Understanding Variation

26 YEARS LATER

IN 1931, Walter Shewhart published his landmark book *Economic Control of Quality of Manufactured Product*. He asserted that his theory and methods were an innovation to the science of management and wrote: "We are sold on the idea of applying scientific principles. However, a change is coming about in the principles themselves, and this change gives us a new concept of control."[1]

W. Edwards Deming supported this idea in a foreword he wrote for the 1986 republishing of Shewhart's *Statistical Method From the Viewpoint of Quality Control*: "Another half-century may pass before the full spectrum of Dr. Shewhart's contributions has been revealed in liberal education, science and industry."[2]

In 1990, QP published "Understanding Variation" by two of this article's authors.[3] The article included examples of the economic and psychological losses associated with interpretations of data without a framework for understanding variation. The economic losses included misguided changes to service delivery, investigations of trends where none existed and increased costs from increased variation. The psychological losses included blaming workers for what were actually faults of the system and experiencing anxiety from false hopes of improved operating conditions.

Correctly assessing variation is fundamental to sound decisions

by Thomas Nolan, Rocco J. Perla
and Lloyd Provost

In 50 Words Or Less

- Decisions made without knowledge of common and special causes often lead to increased variation, poor performance and misattributed credit or blame.
- Extending the application of Walter Shewhart's approach to variation to datasets across a range of publicly available sources is an opportunity to improve decision making and learning from reported data.

Today, 26 years later, big data analytics, data-driven decision making, business intelligence and transparency in public data have created new opportunities for an understanding of variation to guide decision making. The U.S. Bureau of Labor Statistics, for example, is the principal federal agency responsible for measuring labor-market activity, working conditions and pricing changes in the economy. Its mission statement emphasizes the collection, analysis and dissemination of "information to support public and private decision making."[4] Without useful interpretation, however, this dissemination could actually degrade decision making.

We want to extend the application of Shewhart's methods presented in our 1990 article to data sets across a range of publicly available sources—sources that are used by and the basis for the U.S. government and other organizations to assess conditions and make decisions. Compared with data from individual organizations, the scale of these data sets underscores the importance of understanding and applying Shewhart's theory.

Shewhart's theory of variation

Shewhart's theory of variation differentiated between common and special causes of variation in data:

- **Common causes—**Those causes that are inherent in a system (process or product) over time, affect everyone working in the system and affect all outcomes of the system.
- **Special causes—**Those causes that are not always part of a system (process or product) or do not affect everyone, but arise because of specific circumstances.[5]

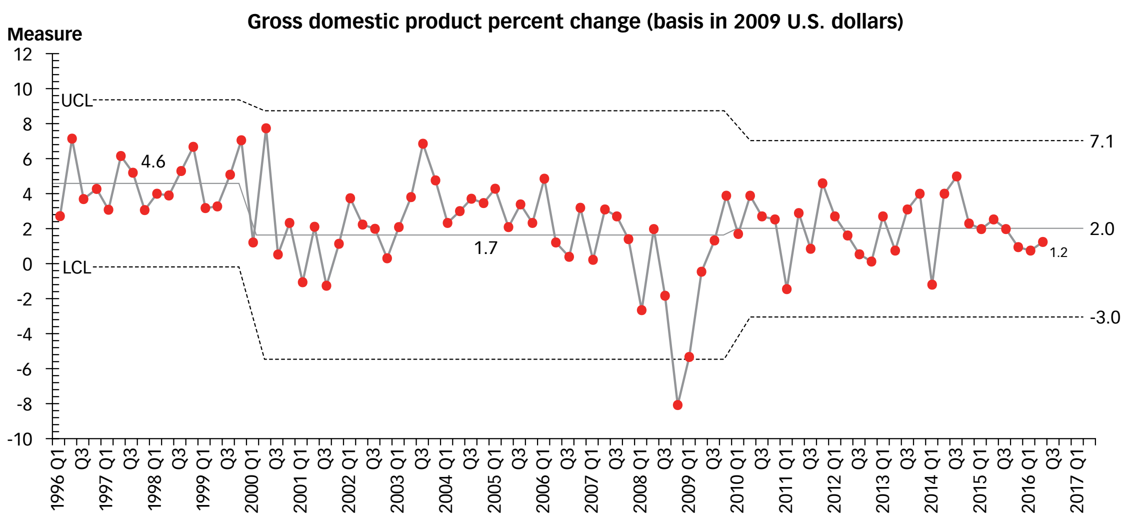
A process or system that has only common causes affecting the measurement of interest is called a stable process. A stable process is one in which the cause system for the measure of interest remains essentially constant over time. A stable process implies only that the variation in outcomes is predictable within limits, not that it has desirable or undesirable performance.

A process with outcomes affected by common and special causes is called an unstable process for the measure of interest, with the magnitude of the variation from one time period to the next being unpredictable. As special causes are identified and appropriately acted on, the process becomes stable.[6]

This theory of variation provides a basis for action to improve a system. A stable system requires a fundamental change to affect its future performance (because it is stable), while an unstable system requires local action depending on the special cause.

In addition to providing the basic concepts of the theory, Shewhart also introduced the control chart method to determine whether variation in a process is due to common or special causes. The Shewhart control chart consists of three lines and points plotted on a graph.

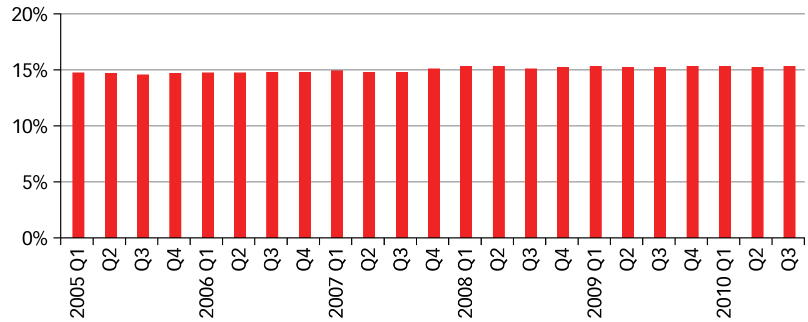
Shewhart control chart example for an economic measurement / FIGURE 1



UCL = upper control limit
LCL = lower control limit

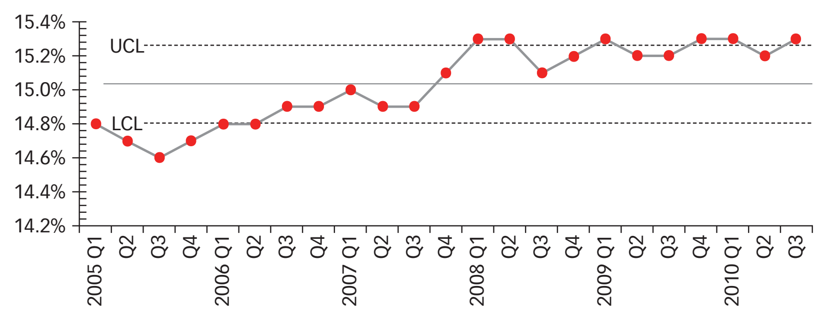
While there are numerous books describing how to construct Shewhart's charts, we will focus on the broader method and its modern applications.[7]

Nursing facility residents with one or more falls with major injury / FIGURE 2



Source: U.S. Department of Health and Human Services, "Health System Measurement Project," https://healthmeasures.aspe.hhs.gov.

Nursing facility residents with one or more falls with major injury (Shewhart chart) / FIGURE 3



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Shewhart control chart method

Figure 1 shows an example of a Shewhart control chart for a popular federal economic measurement—the quarterly change in gross domestic product (GDP). This measurement is usually presented in published reports and on the U.S. Department of Commerce's website.[8] Business media report reactions when the quarterly value is released or revised. For example, the *Wall Street Journal* used the headline "U.S. GDP Grew a Disappointing 1.2% in Second Quarter" for an article that offered this summary of 2016's second quarter:

> Declining business investment is hobbling an already sluggish U.S. expansion, raising concerns about the economy's durability as the presidential campaign heads into its final stretch. Gross domestic product, the broadest measure of goods and services produced across the U.S., grew at a seasonally and inflation adjusted annual rate of just 1.2% in the second quarter, the Commerce Department said Friday, well below the pace economists expected.[9]

Each quarter is treated as a special event. For example, the *Wall Street Journal* recently published these headlines for three sequential quarters:

1. **"U.S. Economy Shows Signs of Gearing Up"**—reporting on 2013's fourth quarter in which there was a 3.5% increase in GDP.[10]
2. **"U.S. Economy Shrinks by Most in Five Years"**—reporting on 2014's first quarter in which there was a 2.1% decrease in GDP.[11]
3. **"Growth Rebound Stokes Fed Debate"**—reporting on 2014's second quarter in which there was a 4% increase in GDP.[12]

These reports clearly suggest big, quarter-to-quarter swings in our economy as if they confer actionable information. The Shewhart chart in Figure 1, however, indicates a stable system for the previous five years. The economic losses associated with the misinterpreted variation in quarter-to-quarter data include the consequences of actions taken by individuals and institutions based on nonexistent trends such as potentially raising or lowering the U.S. interest rate, which carries profound economic implications for global markets as well as the United States. Applying the Shewhart chart method can minimize these losses.

The method's five key components are:

1. **A selection of a measurement and statistic to be plotted.** The choice of measurement will give different insights about a process or system. In the GDP example, the key statistic reported was the change (percentage difference from the previous quarter) in GDP.
2. **A method of data collection from the process or system—observation, measurement and sampling procedures.** These methods provide an operational definition for the measurement, and information in the Shewhart chart always will be conditional on how data are collected and a measurement is obtained. The U.S. Department of Commerce's website offers an extensive explanation

about how GDP data are collected.[13]

3. **A strategy for determining subgroups of measurements, including size and frequency.** The aim of rational subgrouping is to include only common causes of variation in a subgroup, with all special causes of variation occurring between subgroups. The most common method to obtain rational subgroups is to hold time constant within a subgroup (that is, to include data from the same week, month or quarter). Other subgrouping strategies can be used to test theories about potential causes of variation, such as subgrouping by demographics.
4. **A calculation of the center line and limits that provide criteria for identifying a sign of a special cause.** The center line is the average of the individual data points and the limits are based on statistical calculations of common cause variation that establish the upper and lower bounds of system performance. Shewhart's method is empirical and designed to minimize the risk of over and underreacting to the data. "An assignable [special] cause of variation, as this term is used in quality control work, is one that can be found by experiment without costing more than it is worth to find it."[14] In other words, if it costs more to find the problem than the value in addressing it, that is not economical.

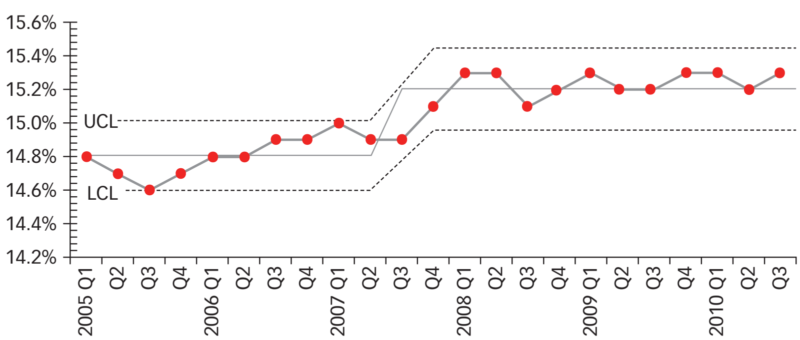
   In most applications, for points that fall outside of Shewhart's three-sigma limits, it will be cost effective to search for a specific cause or to design a test to understand it. For the GDP chart in Figure 1 (p. 30), the fourth quarter of 2008 and the first quarter of 2009 are below the lower limit. All the other values are inside the limits of the chart. When the initial chart was constructed using all the data points, there are some other indications of additional special causes. There were, for example, 19 consecutive quarters above the center line from 1996 through the fourth quarter of 1999. The limits in Figure 1 have been calculated for three time periods to reflect these patterns.
5. **A plan to address the special causes, which uses the new knowledge to improve the system.** The goal of the chart is not to just detect special causes but to identify the cause and gain insights into the causal system affecting the measurement. A discussion about signs of a special cause on the GDP chart in Figure 1 would be instructive reading on the Commerce Department's website and in business journals.

   Currently, because each reported value is already explained in detail, there is no analysis done for the quarters that represent signs of special cause. This is a waste of potential new knowledge and a potential loss for those who assume the point-by-point explanations are informative.

Case studies using government data

We applied Shewhart control charts to data that are publicly reported to inform interested parties about various systems' performances. For each of

Nursing facility residents with one or more falls with major injury (including pre and postshift phases) / FIGURE 4



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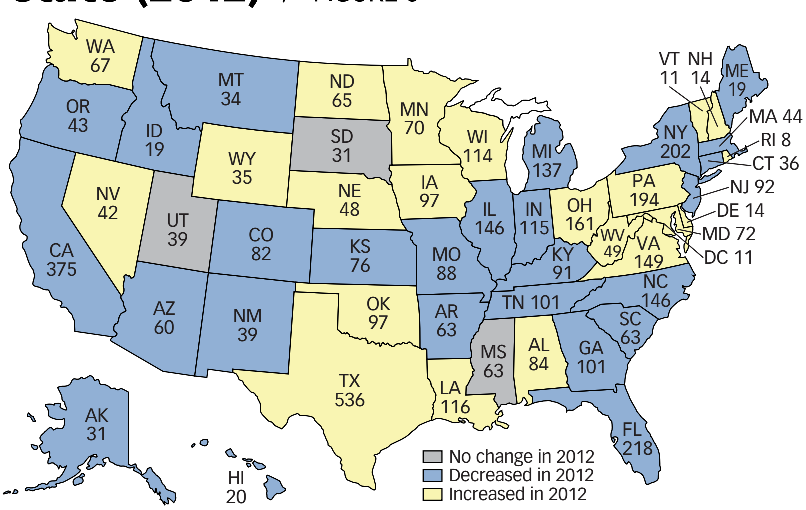
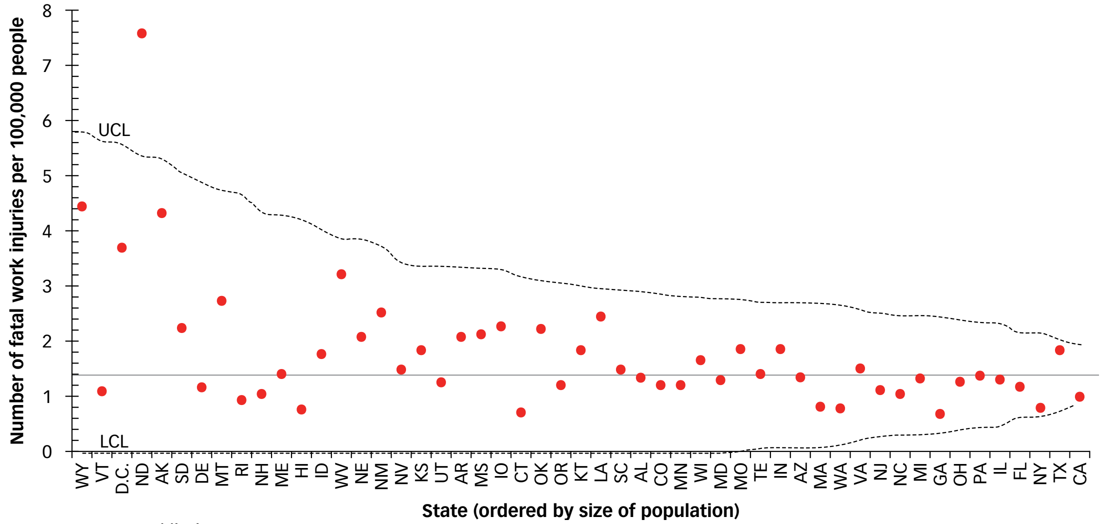
LCL = lower control limit

Number of fatal work injuries by state (2012) / FIGURE 5



Fatal work injury rate by state (2013) / FIGURE 6



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Source: U.S. Bureau of Labor Statistics

these three cases, Shewhart charts are developed, and two questions are asked:

1. Is the process currently stable? That is, are there special causes we can learn from?
2. Based on this knowledge, what type of action makes sense?

Case one—U.S. Department of Health and Human Services (falls with injury):[15] The U.S. Centers for Disease Control and Prevention estimates about 1,800 older adults living in nursing homes die each year from fall-related injuries, and many more suffer permanent disabilities.

Figure 2 (p. 31) shows a graph available through the U.S. Department Health and Human Services that represents the national percentage of nursing home residents who had one or more falls with a major injury. A final analytic report summarizing more recent data for the Centers for Medicare and Medicaid Services in 2011 concluded

ADDITIONAL CASE STUDIES ON VARIATION SOUGHT

The authors presented four examples of publicly reported data in which using Shewhart's theory and method would lead to better reporting and decision making. They are seeking to increase their number of examples to help build the case for broad adoption of Shewhart's method.

The authors ask that you send them interesting examples that illustrate how appropriately using Shewhart's method would lead to more effective learning and better decision making. They have four recommendations for obtaining a better return on the substantial investment in public and private data systems by using this method:

1. **Make data available over time.** Any effective analytic strategy must allow users to understand variation in the systems they are responsible for over time to gain new knowledge as conditions change, and as new programs and initiatives are attempted. Move away from judging or defining a system or results of improvement efforts or policy decisions based on single data points.
2. **Provide data in formats that allow for construction of Shewhart charts.** The data should be made available in formats that allow Shewhart charts to be easily constructed—even if automated chart generation is not possible. For many current data reports, it is either not possible or it takes considerable effort to acquire data needed to construct a Shewhart chart.
3. **Determine whether a process is stable.** Always ask one simple question when making an important decision based on data: Is the process stable over time? Because we live in an era of accountability, there is intense pressure to demonstrate positive results. Yet, decisions we make on variation from one time period to another, often lead to increased variation, poor performance, failure to learn, and misattribution of credit and blame.
4. **Think carefully and creatively about how to stratify data.** Always consider approaches to segment and stratify data that are being presented to inform the public. This increases our ability to learn about the effect of context on variation in the system and understand the impact of changes made to the system over time and whom they affect.

To submit your case study, email Lloyd Provost at lprovost@apiweb.org.—*T.N., R.P. and L.P.*

that "when taking this scale of scored values into account … it is easy to see that they are not changing very much from quarter to quarter" with no reference to a previous upward shift in falls with major injury.[16]

Viewing this data on a Shewhart chart, however, a different conclusion is reached (see Figure 3, p. 31). The upward shift in falls with major injuries begins around the fourth quarter of 2007. We can separate the phases of data (pre and postshift) to gain a better understanding of what's going on.

Figure 4 (p. 32) shows the same chart, but with the center line and limits calculated separately for pre and postshift phases. What we learn from this analytic process is that the rate of falls with major injury fundamentally changed for the worse.

Next, we need to answer case one's two primary questions:

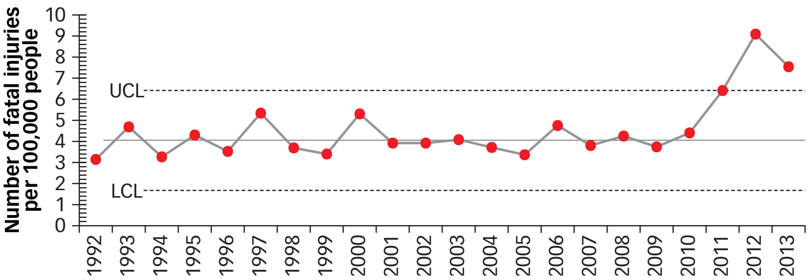
1. **Is the process currently stable?** A special cause began around 2007's fourth quarter. After updating the limits to reflect this change, the harm over time is stable, and we can predict that the percentage of residents with falls will be 14.9 to 15.4% each quarter.
2. **Based on this knowledge, what type of action makes sense?** Using the Shewhart chart method, we observed a national increase of 0.5% (3.4% relative increase) resulting in nine additional expected deaths per year and many disabilities. Why did this increase occur, and what we can learn from it? Identifying the special cause could serve as a productive topic of conversation between the executive branch and the legislative oversight committee.

Case two—U.S. Department of Labor (work fatalities):[17] The Bureau of Labor Statistics (BLS) publishes an annual color-coded map relating to fatal work injuries (see Figure 5, p. 32). The colors show whether a state's number of fatal work injuries increased (yellow), decreased (blue) or stayed the same (gray) from the previous year.

In 2012, North Dakota and Minnesota experienced an increase in work fatalities. In 2011, North Dakota officials were concerned about the increased frequency, which some attributed to growth in the energy sector and an increased number of workers with riskier jobs in sectors such as the oil industry.

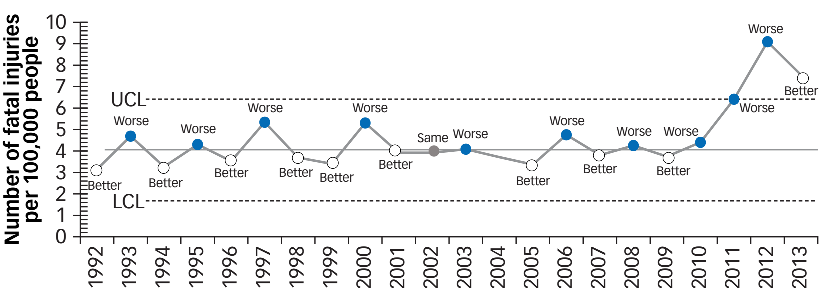
If we calculate a rate[18] and use a Shewhart chart, we see that North Dakota is beyond the upper limit, indicating a fundamental difference from other states in the work environment (see Figure 6, p. 33). Focusing on North Dakota over time

Fatal work injury rate in North Dakota (1992-2013) / FIGURE 7



UCL = upper control limit
LCL = lower control limit

Fatal work injury rate in North Dakota (1992-2013)—chart with limits based on 1992-2010 / FIGURE 8



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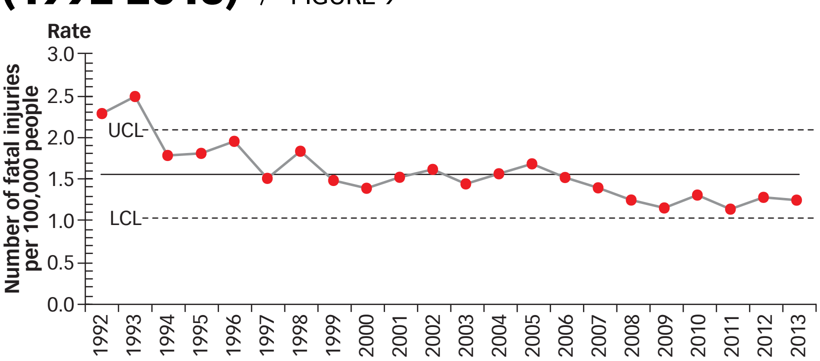
Fatal work injuries in Minnesota (1992-2013) / FIGURE 9



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shows that in 2011 the state was outside the upper limit of its predicted rate of fatal work injuries (see Figure 7).

Despite the fact that data points from 2011 to 2013 are beyond the upper limit and that the report from the American Federation of Labor and Congress of Industrial Organizations recently called North Dakota the most dangerous state to work,[19] the BLS's 2013 map suggested that North Dakota improved because the raw number of fatalities was less than the previous year.

The period-to-period comparison is misleading and contributes to unscientific use of data to support entrenched positions. The stark contrast of these two views of variation is illustrated in Figure 8, which shows each data point on the Shewhart chart using the BLS map's color-coded assessment.

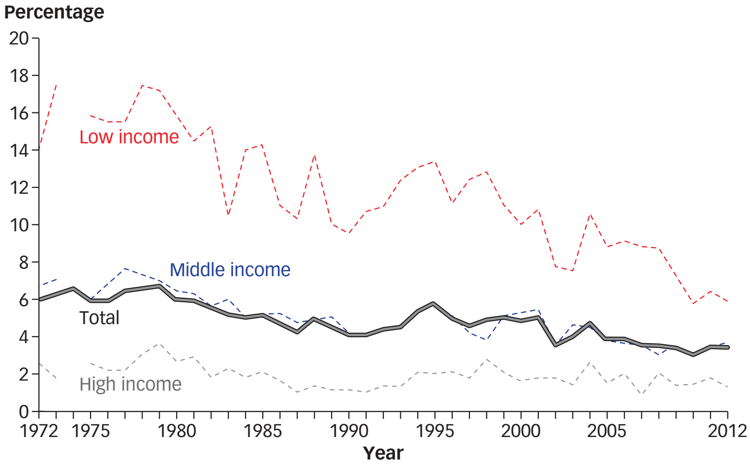
Unlike the Shewhart chart that provides an understanding of the upper and lower limits of fatal injuries over time in North Dakota—that is, a system view of all data—the color-coded map excludes most of the data and limits what the analysis provides to whether conditions are getting better or worse from the prior year.

The BLS's map also labeled Minnesota as having an increase in fatalities from 2012. Compare the North Dakota's chart with Minnesota's (see Figure 9). Although the frequency of injury for these two states was characterized as increasing from 2011 to 2012, they both moved in opposite directions.

Next, we need to answer case two's two primary questions:

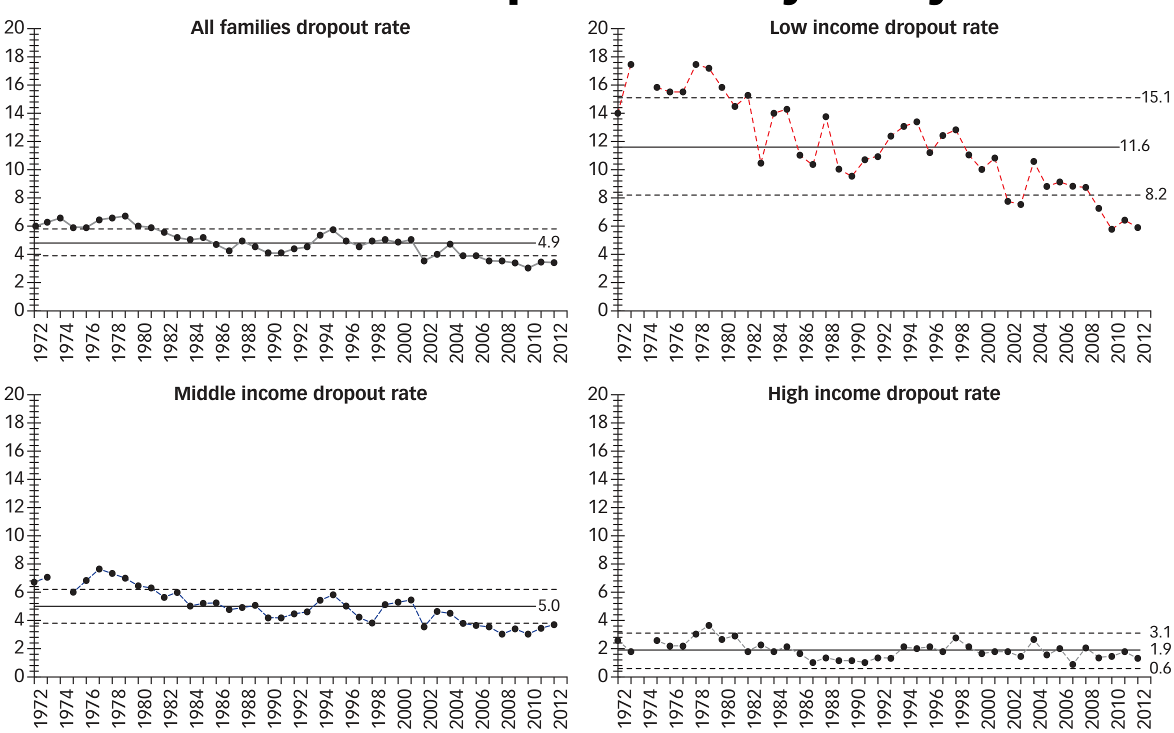
1. **Is the process currently stable or predictable?** There are important special causes in the injury rate comparisons

Dropout rates by family income, 15 through 24-year-olds who dropped out of grades 10 through 12 / FIGURE 10



Source: U.S. Department of Education, "Trends in High School Dropout and Completion Rates in the United States: 1972-2009," https://nces.ed.gov/pubs2012/2012006.pdf.

Shewhart charts of drop-out rates by family income / FIGURE 11



between states and within states over time.

2. **Based on this knowledge, what type of action makes sense?** Part of the BLS's mission is to support public and private decision making, and using a Shewhart chart in its public data displays would help it realize this mission. If Shewhart charts were used, an investigation of changes in systems in North Dakota (becoming more dangerous) and Minnesota (becoming safer) could provide knowledge on which to base improvement efforts for work environments in those states and others.

Case three—U.S. Department of Education (high school dropouts):[20] The U.S. dropout rate has been declining for decades. Part of an annual report from the department depicted this decline for all students and for low, middle and high-income families (see Figure 10, p. 35).

Even a relatively effective time series graph such as this one can be improved using Shewhart charts. From Figure 10's graph, it might be concluded that current approaches to reducing dropout rates are effective, supporting a "more of the same" approach.

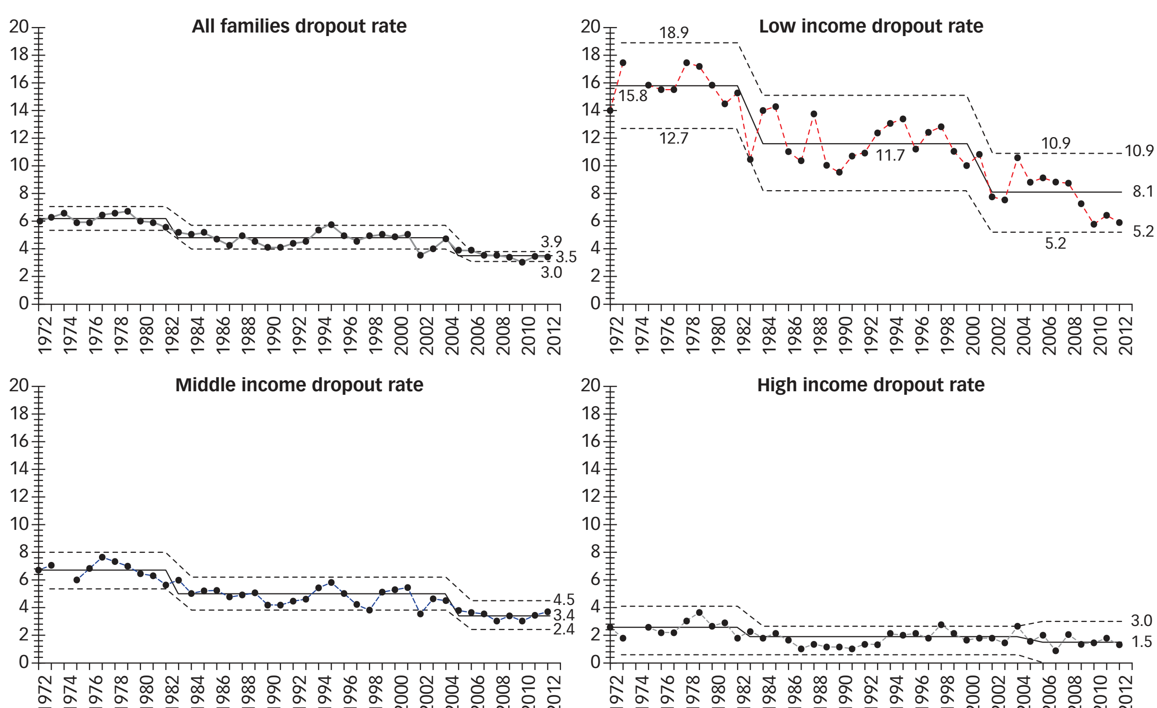
Figure 11 (p. 35) contains four Shewhart charts in a small-multiples layout. The charts show signs of a special cause and suggest the dropout rate has declined primarily because of two special causes (creating three time periods).

One special cause occurs at about 1982 and the other at about 2002. Figure 12 shows these charts with each illustrating these three periods. An analyst can now focus on understanding the changes that occurred during the years that led to these fundamental changes. Also during the most recent period (2002), the low-income dropout rate seems to be decreasing while the rates for the other two groups appear stable.

Next, we must answer case three's two primary questions:

1. **Is the process currently stable or predictable?** From 1972 to 2012, the process was not stable or predictable for all students and for the three levels of family income.
2. **Based on this knowledge, what type of action makes sense?** The U.S. Department of Education invests millions of dollars in the High School Graduation Initiative,[21] also known as the School Dropout Prevention Program. Understanding the cause and effect associated with the special-cause periods could help focus this investment.

Shewhart charts for dropout rates by family income during three periods / FIGURE 12



There were no federal appropriations from 2007 to 2009 for this initiative, but from 2010 to 2014, appropriations jumped to about $50 million annually. Shewhart charts will help us learn about the impact of this funding and whether it makes sense to continue at current levels.

School of variation

When Deming and Shewhart warned about economic losses incurred by not understanding variation, they were not talking in theoretical terms—these losses are real and can influence people's financial, physical, social and emotional well-being. These examples are not even the tip of the iceberg.

Until Shewhart's theory of variation is a standard part of citizen's education, we will continue to have managers, scientists and leaders confusing chance occurrences with special events, which often leads to actions that increase variation and produce worse outcomes. This education can begin immediately if government agencies and other national organizations use Shewhart's theory and the control chart method to report and interpret the data they disseminate.

Respected journalistic institutions also can contribute to this education by moving away from headlines based on uninformative, point-to-point variation to offering conclusions that take into account the scientific meaning of the data based on variation over time.

Where will we be 25 years from now in our understanding of variation? At a minimum, simply asking two primary questions to guide any analysis will lead to a better understanding of variation and more effective decision making. QP

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7. For additional information about how to construct Shewhart charts, read *The Health Care Data Guide: Learning From Data for Improvement* by Lloyd Provost and Sandra Murray (Jossey-Bass, 2011) and *Advanced Topics in Statistical Process Control* by Donald Wheeler (SPC Press, 1995).
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15. Data used for case study one are from the Office of the Assistant Secretary for Planning and Evaluation—Health System Measurement Project. The measurement name used was the "percentage of nursing facility residents experiencing one or more fall with major injury," and the chart type was an individual chart with the numerator and denominator not reported. The subgroup for this case study is a quarter. For more information, visit: https://healthmeasures.aspe.hhs.gov.
16. Laura Smith, Nan Tracy Zheng, Karen Reilly, Stephanie Kissam, Franziska Rokoske, Daniel Barch, Yevgeniya Kaganova, Audrey Etlinger and Jashua Manning, *Nursing Home MDS 3.0 Quality Measures: Final Analytic Report*, Centers for Medicare & Medicaid Services: Division of Ambulatory and Post Acute Care, September 2012.
17. Case study two used data from the U.S. Bureau of Labor Statistics. The measurement name used was the "number of fatal work injuries (2012)," and the chart type was a U-funnel plot, with states ordered by increasing population size with an adjustment for over-dispersion due to large subgroup sizes. States are the subgroup for this case study.
18. Though the U.S. Bureau of Labor Statistics uses total number of hours worked by state in its rate-based calculations of fatal work injuries, these data are not easily accessible to the public. We therefore use population density as a surrogate in our analysis to demonstrate how to learn from variation at the state level. Similar charts can be constructed using different rate formulas. One of the challenges to creating Shewhart charts is that it requires access to disaggregated data, which are often not available through public sources.
19. The American Federation of Labor and Congress of Industrial Organizations (AFL-CIO), *Death on the Job: The Toll of Neglect*, AFL-CIO, 2012, http://tinyurl.com/afl-cio-jobdeaths.
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