fact that the method solves this issue, there are some limitations of the synthetic control application according to Abadie et al. (2015).

Creation of the donor pool should be done carefully. First, units, which were affected by an event similar to the intervention that happened with a treatment unit, should not be a part of the donor pool. Secondly, units, in which the considered outcome was subject to great and unique shocks in the studied period, need to be eliminated, if these kinds of shocks did not have an influence on the treated unit. Finally, to prevent an occurrence of interpolation biases, the donor pool should contain only units, which have the same characteristics as the treated unit. Moreover, only units that have similar features, as the treated unit should be included in the donor pool in order to eliminate a problem of overfitting. A problem of overfitting occurs in a situation when by means of blending idiosyncratic variations among untreated units, characteristics of the treated unit are selected artificially.

The possibility of application of the synthetic control method is associated with a great number of pre-intervention periods. This is important to state because the degree of reliability of a synthetic control is affected by how precise it reflects the features of the treated unit during the pre-intervention period. In addition, it is recommended to have the data about numerous post-intervention periods, in such cases, when an impact from of the intervention rise consistently or varies in time.

Besides, there are two assumptions that should be satisfied in order to make the conclusions about the efficiency of synthetic control method. The first assumption is anticipation effect, which claims that before the intervention there should not be any impact on the outcome variable. The reliability of the obtained results is checked by performing a placebo test. The second assumption is connected with spillover effect, according to this, the outcome variables of the untreated units should not be influenced by the intervention, which affects the treated unit.

4.3 Placebo study

As it was stated in the article of Abadie et al. (2015), let us suppose that the synthetic control method estimated an effect of a certain intervention on the treated unit. The confidence about the reliability of this result would become much less, in case, when more significant effect was found by synthetic control method applied to the other units or periods. This refers to the placebo study, which serves to understand whether the found effect is the result of the considered event or the treated unit without the intervention is not correctly reproduced by the synthetic control.

There are two types of placebo study (Albalate, Padró-Rosario, 2018). First, placebo test in-space is implemented by applying the same method to a non-treated unit, in this case, region. This test is performed by the comparison of the evolution of a region, which is similar to Khakassia but without any similar significant accident happen in reviewed period, with the evolution of the synthetic control of this region. The certainty that the synthetic control estimate represents an impact of the intervention will be much less, if similar or larger effect is found after an application of the synthetic control to the other unit. The reason to do placebo test in-space is to check, whether the effect is the result of other factors than the considered treatment. If other factors have an influence on the impact, the conclusion about non-reliable results can be made.

Likewise, there is the second type of placebo test that can be conducted. This type is placebo test in-time, which is performed by accidentally changing the time of the intervention or a pre-intervention period. Particularly, this type of placebo test can be performed by changing the date of the disaster from 2009 to the other date. This type of test is possible to perform, when there exists a data for many periods without any structural shock to the considered outcome variable. When larger or similar impacts of the treatment were found by the modification of the period, the certainty that an impact found in the treated unit is caused only by the intervention would be much less. In such case, the results obtained would be less reliable.

It should be stated that placebo studies do not generate confidence intervals or posterior distributions. Therefore, the test is limited to answer the question, whether or not the impact from the intervention is greater than evaluated placebo effects. On this basis, conclusion about the reliability of the result is formulated.

5. The "Synthetic" Khakassia and an economic effect on Gross Regional Product per capita

5.1 Data

In order to apply the synthetic control method, it is necessary to find potential comparison units that have the same features, as the treated unit but that did not experience any similar treatment. Therefore, in order to evaluate an economic impact of the accident on Sayano-Shushenskaya dam on Khakassia, there was constructed a donor pool with potential comparison units (55 Russian regions), in which the technological disaster on Sayano-Shushenskaya station or other similar significant disasters did not happen. Krasnoyarskiy Krai region was excluded from the sample because it was also affected by the disaster on Sayano-Shushenskaya dam. Likewise, other several regions were eliminated from the donor pool because in these regions have happened different accidents of the same or higher magnitude. For instance, such accidents include the terrorist attack on a school in North Ossetia that happened in 2004 or catastrophic floods in Far East of Russia that occur periodically and affect simultaneously several regions.

In this research, the variables with available values in pre-intervention and post-intervention periods were used. The studied outcome variable is Gross Regional Product (GRP) per capita that facilitates a comparison between the results in various regions, in order to estimate the economic effect. The variables, which are generally associated with economic development, are used in this research as the predictors. Such variables include investment ratio, population density, share of industry in total production, human capital with different levels of education and average monthly income per capita for a sample of regions. These macroeconomic variables will enable to construct the suitable comparison unit, which makes it possible to compare the "synthetic" Khakassia with the "real" Khakassia.

The data on the outcome variable and predictors was obtained from the official database of Federal State Statistic Service[13]. The database has available information for the pre-intervention period of 11 years and post-intervention period of 9 years, which is necessary to make the research about an impact of the accident on Sayano-Shushenskaya dam on the economy. Hence, the empirical analysis in this paper uses annual regional data for the variables, which were stated above, for the period from 1998 to 2017. Appendix presents a detailed description of the variables.

5.2 Empirical strategy

The outcome variable in Khakassia should be compared to a value of the outcome variable of the suitable comparison unit. Therefore, the evolution of Gross Regional Product (GRP) per capita in Khakassia is compared to a weighted combination of other selected Russian regions, which reproduces the characteristics of Khakassia, if the disaster on Sayano-Shushenskaya hydroelectric power station did

[13] Can be accessed by the link: https://www.gks.ru/statistic.

not happen. The weighted average of the selected Russian regions is the “synthetic” Khakassia without an experience of the accident on Sayano-Shushenskaya dam, which is used to perform a comparison with the “real” Khakassia.

Table 3 states values of the predictors, which are commonly associated with an economic development. The Table represents that the “synthetic” Khakassia, which constitutes the several regions, selected by the algorithm, is a better comparison unit for “real” Khakassia than the mean values of all 55 Russian regions in the donor pool. Therefore, an application of the synthetic control method proves that the obtained synthetic control reproduces predictors of the treated unit more precise than the mean values of the comparison units sample.

Table 3. Predictors means for the “real” Khakassia and the “synthetic” Khakassia

Predictors	Khakassia	Synthetic	Pool
Inv_rate	18.75	17.43	21.13
Population	8 849.12	21 954.47	26 497.78
Indust	85.73	85.56	79.88
Low_edu	0.53	0.71	00.95
Mid_edu	78.11	77.86	78.11
High_edu	21.36	21.34	20.95
lnIncome	4 366.73	4 504.46	4 996.66

Moreover, as it can be noticed from the Table 3, the lagged values of the GRP per capita were not used as the predictors in this research. This type of variables was not selected because Kaul et al. (2015) stated that involvement of the outcome lagged variables as predictors made the other variables irrelevant.

The synthetic control consists of several control units, which have different weights. Table 4 represents Russian regions that were assigned weights and that were chosen to constitute the “synthetic” Khakassia. When the algorithm was used to build the synthetic control, the four its contributors were obtained. Irkutskaya Oblast (54,6%) has the highest weight in the synthetic control. The selection of Irkutskaya Oblast is not unpredictable because by visual inspection of the data it is possible to notice that variables that represent the characteristics of Irkutskaya Oblast in pre-intervention period from 1998 to 2008 are comparable to Khakassia. The other contributors of the synthetic control are Ivanovskaya

Oblast (22,6%), Republic of Udmurtia (16,6%) and Republic of Mordovia (6,1%). The rest of the regions from the donor pool were not considered as the contributors to the “synthetic” Khakassia.

Table 4. Weight matrix of Russian regions that constitute the “synthetic” Khakassia

Region	Unit weight
Irkutskaya Oblast	0.546
Ivanovskaya Oblast	0.226
Republic of Udmurtia	0.166
Republic of Mordovia	0.061

In general, the synthetic control method minimizes the Root Mean Squared Prediction Error (RMSPE), which estimates the loss between the actual evolution of the outcome variable and the synthetic control (Albalate, Padró-Rosario, 2018). While the synthetic control was applied to predict GRP per capita in the “synthetic” Khakassia from 2009 to 2017, the RMSPE was only 0.037, which is less than 4%. Therefore, the conclusion about a minimized loss between the “real” Khakassia and the synthetic control can be formulated.

5.3 Results

The main result of synthetic control method application is presented on the Figure 2. It can be noticed from the Figure that the evolution of the “real” Khakassia’s GRP per capita in a period from 1998 to 2008 is closely resembled by the “synthetic” Khakassia’s GRP per capita. The degree of reliability of the synthetic control is related to an assimilation of the treated unit pre-treatment characteristics (Albalate, Bel, 2020). In this case, it can be stated that the constructed synthetic control resembles the "real" Khakassia relatively precise. Therefore, it is possible to make a conclusion that, in this instance, the synthetic control is quite reliable and its loss is minimal.

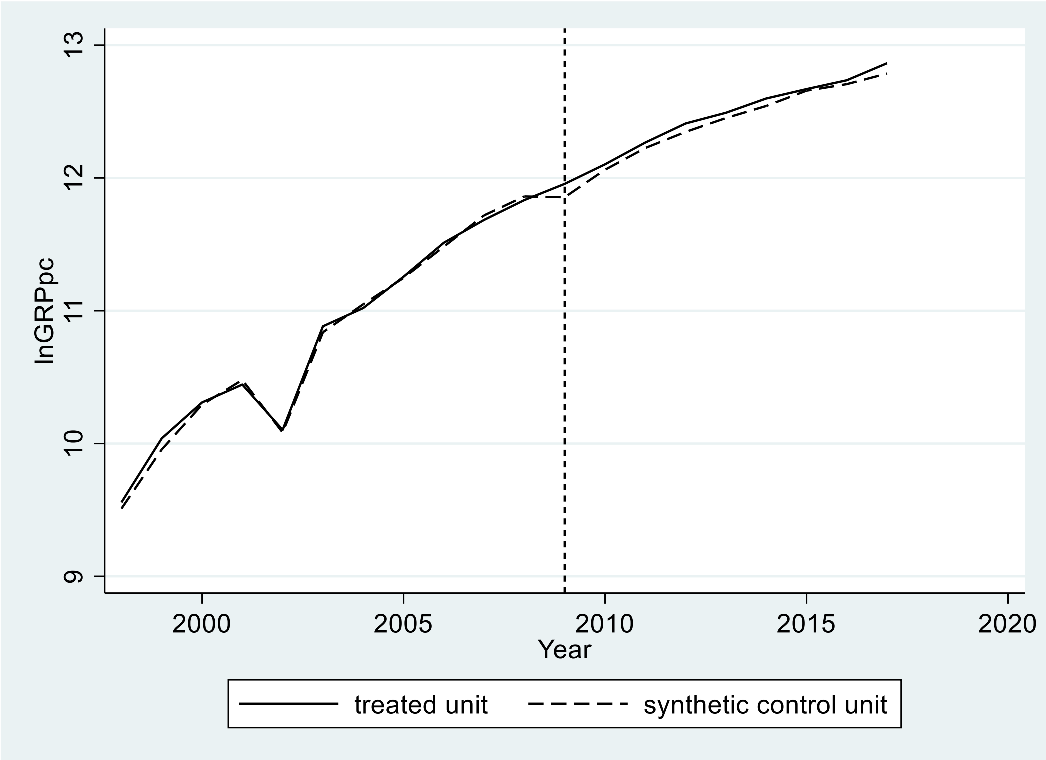

Figure 2. Trends in ln(GRP per capita): "real" Khakassia versus "synthetic" Khakassia

Furthermore, it can be observed from the Figure that from 2009, the evolution of the "real" Khakassia's GRP per capita does not have a significant difference with the evolution of the "synthetic" Khakassia's GRP per capita. In fact, surprisingly, the "real" Khakassia has a bit better performance than a compared synthetic control. It means that the accident on Sayano-Shushenskaya hydroelectric power station did not have a negative effect on the economy of Khakassia; it conversely had a little positive effect on its GRP per capita.

The reliability check of the results, obtained from an application of the synthetic control method, is commonly made by placebo tests in-space and in-time. However, placebo test was not conducted in this research, due to a non-significance of the discovered effect.

The positive non-significant influence of the technological disaster on Sayano-Shushenskaya station on the GRP per capita of Khakassia can be explained by several reasons. First, probably, it can be clarified by the specific of this technological disaster, which affected the dam, several plants and Enisey river much more than Khakassia region in a whole. Secondly, the comprehensive emergency and recovery operations for a liquidation of the accident were started immediately and were organized in a quite properly coordinated way. Such liquidation works made it possible to avoid the extremely negative consequences of this technological disaster. Thirdly, Siberian aluminum and ferroalloy plants, which are the main consumers of the electro energy from Sayano-Shushenskaya station, stopped their work only for a short period because the other nearby stations were able to provide an additional electro energy to them quickly, in order to continue its work and not stop a production for more time. Finally, the accident encouraged an inflow of a great amount of investments for a liquidation of the disaster, dam reconstruction and compensation of losses. As it was already stated above, 40 billion of rubbles were required to finance reconstruction works of the Sayano-Shushenskaya dam[14]. Moreover, JSC Rushydro supported financially families of the workers that were dead in the accident in a total amount of 185 million rubbles[15]. In addition, JSC Rushydro with a participation of Khakassia government performed a complex reconstruction of Cheremushki, the closest village to the station. In particular, the reconstruction of schools, hospitals, roads, bridges and other facilities were conducted. Therefore, the technological disaster on Sayano-Shushenskaya station stimulated an increase of investments, which, in the other case, would not be transferred to Khakassia.

6. Conclusion

An issue of disasters attracts an attention of governments, researchers and other institutions all over the world. It can be explained by the reason that disasters are frequently largescale and happen suddenly, so they can cause various negative consequences to economy and other sectors. There are two types of the disasters: natural and man-made, which include socio-technical and warfare.

Many researches that evaluate an effect of natural disasters on economic growth were already performed. However, an impact of technological disasters on the economy was not studied enough. The reasons for a lack of studies can be connected with a specific of technological disasters, its great diversity and less occurrence, in comparison with natural disasters. Moreover, it can be associated with a challenge to find a suitable comparison unit for a country or a region were technological disaster happened. The synthetic control method that is applied in this paper helps to deal with this problem.

The synthetic control method was used in this study to evaluate an effect of the technological disaster on Sayano-Shushenskaya hydroelectric power station on the economy of Khakassia, the Russian region, where this dam is located. This accident was selected for the research because Sayano-Shushenskaya dam is the most powerful hydroelectric power station in Russia[16] and the catastrophe that happened on this station is considered as the largest hydroelectric disaster in modern Russia (Ismagilov, 2010). Particularly, this technological accident happened in 2009 and entailed 75 deaths of the station workers, economic and energy losses and ecological consequences, connected with emergence of oil spills on the river.

[14] See Ministry of Finance of Russian Federation, Press center, “Comments of Novak A. to news agencies on the meeting about a liquidation of consequences of the accident on Sayano-Shushenskaya hydroelectric power station.”

[15] See JSC “Rushydro”, Sayano-Shushenskiy branch, “Information for lunch of the last hydraulic unit. Realization of JSC “Rushydro” social program on Sayano-Shushenskaya dam.”

[16] See JSC “Rushydro”, Sayano-Shushenskiy branch, “General information.”

In this research, the synthetic control method was applied to evaluate an impact of this catastrophe on the Gross Regional Product (GRP) per capita of Khakassia. In order to perform it, the sample with the other Russian regions and the variables associated with economic development was constructed for the period from 1998 to 2008. After using the algorithm, several Russian regions were chosen to compose the “synthetic” Khakassia. From these regions, Irkutskaya Oblast resembles Khakassia substantially and has the highest weights in the synthetic control.

The results obtained in this study reveal that from 2009 to 2017 the evolution of the “real” Khakassia’s GRP per capita does not have a significant difference with the evolution of GRP per capita of the synthetic control. Particularly, the accident on Sayano-Shushenskaya hydroelectric power station had a non-significant positive impact on the economy of Khakassia. Most likely that the reasons for this result can be related to the specific of this technological disaster and a good coordination of the emergency operations. Moreover, the plants-consumers of the electro energy from this station were rapidly switched to the other stations, which prevented great losses in production. It is also important to mention that the accident stimulated a great inflow of investments to Khakassia.

In order to discover a more significant influence of the accident on Sayano-Shushenskaya dam, the future researches can be conducted. The possible options for the future investigations can be connected with an application of the other method or selection of the other outcome variable (not GRP per capita) and an implementation of the synthetic control one more time. In addition, the future studies can analyze an effect of the accident on Sayano-Shushenskaya dam on the economy of Krasnoyarskiy Krai, the region that was also affected by this disaster. Probably, such modifications can facilitate to find a more significant economic effect caused by the technological disaster happened on Sayano-Shushenskaya hydroelectric power station.

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8. Appendix

Variables Description

- Investment ratio (%): Gross Total Investment over GRP.
- Population density (people per square kilometer).
- Share of industry (%): Industry production over total production.
- Human capital with low, middle, high levels of education (%): Percentage over working-age population.
- Average monthly income per capita (RUB).
- Gross Regional Product (GRP) per capita (RUB).