

Mapping the Shape of the U.S. Economy: A Topological Data Analysis Approach with BallMapper

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ABSTRACT

Topological Data Analysis (TDA) is a new data analysis method which gained popularity starting in the early 21st century. Currently, a large body of TDA research utilizes the traditional Mapper algorithm. We aim to expand the body of literature on BallMapper, a new, Mapper adjacent algorithm. Applying BallMapper to widely used, U.S. macroeconomic data from the Bureau of Economic Analysis (BEA), the Federal Reserve Bank (FRB), and Bureau of Labor Statistics (BLS), we do this in three parts. Specifically, we show an example of BallMapper's utility in exploratory data analysis which also provides an example of how to interpret BallMapper's output; analyze our topological graphs to notable historic economic events; and test the stability of BallMapper's output and the topological graph's features. Results show. [...]

INTRODUCTION

Topological Data Analysis (TDA) is a new and emerging field of data analysis that is increasing in popularity. At a high level, the traditional applications of TDA use two tools: an algorithm called Mapper that produces a network-like graph and an analysis technique called Persistence Homology. Mapper can be thought of as carrying out a statistical analysis with just pictures; it might confirm a hypothesis but is not enough to say something is statistically significant. Persistence Homology on the other hand is more akin to doing an analysis of variance (ANOVA). It provides the statistical, in our case mathematical, backing to what we might see if we were to only plot the data. Moreover, the combination of Mapper and Persistence Homology is what forms the central argument for TDA: data contains an underlying shape.^{1, 2}

For this analysis we will be focusing on the graph creation portion of TDA. Specifically, we are examining various macroeconomic indicators of the United States of America (U.S.) using a Mapper-adjacent algorithm called BallMapper(BM).³ BallMapper is of particular interest to us because it significantly reduces the parameters to create a topological map. It simplifies traditional Mapper by reducing the need for the user to pass data through multiple functions, each with their own parameters.⁴ One benefit to this reduction in parameters is that it removes some of the barriers to learning Mapper (or Mapper-like algorithms), and more generally, TDA. Those who have a mathematical background, introductory course in Topology, or conceptual knowledge of data science methods and algorithms will fare much easier. However, if you are not equipped with any of the aforementioned tools, TDA might seem unnecessarily complicated for data analysis.

Beyond the main objectives of this analysis, we hope that this paper serves as an on-ramp for anyone interested in TDA but feels inundated with jargon upon early stage researching. Our objectives are to add to the small body of literature whose main focus is applications with BallMapper.⁵ We go about this by first showing BallMapper's use in exploratory data analysis (EDA). Using our

¹<https://arxiv.org/pdf/2504.09042>

²Chazal F and Michel B (2021) An Introduction to Topological Data Analysis: Fundamental and Practical Aspects for Data Scientists. Front. Artif. Intell. 4:667963. doi: 10.3389/frai.2021.667963

³<https://arxiv.org/pdf/1901.07410>

⁴add reference

⁵add Mapper survey paper reference here

results from EDA, we then will compare BallMapper’s outputs (topological graphs) to notable historic economic events [and maybe less known?]. Lastly we will test the stability and consistency of BallMapper’s output. The conclusion will talk broadly about results and other considerations of note, and the discussion will elaborate on future work and questions for research.

METHODS AND PROCEDURES

PROCEDURES

Data

This paper relied on three publicly available data from US government sources. The Bureau of Economic Analysis (BEA), The Federal Reserve Board (FRB), and The Bureau of Labor Statistics (BLS). The data were gathered using R using two application programming interfaces (APIs): one for data from the BEA, and the other from the Federal Reserve Economic Data (FRED) API. FRED aggregates data from national and international sources, as well as public and private sources. We additionally used recession dates based on business cycle contractions and expansions provided by the National Bureau of Economic Research (NBER).

These agencies were selected because of they are authoritative sources for U.S. economic data. Their widespread use in both the private and public sector gives us high confidence in the accuracy and integrity of the data. ⁶

Looking the *Year Start* and *Year End* in Table 1, we elected to exclude Employment Cost Index (ECI) and Foreign Direct Investment (FDI) due to their limited available years. Of the remaining data series, New Privately-Owned Housing Units Started (Housing Starts) has the smallest range and will provide the range of years used for our analysis - 1959-2024.

Series Name	Year Start	Year End	Data Frequency	Data Type	API
Gross Domestic Product	1930	2024	Annual	Flow	BEA
Personal Income & Outlays	1948	2024	Annual	Flow	BEA
Foreign Direct Investment	2014	2024	Annual	Flow	BEA
Federal Funds Rate	1955	2024	Annual	Rate	FRED
Employment Cost Index	2001	2025	Quarterly	Index	FRED
Consumer Price Index	1947	2025	Monthly	Index	FRED
New Privately-Owned Housing Units Started	1959	2025	Monthly	Flow*	FRED
Producer Price Index - All Commodities	1913	2025	Monthly	Index	FRED
Unemployment Rate	1948	2025	Monthly	Rate	FRED

Table 1: *Housing Starts is considered a flow because it is provided as a Seasonally Adjusted Annual Rate (SAAR).

Table 1 also shows that our data came in annual, quarterly, and monthly time frequencies. We are interested in annual data for this analysis so some data considerations are as follows because not all our data provided in Real dollars, were given as a rate (growth rate, proportion rate, or fixed rate), or on a similar scale (i.e., rate, millions of dollars, index). Additionally, BallMapper is less effective and inefficient to use when the input data variation there is large variation in the scales of each dimension of the dataset (columns). ⁷ To aide BallMapper, we transformed our data to either a rate or a percentage change from the previous year where appropriate. This ensures all dimensions of our data stay on a 0-100 scale and helps with the time complexity of BallMapper.

⁶Hughes-Cromwick, Ellen, and Julia Coronado. 2019. "The Value of US Government Data to US Business Decisions." Journal of Economic Perspectives 33 (1): 131-201346. DOI: 10.1257/jep.33.1.131

⁷[find reference]

Pre Analysis Calculations

The first data series we needed to make adjustments for was Personal Income and Its Outlays; specifically, Personal Income and Its Disposition (Personal Income).⁸ Personal Income is reported in nominal dollars, which does not account for inflation, so our first calculation is to adjust Personal Income for inflation using Consumer Price Index (CPI) data.⁹

$$\text{Real Dollars} = \frac{\text{Nominal Dollars}}{\text{CPI}} * 100 \quad (1)$$

From Equation 1, we then take the log difference (Equation 2) and multiply it by 100 to get a percentage change for the preceding year. This log difference helps to make our data more linear which aides the BallMapper algorithm's use of the standard Euclidean Distance between each row of data.^{10 11}

$$\Delta \ln (\text{Real Level}) = \ln (\text{Real Level}_t) - \ln (\text{Real Level}_{t-1}) \quad (2)$$

Additionally, we applied Equation 2 to New Privately-Owned Housing Units Started (Housing Starts), Producer Price Index - All Commodities (PPI - All), and CPI and multiplied each of those by 100 to get the percent growth from the preceding year for Housing Starts, Consumer Inflation (Demand-Pull Inflation), and Producer Inflation (Cost-Push Inflation), respectively.

PPI_All only include Farm products, processed foods and feeds, Industrials, and other commodities such as rubber, lumber, machinery, and aircraft since 1959. Most all services only have data series from 2009 on wards.

and is increasingly being applied to From the small body of literature we have reviewed, TDABM has removed many of the parameters that are required for more traditional methods of TDA. Generally speaking, traditional TDA contains four broad steps, each with multiple user-defined parameters. Conversely, TDABM has reduced this process to an the user selecting their data, a coloring variable and an epsilon value – details on this follow below. What should be noted, although TDABM reduces the number of steps needed to produce similar outcomes of traditional TDA methods, we lose control of being able fine tune out outputs. We also find that interpreting results becomes more difficult. However, TDABM is still in its infancy, so there is not a large body of research on interpretation. (Paweł Dłotko 2019) One major motivation for this paper is a paper written by Paweł Dłotko, Rudkin, and Qiu (2019) that applied TDABM to a global macroeconomic dataset to compare how countries have evolved over time, their transformation from the Great Depression Era, and various views on wealth and inequality. We could not find other TDA literature found specifically focused on the macroeconomic economy of singular countries. Hence, our topic of choice.

METHODS

BallMapper

- Summary of algorithm
- correlation considerations

Exploratory Data Analysis (EDA) Application

- known interpretations

Small Comparative Analysis

- “New Deal”
- 08 financial crisis
- Covid
- Flash Crash 87
- Tech Boom

⁸Table 2.1 from the BEA's Interactive Data, National Data section.

⁹<https://www.dallasfed.org/research/basics/nominal>

¹⁰<https://econbrowser.com/archives/2014/02/use-of-logarithms-in-economics>

¹¹<https://www.numberanalytics.com/blog/log-transform-econ-how-to-guide>

- AI Boom
- Oil Embargo/ high unemployment

Robustness and Stabilization

- Shuffle Dataset -> Run BallMapper
 - Look at:
 - *

nodes

- * coloring consistency
- * look at financial application and brexit vote

CONCLUSION

DISCUSSION

REFERENCES

Old Paper

Old Intro

Dłotko demonstrates that, mathematically, TDABM produces a near similar output to that of traditional TDA methods via a factor map (Paweł Dłotko 2019). TDA BallMapper and closely follows other papers that have applied TDABM. We will begin with a general overview of TDABM: current published literature and useful concepts to know. We then will describe our data and reasoning behind their selection. Our Methodology and Results will touch on more theoretical concepts behind TDABM and then address a couple of findings, respectively.

TDA BallMapper

TDABM, and in general TDA, believes that data contains a “shape” to it. It pulls ideas from the branch of Mathematics, Topology. At a high-level, Topology focuses on the properties of geometric shapes when you deform them without breaking them, e.g. bend, twist, scrunch. The following is a basic overview of TDABM ¹².

BallMapper Algorithm

Before going over the algorithm there are a few For the following algorithm some useful definitions are as follows: - We will use the word pointcloud instead of dataset. - Conventionally the Euclidean distance metric is used; let $d = \text{dist}()$ is used as our distance metric, denote d The core steps of the TDABM algorithm are as follows:

1. From your dataset (pointcloud) select a random point, α_n , and draw circle with radius epsilon, ϵ .
2. For some distance metric where d is the distance from, any points inside the circle will be associated with point α_n .
3. Repeat steps 1 - 3 until there are no more points to select and you have a set $\alpha_1, \dots, \alpha_n$.

¹²Some very good examples and explanations can be found in (Dłotko, Qiu, and Rudkin 2022) and (Paweł Dłotko, Qiu, and Rudkin 2019) which touch on the finer details of TDABM algorithm. A very good illustrative example can be seen in the pre-print (P. Dłotko, Qiu, and Rudkin 2021).

4. Draw an edge between α_i and α_j if they share a point(s) for our set $\alpha_1, \dots, \alpha_n$.

Although the above list five steps, it should be noted that this is just the algorithm and is all done with one function call.¹³ From the steps above, the only thing the user of TDABM is responsible for is creation of a pointcloud and choosing an appropriate ϵ .

Procedures

Pointcloud Construction

A primary challenge we encountered when selecting variables for analysis was the variability of time period coverage. Some data spanned from Depression Era 1929 all the way up to 2024. Looking at our final nine variables (see [?@fig-corr](#)) and the range of years available by by source ([?@fig-years](#)span), we limited our years to 1960 - 2024 due to Housing Starts data having the smallest range of years.

Some of the data was only available by month. In these cases we calculated annual changes by finding the difference between January of the current year and January of the previous year. Note, this reduced the number of years in our data set by one. We also standardized the data by converting non-rate based data to percent changes from the previous year to ensure consistency across all variables (Equation 3). One feature of TDABM is that it can be sensitive to data with large scale differences. This not only reduces how precise you can be when selecting a parameter, but can also significantly increase computation time.

Looking at our correlation table ([?@fig-corr](#)), we observe moderate to strong correlations between the pairwise combinations of GDP, PCE, Ig, and Imports. We also see a strong correlation between CPI and Interest Rates. Since these correlations are moderate to high, it's worth noting that the shape of our output may be reflected by these correlations. They also could express themselves with similar coloring of TDABM graphs ([Pawel Dłotko, Rudkin, and Qiu 2019](#)).

Cloud Building

In our Data section, we noted that some calculations were needed before our analysis. Additionally, for the Federal Funds Rate, the Unemployment Rate, and CPI we had to take extra steps and considerations while constructing out pointcloud. Since the Federal Funds Rate and the Unemployment Rate are already a rate-based measurements, instead of taking a percent change from the previous year, we instead took the standard non-weight average rate by each year. For CPI, this data was given on a monthly-basis, we calculated it using our [General Percent Change Formula](#) with $k = 12$.

Results

Interpretation of TDA BallMapper Graphs, An Abridged Version

In Figure 1 we are presented with what looks like a graph, in the mathematical sense; a display of points (nodes) and edges –some connected while others are not connected at all (satellites). If we do not change the poincloud or ϵ of our TDABM graph, we will get the same “shape” of the graph regardless of the coloration we choose.

Nodes are colored depending on the users interest. In (?), we are focusing color by year. Coloration calculated by taking the average of the data that is “inside” each node, in our case the average value of the years. Further, if there is only one data point in a node (i.e. a satellite points), the node will appear small and the coloration will reflect as seen on the legend. Conversely, if the node is large, this indicates more data is “inside” the node, and the average value could be reflecting the mean values of a large or small variance.

¹³There are packages available both in R and Python under the names BallMapper and pyBallMapper, respectively.

General Figure 1 Remarks

We initially notice a large connected component¹⁴ (component A) on the right side of our graph, as well as a smaller connected component (component B) on the lower left side. Noting the coloration, there are three main sections: the right, bottom, and upper-left. On the bottom and sweeping upward to the left we see there are multiple satellite points. These can be of interest because they may indicate outliers in our data.¹⁵ Focusing back towards component A, we notice that the two largest nodes, 28 and 22, which seem to represent the late 2010s and the dot-Com boom, respectively. We also note that there is a arm coming off the upper-right portion of component A, as well as smaller, lollipop, features emerging at the bottom and top of component A.¹⁶

Time Travel

Looking at Figure 1, we see that our graph is colored by year.¹⁷ In this section we will only highlight a few observations in detail due to the nature of this paper. Additional areas for investigation can be found in the Conclusion.

Mentioned above, we observed the satellite points in the lower half of the graph. If we look at the upper-right quadrant, we see that it consists of nodes {1, 16, 25, 27}. Looking at [?@tbl-covidplus](#) we see that it covers the 2020 Pandemic and the Financial Crisis and its aftermath. Seeing a general coloration from the recent 10 - 15 years we would expect to see some of the recent outlier economic events here. Indeed, node 25 consists of two of the most recent economic downturns, 2009 and 2020. However, what is interesting is that node 27 consists of three years closely following the 2008-2009 Financial crisis. However, the years following the 2020 COVID Pandemic can be found scattered across nodes {6, 8, 24, 28, 29}. Looking at node 27 we find that the common thread is high unemployment. In contrast, the years following the Pandemic are not the same year to year.¹⁸

Shifting our focus towards component A, it consists of data most similar to the economic years between the 1990s - 2010s. Meanwhile, looking at component B and the general lower area of our graph, we see that it represents the Great Inflation period of the 1970s - early 1980s [ivestopedia article]. Looking at nodes 12 – 20, we get exactly ten years of data¹⁹ where there was know high inflation, high unemployment, and in general know to be bad time economically for the US ([?@tbl-greatinflation](#)). Something of interest to note is that nodes 14 and 15 consist of 1976 - 1978. This three year period based on data seems to show more normal economic conditions. On the other hand, we see that all the other years in this grouping (nodes 12 – 20) show signs of a struggling economy in some way.

Discussion

This paper serves as a proof-of-concept of the usefulness of TDABM as a methodology for exploratory data analysis. By no means is this a totally comprehensive method to gain insight into data, but instead TDA BallMapper proves itself to be useful tool when employed in addition to other traditional analyses.

In our Results section we briefly went over two ways to interpret TDABM graphs. As seen in many other, longer papers written by Dlotko and colleagues, there is a lot of room to expound our TDABM graph here, though that is beyond the scope of this paper. In general, though, we can see that TDBM can give insight into our data that we might not see otherwise. Seeing that there is data that is not like the others gives an indication that there is something to investigate. Consider our comparison of the 08' - 09' financial crisis and the 2020 COVID Pandemic: We see learned that the years following the financial crisis were similar economically. Another way to view this is, clustering reveals that the financial crisis was a singular problem that spurred the collapse of the financial system. Conversely, the COVID pandemic was a singular issue but exposed many different weaknesses in our current world.

For the future development of TDABM, and TDA in general, there are many possibilities of future research and one glaring downside. The downside to TDA is that it is a high barrier to entry to understand the methodologies inner workings. Those with a technical background will have an easier time, but nonetheless a higher barrier than methods such as linear regressions. Subject wise, TDA has an advantage in some of the social sciences because it can be somewhat of a bridge between qualitative and quantitative analyses. TDABM has been used to analyze the Brexit Vote data, seeking to understand quantitative and qualitative motivations behind its outcome Rudkin

¹⁴In graph theory, a connected component is one in which there exists a path from a node to every other node for a set of nodes and edges.

¹⁵We have not found any literature yet on whether this observation is empirically true.

¹⁶The observations mentioned above good starting places for interpreting BallMapper graphs.

¹⁷Supplementary graphs displaying coloration based on different variables can be found in Supplement_1.pdf.

¹⁸2021: An outlier, we see higher levels of unemployment and inflation. We see high PCE, Ig, and imports; 2022: Nodes {8, 28} we see that there is higher than normal inflation, export, and imports; 2023: Nodes {6, 24}, we see low inflation and low unemployment.

¹⁹1974 - 1984

et al. (2023). TDA also has the advantages of dimension reduction which could be useful to the life-sciences. Fields such as genetics, chemistry, and biology have many fields of data, and being able to consolidate it into an understandable form could benefit the body of knowledge greatly.

Endnotes

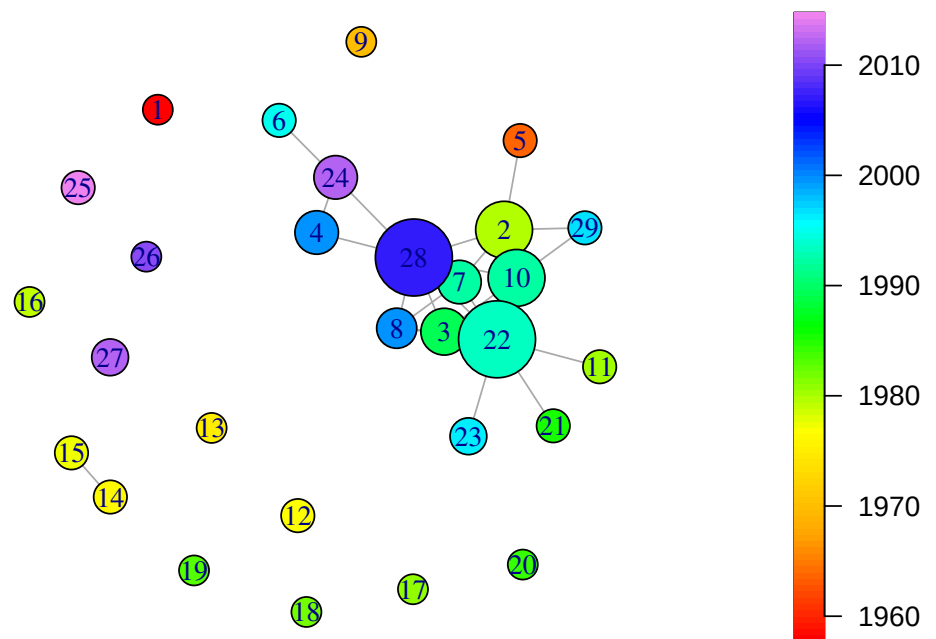
General Percent Change Formula

$$\Delta p_n = \frac{p_n - p_{n-k}}{p_{n-k}} \text{ for some } p \in P \text{ and } n > 0 \quad (3)$$

where P is a column of our data with x_1, \dots, x_n observations and k is a lag integer such that $k > 0$.

Appendix

BallMapper output Colored by Year



Epsilon: 0.45

Figure 1: Data is normalized on a [0,1] scale due to all variables not being normally distributed See Supplement_2.pdf.

References

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- Rudkin, Simon, Lucy Barros, Paweł Dłotko, and Wanling Qiu. 2023. “An Economic Topology of the Brexit Vote.” *Regional Studies* 58 (3): 601–18. <https://doi.org/10.1080/00343404.2023.2204123>.

Data Sources

- Bureau of Economic Analysis
 - Real Exports and Imports
 - New Foreign Direct Investment in the United States
 - Real GDP
 - Personal Income and Its Disposition
- Federal Reserve Bank
 - Selected Interests Rates
- Bureau of Labor Statistics
 - CPI
 - Employment Cost Index
 - PPI
 - Housing Starts
 - Unemployment Rate