Forecasting of a Technology Using Quantitative Satellite Lifetime Data

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ABSTRACT[1]

Technology forecasting plays an important role in the research and development of products in any company or organization. A well-designed forecast study would help to get the maximum expected gains from future conditions while minimizing expected losses. This article focuses on forecasting of average satellite lifetimes. In this article, using data for the launch dates of satellites, we will analyze their failure (expiration) dates to better understand the curves most suitable for determining trends in satellite lifespans. This article also discusses the prediction of lifetimes of satellites currently in orbit, as well as those to be launched in the future.

One goal of this paper is to explain the importance of forecasting and to give a brief explanation of forecasting methods. Another objective is to develop a best fit curve from the available past performance data of satellites by using techniques such as regression analysis, general curve fitting and valuation methods.

Key words: Forecasting, Lifetime

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1. INTRODUCTION

Over the past century, interest in forecasting techniques has grown as businesses and governments have understood the importance of predicting future performance of technologies. It has transpired that predicting knowledge about the future of technology assists decision making in achieving organizational objectives. Firms of all sizes depend on innovation for their growth as well as their survival. Technology forecasting studies that recognize innovations with the greatest potential will significantly aid in the development of innovation strategies.

Technology forecasting research can raise awareness and alert leaders including corporate businesspeople to new opportunities in science and technology. Governments strive to use the outcome of these studies as a tool to strengthen research policy for economic development and to create consensus in science and technology policy supported by regional and national innovation models. Some academic future studies aim to develop the field as well as raise general awareness [1].

According to Hu et al. (2015), "The senior U.S. strategic bomber B52 lifetime can last as long as 84 years! How do they know this? Because we can estimate how long an equipment will last that we can predict in probabilistic terms or mean time between failures using probability reliability analysis (PRA) engineering that using stochastic equations” [2].

Regarding which of Moore’s law vs. Wright’s law curves “is better for predicting future satellite lifetimes based on year of death, Wright's law seems superior simply because (1) Moore's law on lifetime as a function of the end year began failing […] in 2017 and will reach an even greater level of impossibility in 2046; and (2) launch year cannot work for recent years for which longer-lived crafts are still operational.” [3] Thus, Moore’s law for this particular metric is applicable up to a certain period and after that period Moore’s law is not applicable.

2. TECHNOLOGY FORECASTING METHODS

Lifetime prediction of any equipment may face three engineering problems [2]:

- How to determine the lifetime of a piece of debugging equipment that has not been used yet.
- How to estimate the remaining lifetime of an equipment that has worked for some time (normal lifetime).
- How to estimate the lifetime of an equipment that is powered off and kept in storage.

Different kinds of forecasting methods and techniques are currently being used by professional forecasters. The selection of a particular method of forecasting depends on many factors like how much time is needed for forecasting, the accessibility and importance of data, availability of time to be devoted to forecasting and how much the value of the forecast is to the organization.

Where historical data is unavailable, qualitative forecasting approaches are necessary. These kinds of forecasts are subjective and based on customer and expert opinions and judgments rather than hard data.

According to Firat et al. (2008), technology forecasting methods are classified into 9 families as follows [1]:

- Expert Opinion
- Trend Analysis
- Monitoring and Intelligence Methods
- Statistical Methods
- Modeling and Simulation
- Scenarios
- Economics Methods
- Descriptive and Matrices Methods
- Creativity

Each of these families has different techniques. Consider trend analysis and its importance. Trend analysis techniques use historical data for prediction and extrapolating trends into the future. The methods in trend analysis include:

- Trend Extrapolation
- Long Wave Analysis
- Precursor Analysis
- Trend Impact Analysis

Technology forecasting by trend analysis is frequently used in econometrics. A few examples are regressive analysis, exponential smoothing, growth curve fitting etc.

The evaluation of quality of fit in analysis the data is one of the most important steps in curve fitting. The most used method for determining optimal parameters is the least square method. The major principle on which it is based is that how big the difference is between data points and predictions is a good measure of how well the curve fits the data. Models can be analyzed for fit using this approach using computer programs.

Regression analysis is one of the methods that focuses on statistical prediction questions like how much uncertainty is present in a curve that is fit to data with random errors. Fitted curves can be used to help model data, infer function values when no data is available, and summarize the relationships between two, three or more variables [4].

3. CASE STUDY

Quantitative analysis in technology forecasting uses previous performance data or historic data to identify technology trends from patterns of performance, precursor relationships and any constant percentage rates of change to be found.

To do forecasting analysis using quantitative data includes choosing a technology of interest, collecting the historical data to forecast from and analyzing the pace of technology change over time against known characteristic trends of changing technology. The quantitative outcomes of qualitative forecasts can be, for example, integrated into a QTF-based forecasting system [5].

Data used for this study was downloaded from the site planet4589.org/space/gcat/data/cat/psatcat.html. This dataset gives information about satellite catalog number, launch date, death date, category, etc.

After downloading the data, some general steps like data cleaning and data organizing were done using Python. Once the data was ready for use in the next step, we analyzed how best to fit the data to curves whose extrapolations provide forecasting.

This data has values from 1957 to 2020 and we used it to determine average satellite lifetime by year of satellite failure. The average lifetime was calculated as the difference between death year and launch year, multiplied by a constant to estimate lifetimes in the unit of days. After getting average lifetimes for all available years, the next step was to analyze them to forecast future values and make forecast curves.

This analysis was carried out using Excel Solver, a Windows-based tool that can be used for solving non-linear regression problems. Solver can be successfully used for modeling data obtained in a variety of analytical contexts, based on test and experimental data sets. Solver is a useful vehicle for teaching the concepts of iterative curve fitting techniques since Excel is almost universally available [5].

The relation between the dependent variable of average lifetime and the independent variable of death year are drawn and shown in Figure 1. The relation between these two parameters has been generally increasing from the first satellite launch in 1957 to the present.

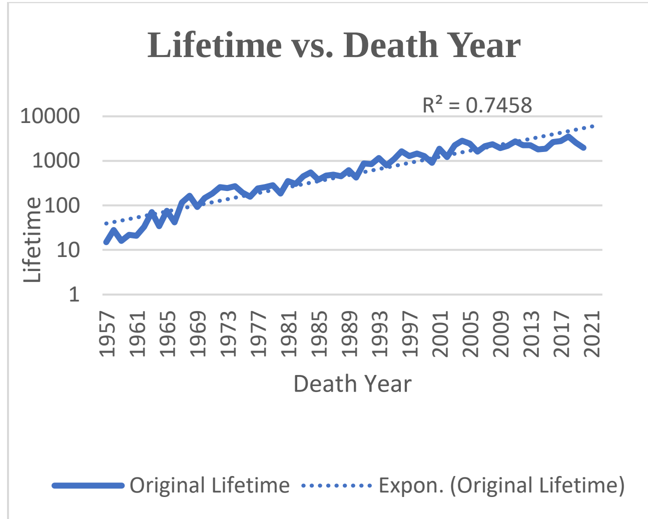

Figure 1. Average Lifetime in Days Vs. Death Year. Vertical Scaling is Logarithmic.

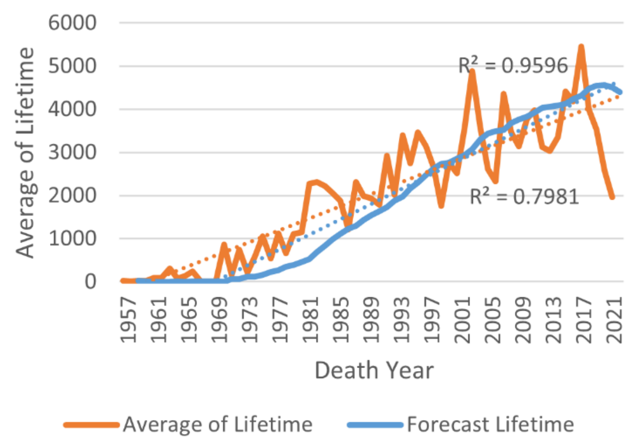

Figure 2. Average Lifetime by Year of Failure, for Technology and Communication Satellites Only.

Figure 2 indicates the relation between death year and average lifetime of technology and communication satellites only. For these satellites' data, the R^2 value is 0.79. Note that the noise and data quality play important roles in quantitative forecasting methods.

In a regression model, R^2 gives a statistical measure of fit that for a nonlinear model such as this estimate how much of the variance in a dependent variable is explained by an independent variable. This indicates the relationship strength between dependent variable and an independent variable. R^2 value ranges from 0 to 1.

Based on the proportion of total variance in the data described by the model, it provides a measure of how well observed outcomes are predicted by the model.

Figure 3 was generated using Minitab 19 for the data sets used to construct Figure 2 consisting of technology and communication satellites. This figure illustrates that the normal probability distributions hold reasonably well when the residuals are between (-2,500, 2,500) and less well otherwise. The residuals versus fits plot form a funnel indicating less accuracy as fitted values increase.

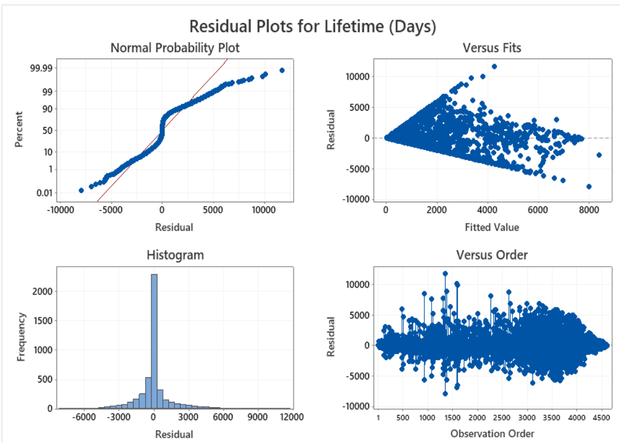

Figure 3. Residual Plots for Figure 2 Data.

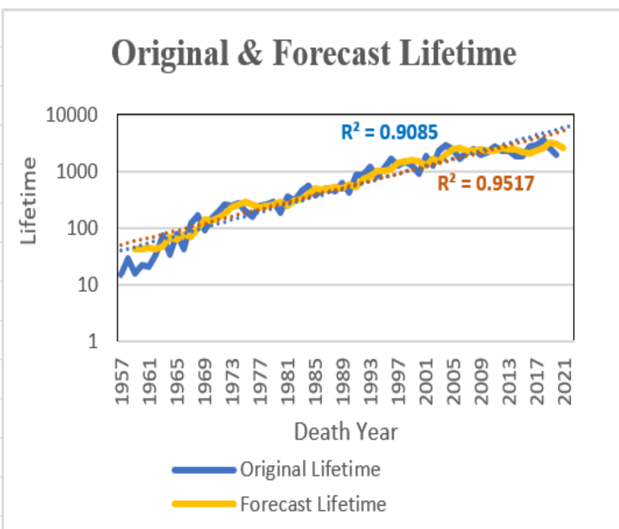

Figure 4. Original and Predicted Lifetimes.

Figure 4 shows the original lifetime and predicted lifetime values. For this analysis we applied nonlinear regression using Solver.

From the graph, the R^2 value for original lifetime data and predicted lifetime data are different. Both values are fairly high, but the predicted curve is better than the original curve. Moore's early discovery is important to remember in this case because it exemplified how technological change is often exponential.

If we observe the curves in Figure 4, the original values and predicted values are not much different from each other. The average percentage error for this forecasting is 25%.

For 2021-launched satellites the estimated lifetime value is 2560 days. It is an estimation based on the history of satellite lifetimes. So, the 2021 lifetime may have an error of 25% or less. Depending on the satellite, its useful lifespan will likely range from 5 to 15 years. It is difficult to plan them to last much longer than that, because the solar arrays fail or because they run out of fuel needed to keep them in the proper orbit.

The predicted values are estimated and perhaps better than original values, but the difference is likely not much in a good forecasting model.

Figure 5 below shows a fitted trend equation of $Y_t = -544.7 + 47.66t$ for time t, and a Mean Absolute Percent Error (MAPE) of 250% indicating a bad fit to the trend curve.

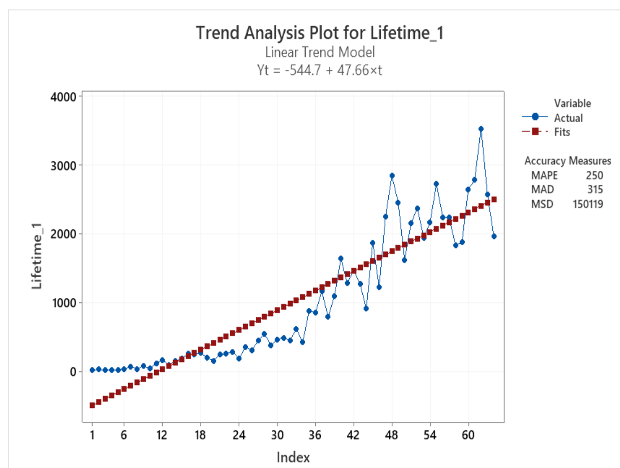

Figure 5. Trend Analysis for Original & Predicted Lifetimes for Data of Figure 4.

“Index” in the horizontal axis of Figure 5 above and Figure 7 below indicates the bucket size for data values as determined by Minitab for the 5450 data values inputted. The residual plots for Figure 5 are shown below in Figure 6 indicating decreasing fits from mid-section onward even though normality is fairly reasonable.

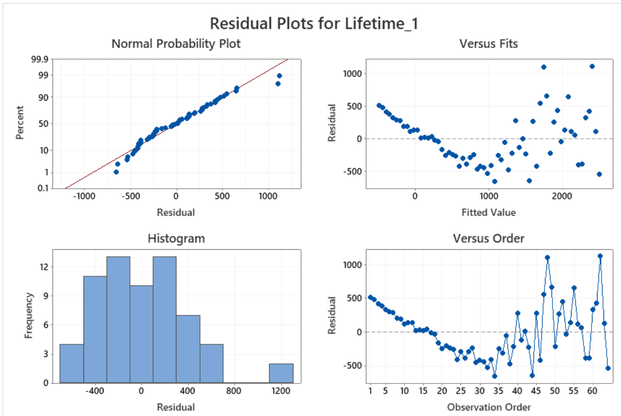

Figure 6. Residual Plots for Trend Analysis of Figure 5.

The Mean Absolute Percent Error (MAPE) value is reduced by smoothing the time series data as shown in below Figure 7 where MAPE is 20.5% and a more symmetrical histogram of residuals was found as shown in the residual plots of Figure 8.

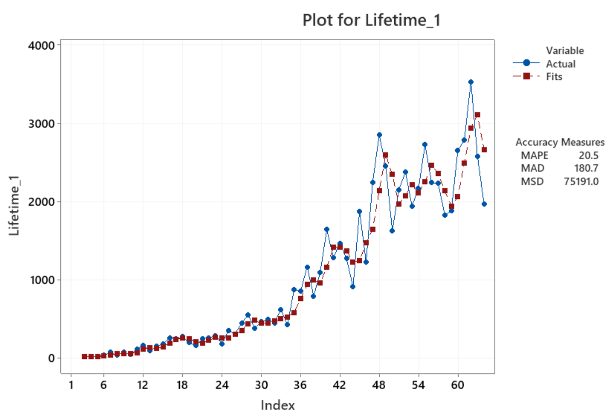

Figure 7. Smoothed Time Series Plot for Figure 4 Data.

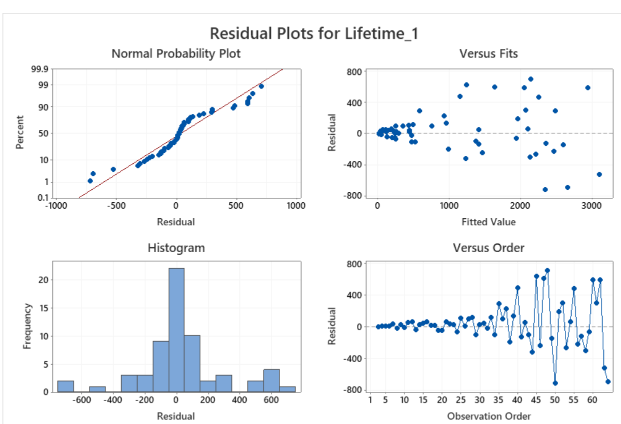

Figure 8: Residual Plots for Smoothed Figure 4 Data.

Figure 8 shows residual plots for a minimally smoothed version of the “Original and Predicted Lifetimes” data from Figure 4.

4. CONCLUSION

We analyzed quantitative data about satellite lifetimes to develop and curve fit models that circumvent noise and provide predicted values for average lifetimes by year of failure. Since dependable tests for costly equipment like satellites can be infeasible, analysis approaches such as discussed here become important. Other approaches can focus on qualitative information and this can use customer opinions, as well as expert experience and expertise.

This article discussed how to analyze satellite lifetimes to find curves that fit the data. The fitted curves often proved to be very close to actual data values. The errors were often low. Quantitative prediction can help an organization, but it may be helpful to give more recent data more weight, since underlying engineering and social processes may change over time. This would potentially allow improved identification of patterns that could lead to improved predictions.

Future research will be dedicated to analyzing the half-lives of satellites and using that to focus on projecting future lifetimes of satellites by launch year rather than, as in the present study, estimating conformance of satellite lifetime data to fitted curves that remove noise from the data to predict underlying (denoised) lifetimes of satellites by year of failure.

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