The State of Statistical Process Control: An Update

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Topics

- Brief introduction
- Profile monitoring
- Health-related surveillance
- Contrasts between industrial and health-related surveillance
- Other areas of research and application
Keys Aspects of Statistical Process Monitoring

1. Data are collected over time.
2. Shifts in parameters of underlying models are to be detected as quickly as possible.
3. A “signal” is given that a change from the baseline has occurred.
4. One wants to control the “false alarm rate”.
Sample Mean

\[ \bar{X} = 100.035 \]

Sample Range

\[ R = 2.239 \]

UCL = 101.32

LCL = 98.744

\[ \bar{X} \]

Xbar-R Chart of Quality Characteristic
Profile Monitoring: The objective is to monitor functional data over time.

Linear Profile Data Framework:

Response (Y) vs. Explanatory Variable (X)

- \( j = 1 \)
- \( j = 2 \)
- \( \ldots \ldots \ldots \)
- \( j = k \)

\( n = 10 \) sample profiles with \( n > 1 \) observations in each profile
Profile Monitoring

Example 1: Semiconductor Manufacturing (from Vivek Ajmani)

NWD C Lot Level Data
NSJ203
Fmax vs. ACLEMN by PL1_WW

- 215 N=10 X=2409 S=134 Med=2429 IQR=38
- 216 N=40 X=2420 S=102 Med=2419 IQR=131
- 217 N=8 X=2345 S=109 Med=2321 IQR=184
- 218 N=15 X=2344 S=93 Med=2303 IQR=160
- 220 N=1 X=2.48E+03 S=0.00E+00 Med=2.48E+03 IQR=0.00E+00
- 221 N=7 X=2329 S=104 Med=2378 IQR=209
- 222 N=18 X=2353 S=98 Med=2340 IQR=191

Symbols:
- ▲ 215
- □ 216
- ▼ 217
- ◼ 218
- ▼ 220
- ▲ 221
- ▼ 222
Example 2: Vertical Board Density Profile Data from Walker and Wright (JQT, 2002)

We have 24 profiles of vertical density, each profile consists of $n = 314$ measurements.
Profile Monitoring

Example 3: Fitted Dose-Response Profiles of a Chemical (DuPont)
Example 4: Signature Analysis for Stamping Process Monitoring and Diagnosis (from Jan Shi, Georgia Tech)
Example 5: Roundness profiles obtained by turning (from Bianca Colosimo, Politecnico di Milano, Italy)

100 cast C20 carbon steel cylinders (supplied in Ø30 mm rolled bars) machined to nominal Ø26 mm. Each profile was sampled 748 times by a CMM.
Applications of Profile Monitoring

- Stamping processes
- Calibration of measurement devices
- Dimensional and shape control
- Paper quality
- Spectroscopy
- Laser sensor data in lumber manufacturing
- Automobile air bag quality
- Wind turbine power curves
- Asphalt quality
Some Models for Profiles

- Simple linear regression
- Polynomial regression
- Multiple regression
- Nonlinear regression, including logistic regression
- Mixed models
- Wavelets
- Nonparametric smoothing
- ...
Review papers on Profile Monitoring


Biosurveillance

Healthcare Monitoring


- **Hospital and physician performance tracking** (often risk-adjusted) See Thor et al. (2007) *Quality & Safety in Health Care*.

Public Health Surveillance

- **Monitoring of incidence rates** (temporal and spatiotemporal, chronic disease and infectious disease)

- **Syndromic surveillance** – involves use of multiple dissimilar data streams to detect outbreaks or attacks
Examples of health care variables

- Lab turnaround time
- Days from positive mammogram to definitive biopsy
- Patient satisfaction scores
- Medication error counts
- Emergency service response times
- Infection rates
- Mortality rates
- Number of patient falls
- Post-operative length of stay
- “Door-to-needle” time ......and many others...
Risk adjustment is most often necessary in comparing rates between hospitals and doctors due to differences in patient mix, i.e., varying health risk factors of patients.

See [http://www.sfar.org/t/spip.php?article60](http://www.sfar.org/t/spip.php?article60) for information on various ICU and surgical risk scoring methods.
Table 1  Parsonnet risk factors

<table>
<thead>
<tr>
<th>Parsonnet factor</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Patient factors</strong></td>
<td></td>
</tr>
<tr>
<td>Female sex</td>
<td>1</td>
</tr>
<tr>
<td>Left ventricular ejection fraction 30-49%</td>
<td>2</td>
</tr>
<tr>
<td>Preoperative balloon pump</td>
<td>2</td>
</tr>
<tr>
<td>Weight ≥1.5 times ideal</td>
<td>3</td>
</tr>
<tr>
<td>Diabetes</td>
<td>3</td>
</tr>
<tr>
<td>Hypertension (systolic pressure &gt;140 mm Hg)</td>
<td>3</td>
</tr>
<tr>
<td>Left ventricular ejection fraction &lt;30%</td>
<td>4</td>
</tr>
<tr>
<td>Age 70-74</td>
<td>7</td>
</tr>
<tr>
<td>Dependent on dialysis</td>
<td>10</td>
</tr>
<tr>
<td>Emergency due to failure in cardiac catheter laboratory†</td>
<td>10</td>
</tr>
<tr>
<td>Age 75-79</td>
<td>12</td>
</tr>
<tr>
<td>Age ≥80</td>
<td>20</td>
</tr>
<tr>
<td>Catastrophic state</td>
<td>30</td>
</tr>
<tr>
<td><strong>Procedural factors</strong></td>
<td></td>
</tr>
<tr>
<td>CABG at time of valve surgery</td>
<td>2</td>
</tr>
<tr>
<td>Valve replacement:</td>
<td></td>
</tr>
<tr>
<td>Tricuspid valve</td>
<td>3</td>
</tr>
<tr>
<td>Aortic valve (gradient ≤120 mm Hg)</td>
<td>5</td>
</tr>
<tr>
<td>Mitral valve (PASP &lt;60 mm Hg)</td>
<td>5</td>
</tr>
<tr>
<td>Congenital heart disease</td>
<td>5</td>
</tr>
<tr>
<td>Left ventricular aneurysm</td>
<td>5</td>
</tr>
<tr>
<td>First reoperation</td>
<td>5</td>
</tr>
<tr>
<td>Valve replacement:</td>
<td></td>
</tr>
<tr>
<td>Aortic valve (gradient &gt;120 mm Hg)</td>
<td>7</td>
</tr>
<tr>
<td>Mitral valve (PASP ≥60 mm Hg)</td>
<td>8</td>
</tr>
<tr>
<td>Second or subsequent reoperation</td>
<td>10</td>
</tr>
<tr>
<td>Heart transplantation</td>
<td>15</td>
</tr>
</tbody>
</table>

CABG=coronary artery bypass grafting. PASP=pulmonary artery systolic pressure.
*Add all weights that apply to patient and type of operation—for example, female patient having tricuspid valve replacement has estimated risk of 1+3= 4%.
†For example, cardiac perforation.

http://www.sfar.org/scores2/parsonnet2.html
Example of a two-sided risk-adjusted CUSUM chart (provided by Stefan H. Steiner)
The CUSUM chart is the best option.

- It can be risk-adjusted.
- It has optimality properties in detecting sustained shifts in the process.
- It has good inertial properties.
- It can be designed based on meaningful performance measures such as average run length (ARL).
- It can be run in the background with a more interpretable chart if necessary.
Cluster Detection in Public Health Surveillance

There are some new methods for detecting clusters prospectively, i.e., as they are forming with spatiotemporal data.

This is a very challenging problem.
Scan Methods

Kulldorff’s (2001, JRSS-A) SaTScan™ methods (available at [www.satscan.org](http://www.satscan.org)) are very popular.

A window moves and varies in space and time. It is a likelihood ratio-based method that incorporates simulation to determine decision rules.

Performance Metrics

In industrial SPC the key performance metrics are based on the time-to-signal.

Health-related metrics include sensitivity, specificity, probability of a false alarm, probability of successful detection, predictive value, recurrence interval, etc., etc.

(See Fraker et al., 2008, Quality Engineering)
In industrial applications the focus is on the time to the first alarm, whereas in public health surveillance monitoring is ongoing and methods are not reset after an alarm.
The **recurrence interval** (RI) is the fixed number of time periods such that the expected number of signals is one. It is estimated as the reciprocal of the proportion of plotted points beyond the control limits.

The **average time-to-signal** (ATS) is the expected number of time periods to obtain the first signal.

With on-going monitoring the **average time between false alarms** becomes important.

If consecutive signals over time are considered as only one signal event, the RI value contains little information on time-to-signal or time-between-alarms performance.

The clustering of signals is ignored with use of the recurrence interval.
Health-related vs. Industrial Applications

In health-related applications...

- Data are more often attribute (yes/no) data with 100% inspection with an assumed underlying Bernoulli, Poisson, geometric or exponential distribution.

- Methods are frequently evaluated only on an example case study dataset. Data models are rarely used relative to the industrial SPC literature.
In health-related applications...

- ... outbreaks are most often of limited duration.
- ... methods are usually one-sided.
- ... monitoring schemes are usually not reset after a signal.
In health-related applications...

- ... *p*-values and scan methods are more often used in surveillance.

- ... baselines, often seasonal, change frequently even for “in-control” processes.

- ... control limits are updated frequently, although “guard-bands” are sometimes used.
Some Healthcare Monitoring Review Papers


The profile monitoring and spatiotemporal surveillance research done in the last ten years is in line with the recommendations of Nair V, Hansen M, and Shi J (2000), “Statistics in Advanced Manufacturing”, JASA, 95 (451), 1002-1005.
Some Other Areas

- **Adaptive Control Charting** (Tsung and Wang, 2009)
- **Autocorrelated Data** (Psarakis et al. 2007, *QTQM*)
- **Change-point Methods** (Work by Emmanuel Yashchin, Joe Pignatiello, and Doug Hawkins)
- **Effect of Parameter Estimation** (Jensen et al. 2006, *JQT*)
- **Financial/Economic Applications** (Emmanuel Yashchin, Marianne Frisén, and Wolfgang Schmid)
- **Multivariate Charts** (Bersimis et al. 2007, *QREI*)
- **Sampling Issues** (by Marion Reynolds, Zachary Stoombos, and others)

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There are many important applications and research opportunities in the process monitoring area, especially in profile and health-related monitoring.
References


