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# Operational Decision-Making in Healthcare Using Control Charts

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# OPERATIONAL DECISION-MAKING IN HEALTHCARE USING CONTROL CHARTS

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OPERATIONAL DECISION-MAKING IN HEALTHCARE USING CONTROL CHARTS

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# ABSTRACT

The primary objective of this thesis was to design a framework supplemented with guidelines for the healthcare managers to select an appropriate type of control chart for operational decision-making. A systematic literature review was conducted to gauge the extent to which control charts were being used in a healthcare setting for clinical decision-making and operational decision-making purposes. The findings showed that the application of control charts was almost equal for the clinical decision-making sector and the operational decision-making sector. On further analysis, the ability of control charts to function as a standalone tool was affirmed by the vast majority of studies where it was deployed as a primary tool for quality improvement purposes.

The framework contains some prerequisites with regards to data collection and construction of control charts. Also, the metrics involved are clearly identified: Quality, Financial, Volume and Utilization; and subsequently defined. The guidelines were created keeping the metric and possible scenario/s that can be associated with it into consideration. These guidelines would save the healthcare managers their time and significantly reduce the chances of selecting an inappropriate type of control chart. Potential operational areas for the usage of control charts are also discussed in the thesis.

In order to demonstrate the way in which the prescribed framework can be implemented in a real-life hospital environment, a regional hospital was chosen and the yearly rate of Surgical Site Infections (SSI) for colon surgery was monitored using an appropriate control chart which was selected by following the guidelines outlined in the framework.

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# 1. INTRODUCTION

The healthcare industry is one of the largest and fastest growing industries in the world (KFF, 2006). Moreover, the cost of healthcare is continuously rising. Its sheer size and the diverse nature of operations make it susceptible to errors which furthermore increases the overall cost for the provision of services. Quality in healthcare, on the other hand, is of paramount importance because even a slight decline could cause significant consequences in terms of life or death for the patient (Prajapati & Suman, 2018). Therefore, it is crucial that healthcare services are provided at a reasonable cost with an appropriate quality. To address cost and quality issues, quality and process improvement methods and tools are often suggested and have been adopted by the industry since the early 1999s (Chassin & Loeb, 2011). Statistical process control (SPC) with its many tools and methods is one such strategy used by the healthcare professionals in order to monitor processes and identify issues. Among SPC tools, control charts are being used increasingly to detect variations in the processes.

The motivation behind this research was to design a framework that could be employed in implementation of control charts in the healthcare sector for operational decision-making. The framework provides a methodological approach and helps healthcare professionals in understanding and selecting key quality indicators to monitor using control charts for improving their processes. The framework focuses mainly on the operational decision-making as opposed to clinical decision-making. Clinical decision-making in healthcare is defined as the decisions made by doctors or nurses when they monitor clinical variables relevant to patients' courses of treatment or health status;

whereas operational decision making in healthcare is defined as the decision making carried out to improve the process indicators relevant to the operations of the organization such as hospital revenue, wait times, and patient volume.

Control charts are visual tools generated by statistical analysis of process data. They help in monitoring key performance indicators and in revealing the variation in a process and furthermore, allow identifying whether this variation is due to special or common causes. Common cause variation is the variation inherent in the process and is a natural variation when the process is operating under normal conditions. Special cause, on the other hand, signals an unexpected, unpredictable or unusual factor impacting the operation of the process.

The trends in use of control charts in the healthcare sector show that their use in operational decision-making is slightly higher than their use in clinical decision-making. However, there is a lack of framework to ensure smooth deployment of control charts for quality and process improvement from an operational perspective. There is a need to clearly define the metrics involved and monitor the most important ones to effectively use available resources, make better decisions and generate policies conducive to the process changes targeted with the improvement initiative. To address this need, this thesis prescribes a set of guidelines for healthcare managers in using control charts in operational decisions. A case study is presented to demonstrate the use of the proposed framework. The data for the case study was extracted from the *healthdata.gov* website and contained the information for the surgical site infection at a particular hospital from the year 2013 to the year 2019. The proposed framework provides an understanding of the metrics commonly used in improvement initiatives and the types of variables that may be closely associated with them; and provides recommendations on key factors for successful implementation such as selection of appropriate control limits, training of the hospital staff in the data collection process, and transparence in executing the improvement project.

# 2. METHODOLOGY

The first part of this chapter provides the theory of control charts. The second part describes the systematic literature review followed to identify and summarize the existing evidence on the use of control charts in healthcare, which was then used to build the framework proposed in this research.

## 2.1. Control Charts

Control charts were developed by Walter Shewhart for monitoring and controlling key performance indicators in the manufacturing industry. (MacCarthy & Wasusri, 2001). Shewhart aimed to reduce variation in the manufacturing of telephone components when he was working at Western Electric. During his studies he realized that variation would always be a part of the process and further recognized the need to classify the variation observed in a process, whether it was expected or unexpected, called common cause and special cause respectively (MacCarthy & Wasusri, 2001). Control charts are graphical tools that plot the process data to visualize whether a process being monitored is stable or not. A stable process, also called a process in-control, exhibits only common causes of variation. Common cause variation is a source of variation that is natural and expected and is inherent to the process. On the other hand, a process that is not stable, i.e. not in control or out-of-control, depicts special cause variation; variation that is not a natural part of the process. Monitoring a process with control charts aims to reveal the special causes.

A control chart typically consists of a centerline, an upper control limit and a lower control limit, and the control limits are set at ± 3 standard deviations (σ) from the centerline. $\pm 3\sigma$ are industry standards and were selected to balance Type I and Type II errors in statistical decision-making (Benneyan, Lloyd & Plsek, 2003). Type I and Type II errors occur when the data leads to decision-making that contradicts with the real status of the process. Type I error (**α**) also known as a false positive happens when the system incorrectly signals about the existence of special cause variation when in fact the process is in control. Reducing the σ limits increases the risk of Type I error. Type II error (**β**) also known as a false negative happens when the chart does not signal about the presence of a special cause when in fact the process is unstable. The risk of Type II error increases when the σ limits are widened.

The control charts are selected based on the type of data being monitored: attribute or variable. An attribute data, also referred to as a count data, means it can be counted and the variables data is the data which is usually measured on a continuous scale. An example of an attribute data is the number of doctor visits made by a patient in a year since it is a count item and will only take discrete values. An example variable data is the body temperature of a patient since it has to be measured and is on a continuous scale. Table 2.1 shows the list of commonly used control charts by their types; Tables 2.2 and 2.3 provide the formulas used for calculating the limits of the attribute and variable control charts.

**Table 2.1 Classification of Control Charts Based on their Functions**

| Chart Type | It is used to plot: | Data Type [V: Variable; A: Attribute] |
|---|---|---|
| *X-bar* chart | the arithmetic means of successive samples of constant size | V |
| *R-chart* | the range of subgroups | V |
| *s-chart* | the standard deviation of subgroups | V |
| *XmR chart* | individual observations with *X* indicating observation and *mR* indicating moving range | V |
| Run Chart | individual observations over time (without control limits) | V or A |
| *p*-chart | the proportion of non-conforming units in a sample | A |
| *np*-chart | the number of non-conforming units in a sample | A |
| *u*-chart | the average number of defects per unit | A |
| *c*-chart | the total number of non-conformities per unit | A |
| *EWMA* chart | individual observations with each observation receiving less weight as they are further from the current observation | V |
| *CUSUM* chart | the cumulative sums of deviations of observations from a target value | V or A |
| *g-chart* | the number of days between rare events or the number of opportunities between rare events | A |

**Table 2.2 Control Charts for Attribute Data**

| Type of control chart | Lower control limit (LCL) | Center line (CL) | Upper control limit (UCL) | Comments |
|---|---|---|---|---|
| *C-chart* | $\bar{c} - 3\sqrt{\bar{c}}$ | $\bar{c}$ | $\bar{c} + 3\sqrt{\bar{c}}$ | Preferable to use when the sample size (n) remains constant, where $\bar{c}$ = count per subgroup |
| *U-chart* | $\bar{u} - 3\sqrt{\bar{u}}$ | $\bar{u}$ | $\bar{u} + 3\sqrt{\bar{u}}$ | Generally used when the sample size (n) does not remain constant, where $\bar{u}$= average count per subgroup |
| *P-chart* | $\bar{p} - 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$ | $\bar{p}$ | $\bar{p} + 3\sqrt{\frac{\bar{p}(1-\bar{p})}{n}}$ | Used when proportion of non-conforming items is an area of interest and sample size (n) is not constant |
| *Np chart* | $n\bar{p} - 3\sqrt{n\bar{p}(1-\bar{p})}$ | $n\bar{p}$ | $n\bar{p} + 3\sqrt{n\bar{p}(1-\bar{p})}$ | Used when the sample size (n) remains constant and when number of nonconforming items is an area of interest |
| *G-chart* | $\bar{g} - 3\sqrt{\bar{g}(\bar{g}+1)}$ | $\bar{g}$ | $\bar{g} + 3\sqrt{\bar{g}(\bar{g}+1)}$ | Used when one has to monitor the rare events |

**Table 2.3 Control Charts Formulas for Variables Data Type**

| Type of control chart | Lower control limit (LCL) | Center Line (CL) | Upper control limit (UCL) | Comments |
|---|---|---|---|---|
| *X-bar* | $\bar{\bar{X}} - A2 * \bar{R}$ | $\bar{\bar{X}}$ | $\bar{\bar{X}} + A2 * \bar{R}$ | Value of A2 is used from a standard table and depends on the number of subgroup size selected. $\bar{R}$ represents the Range average |
| *R chart* | $\bar{R}$* D3 | $\bar{R}$ | $\bar{R}$* D4 | Generally used for subgroup size of 10 or less. Values of D3 and D4 can be found out from a standard table depending on the subgroups |
| *S chart* | $\bar{S}$ * B3 | $\bar{S}$ | $\bar{S}$ * B4 | Generally used for subgroup size exceeding 10. Values of B3 and B4 can be found out from a standard table depending on the subgroups |
| *MR chart* | $\bar{MR} * D3$ | $\bar{MR}$ | $\bar{MR} * D4$ | Values of D3 and D4 come from a standard table depending on the number of subgroups and $\bar{MR}$ represents moving range average |

The control charts presented in Table 2.2 and Table 2.3 fall under the category of Phase I charts. Phase I control charts are used when the process stability is not known and generally one is interested in detecting large changes in the process. There are other charts such as EWMA and CUSUM charts that fall under the category of Phase II control charts. Phase II control charts are typically used when the process is already in control and one is monitoring the process to specifically detect small changes in the process. However, for the purpose of this thesis, our focus is on Phase I charts only. Selecting subgroups is an important factor in constructing control charts. A subgroup is defined as a group of units that are created under the same set of conditions. Rational subgrouping is one strategy to select subgroups. Rational subgrouping advocates for selecting subgroups in a manner where the variation within subgroups should be as small as possible which helps in detection of variation among subgroups with ease (Montgomery, 2013).

## 2.2. Systematic Literature Review

In efforts to build the proposed framework, first a systematic literature review was conducted. The search protocol for this review is summarized in Figure 2.1.

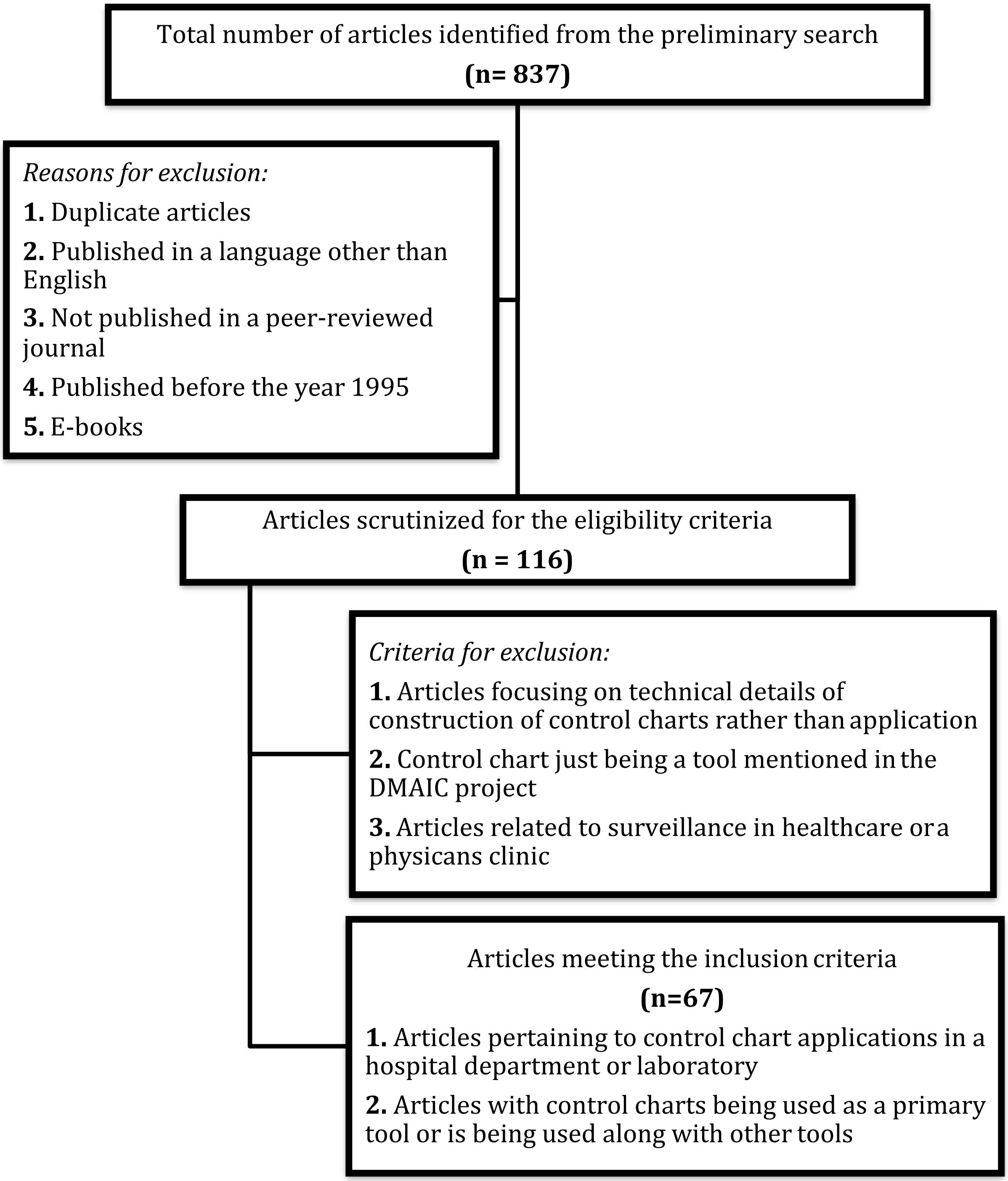


**Figure 2.1 Strategy for Study Selection**

The review was focused on the questions "how extensive is the use of control charts in operational decision-making at hospitals?" and "what are the metrics targeted when the operational decision-making is concerned?”. The keywords used for the search were ‘control charts in healthcare’ & ‘statistical process control in healthcare’. The search included PubMed, Web of Science, ABI/INFORM, Academic Search Premier, EBSCO, Emerald Full Text Journals, Engineering Management, Industrial Engineering and Operations Management Collection, KNOVEL Library Collections, Pro Quest Direct, Sage Premier Collection, Taylor & Francis, Wiley Online Library, Medline. This search returned 837 articles, which were then narrowed down to 116 by eliminating duplicate articles, e-books, articles written in a language other than English, not published in a peer-reviewed journal and published before the year 1995. Then, studies with application scope that extend the boundaries of a hospital, such as control charts used for public health surveillance, or control charts being applied in a general physician’s clinic and studies which included control charts as a quality improvement tool but did not necessarily document the type of control chart or the specific contribution of the control charts in the improvement process were excluded. The remaining studies were then further filtered based on the following inclusion criteria:

- Studies pertaining to control chart applications in a hospital department or laboratory
- Studies where control charts is being used as a primary tool or is being used along with other tools

In the end, there were 67 studies that matched the search criteria. The shortlisted studies were then analyzed in detail to depict the current usage of control charts at hospitals.

The use of control charts from application perspective including application areas, application type: for clinical decision-making or operational decision-making, and type of charts used are presented in Sections 2.2.1 and 2.2.2. Other key findings such as classifications of studies by country, publication year, and publication journal are discussed below.

***Country Distribution***

The distribution of studies by country (see Table 2.4) shows that the top three countries with the highest number of the studies are U.S., U.K. and Australia; which accounted for almost 61% of the total studies (n=67). Canada and France accounted for 3 studies each while Switzerland and India accounted for 2 studies each. The rest which included Taiwan, Turkey, Germany, Nigeria, Spain, Korea, Qatar, Thailand, Singapore, Israel, Brazil and Italy all had single studies each. There were 4 studies where the country of origin was not specified. The results show that the U.S. hospitals have the lead on use of control charts. Although it is possible that more authors may be publishing studies that were conducted in the U.S., the quantitative difference between the number of studies from the U.S. and other countries is so large to support the conclusion that control chart usage is more common at U.S. hospitals.

**Table 2.4 Country Wise Distribution of Studies**

| Country | Number of studies |
|---|---|
| U.S.A. | 25 |
| U.K. | 10 |
| Australia | 6 |
| Canada | 3 |
| France | 3 |
| Switzerland | 2 |
| India | 2 |
| Brazil , Germany, Israel , Italy , Korea , Nigeria , Qatar , Singapore , Spain , Taiwan, Thailand , Turkey | 1 per country |
| Unspecified | 4 |

### *Publication Year*

The earliest applications of control charts appear in the literature from the year 1997, as shown in figure 2.2. Thereafter, somewhat a steady increase is observed with some exceptions, particularly years 2002, 2005 and 2014. Overall, an upward trend is visible in use of control charts in healthcare.

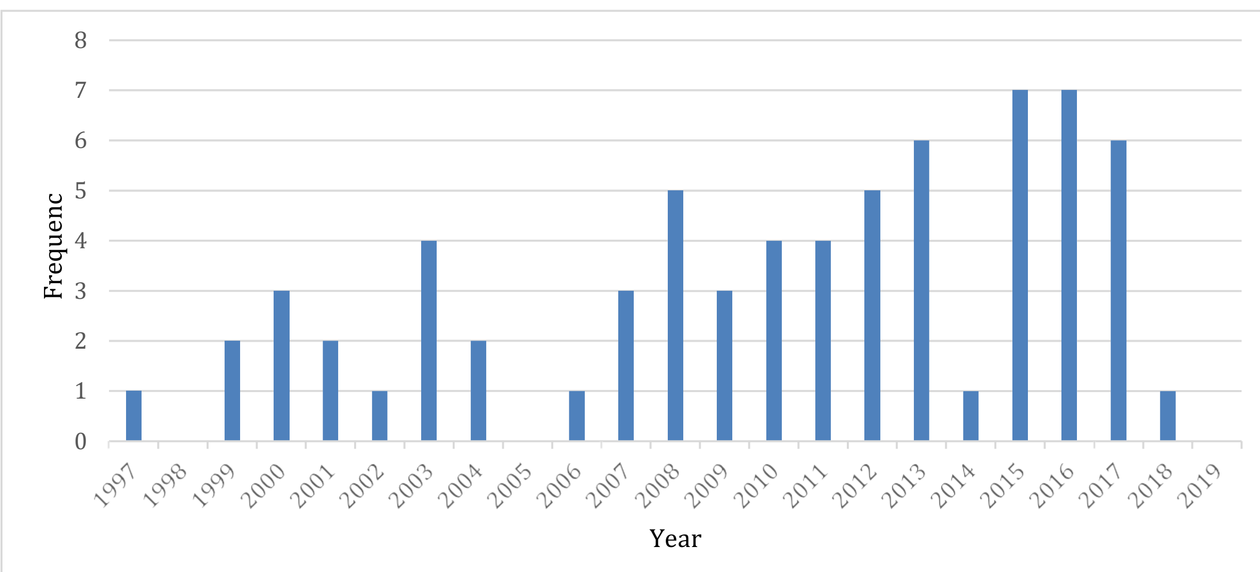


**Figure 2.2 Control Charts in Healthcare - Studies Published by Year**

***Publication Journal***

Figure 2.3 shows the number of studies found in different peer-reviewed journals. The highest number of studies was extracted from the *International Journal for Quality in Healthcare* with 13 studies. This was followed by the *Quality Management in Healthcare* journal with 10 studies. The *International Journal of Healthcare Quality Assurance* contributed with 9 studies while *BMJ Quality & Safety* yielded 8 studies. *American Journal of Medical Quality* and *International Journal of Lean Six Sigma* provided 4 studies each. These six journals collectively accounted for approximately 72% of the total selected studies. These findings indicate that the majority of the studies come from publications focusing on healthcare than those with a general focus on quality.


**Figure 2.3 Frequency of studies in the Selected Peer-Reviewed Journals**

A few studies were found that focus broadly on the application of control charts in a healthcare setting as a quality improvement tool, however, there were no studies that classified control charts in healthcare based on usage purpose and metrics involved or that prescribed a set of guidelines for their implementation. Given the diverse nature of the healthcare industry it is instrumental to classify the decisions into separate domains in order to effectively study the metrics involved and the factors contributing to the success of the deployment of control charts in their context. Sections 2.2.1 and 2.2.2 explain control chart usage from clinical decision-making and operational decision-making perspectives respectively.

### 2.2.1. Control Charts for Clinical Decision-making

Clinical decision-making in healthcare may be defined as the decisions made by doctors or nurses to choose a future course of action for their patients. In this decision making process control charts help them in monitoring individual patient data such as the daily systolic blood pressure levels of patients suffering from hypertension, blood glucose levels of a diabetic patient or the serum creatinine levels of a patient who has undergone kidney transplant (Suman & Prajapati, 2018).

Figure 2.4 shows the number of studies published from the year 1997 till the year 2019, in which control charts were used for clinical decision-making. The number of clinical studies published was highest in the year 2016 at a total of seven studies followed by the year 2017 with a total of four studies. It can be seen that there is a uniform trend from the year 1997 till the year 2004 barring a few data points in between. Overall, there is no significant increasing or decreasing trend found with respect to the studies published, nevertheless, the last two years on the chart point to an increasing trend but more data is needed to confirm.

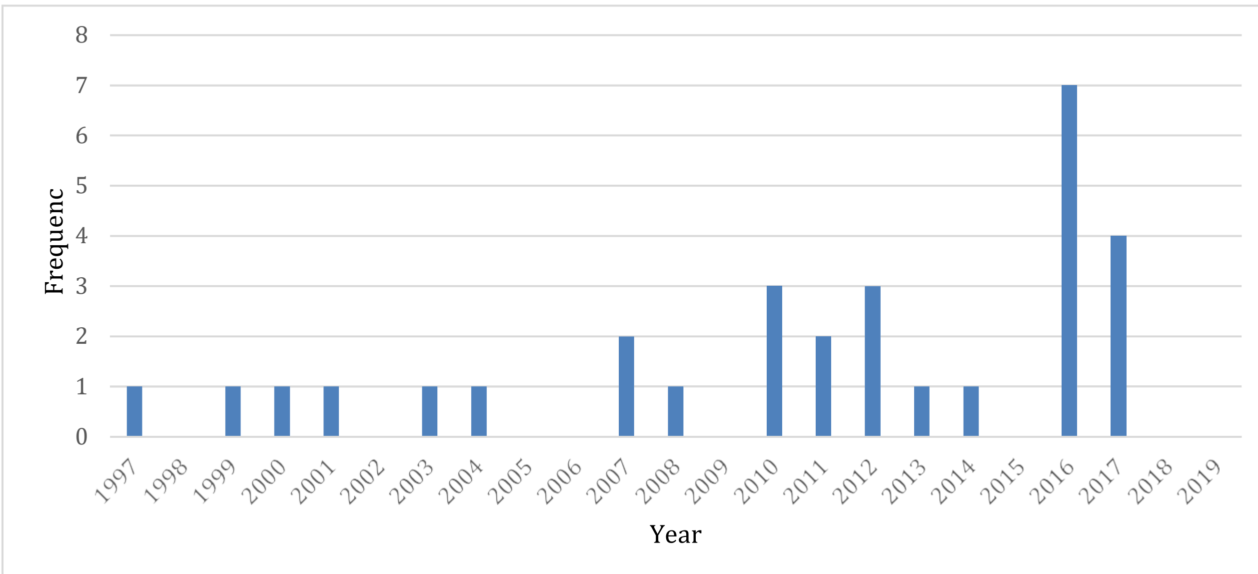


**Figure 2.4 Control Charts in Healthcare - Clinical Studies Published by Year**

One of the earliest documentations of control charts being used for clinical decision-making was in the emergency department where *p*-charts were employed to monitor the number of births with cesarean section (Kaminsky et al., 1997). Morton *et al.* (2001) suggested the use of control charts over traditional monitoring methods for the detection and monitoring of hospital acquired infections. Their idea was to use Shewhart charts for detecting changes in the number of monthly infections in a hospital. In their study, ± 2σ control limits were used to mitigate the risk for patient safety. Narrowing control limits is a known approach in cases where the variable monitored is directly related to patient safety, it is however advised to set the control limits at ± 3σ to lessen the risk of false positives if patient safety is not a concern in the study (Benneyan et al., 2003).

The control charts are used in many areas in a hospital for clinical decision-making, for example Emergency, Surgery, Radiology, and Cardiology (Suman & Prajapati, 2018). Fuangrod *et al.* (2016) documented the use of *I-MR* chart in radiology for monitoring the gamma pass rate for two different radiation therapy procedures in individual patients. Limaye *et al.* (2008) demonstrated the use of *g*-charts, a type of chart used for attribute data to monitor the number of events between rarely occurring nonconforming incidents, in the surgery department to monitor the number of days between the hospital acquired infections such as Blood Stream Infections (BSI), Ventilator Associated Pneumonia (VAP) and Urinary Tract Infections (UTI). In addition, they depicted the use of *u*-charts for monitoring the number of infections per month per 1000 patient days. Choi *et al.* (2017) documented the use of *p*-chart in an emergency department to monitor the proportion of single blood cultures sent to the laboratories before and after education intervention.

The type of control charts used depends on the variable to be monitored and the type of underlying distribution it follows. Figure 2.5 shows the control chart types and their frequency of appearance in the studies that involve clinical decision-making. We see that the *p*-chart is the most popular type of control chart in clinical decision making. It is used to monitor clinical variables which are binomial in nature such as monitoring the proportion of surgical complications in a month, and percentage of surgical site infections in a month. The use of *Xbar* chart is the second highest in the clinical studies. There are many quality indicators relevant to clinical decision making that fall into variable type data such as blood glucose levels of a patient, serum creatinine level in the body, etc.

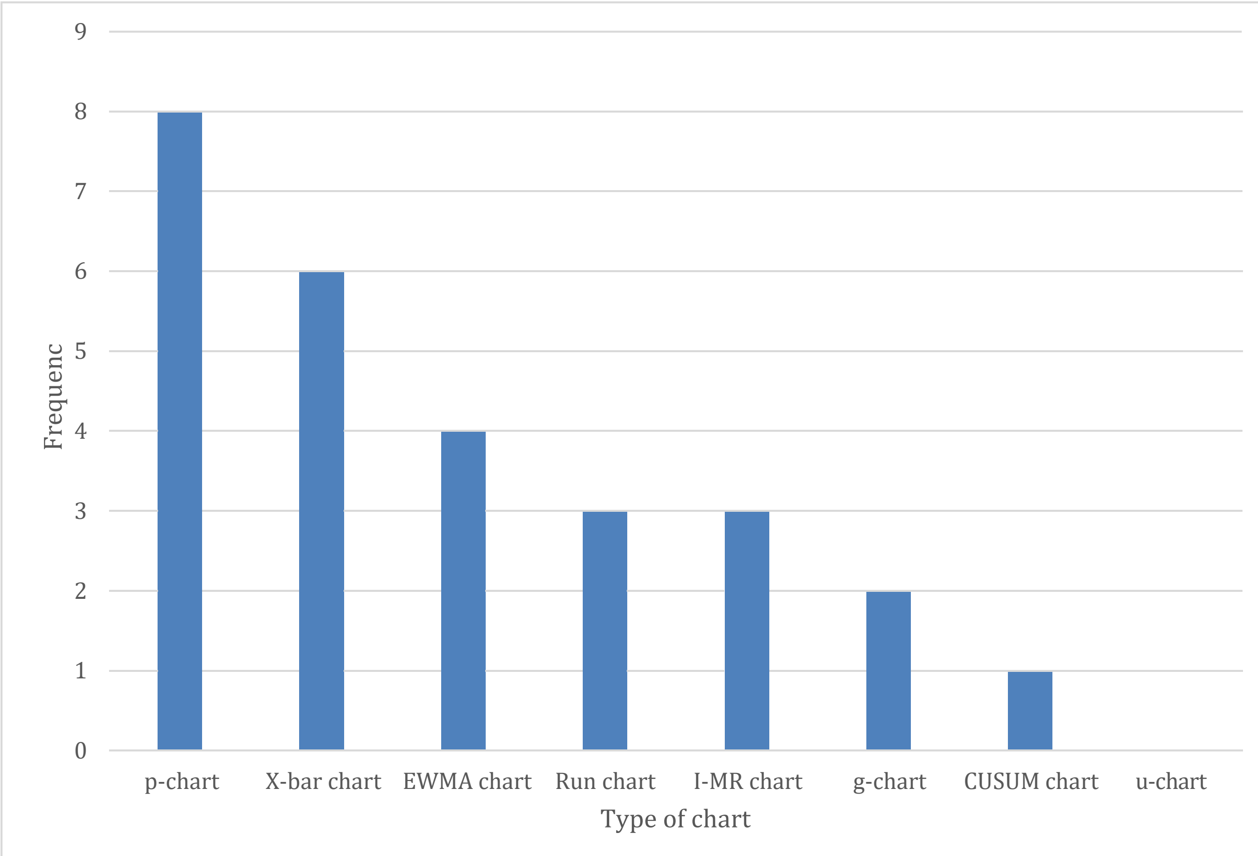


**Figure 2.5 Frequency of Control Chart Types Used in Clinical Studies**

### 2.2.2. Control Charts for Operational Decision-making

Operational decision-making in healthcare may be defined as the decisions made by the healthcare managers in order to improve the process indicators relevant to the operations of the organization which can include parameters such as hospital revenue, wait times and patient volume. Figure 2.6 represents the number of operational studies published from the year 1997 till the year 2019. The number of studies published peaks in the year 2013 and the year 2015 with a total of five studies in each year. Moreover, from the year 2008 to the year 2012 there was somewhat of a uniform trend similar to from the year 1999 to the year 2004.

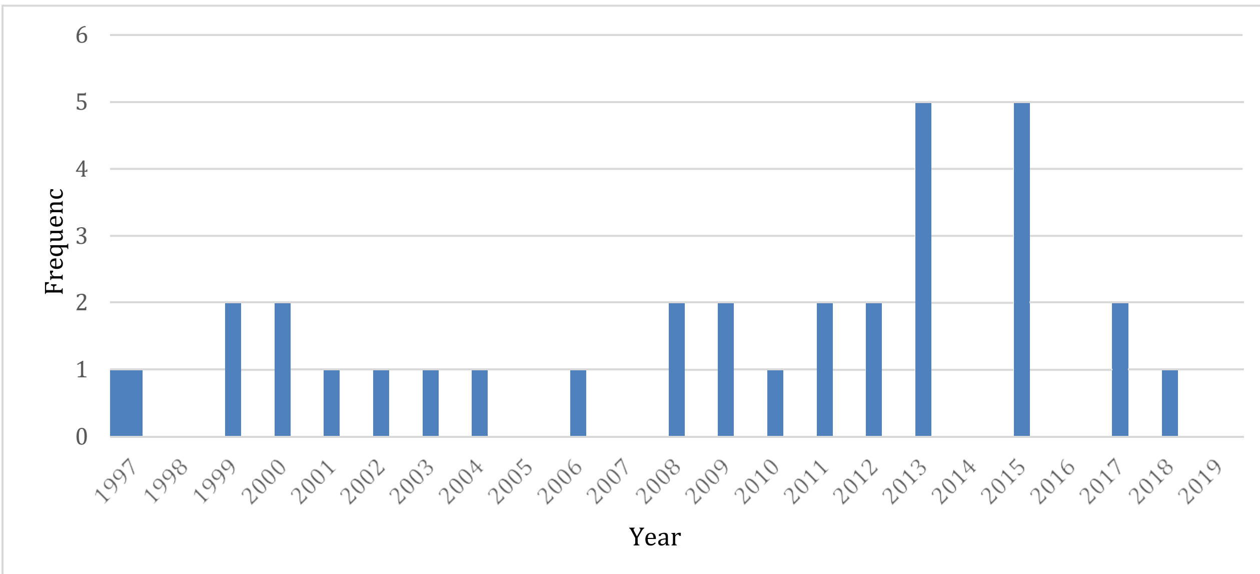


**Figure 2.6 Operational Studies Published on a Yearly Basis**

The use of control charts in operational decision-making appear in literature slightly more than their use in clinical making, therefore, there are more examples to understand their use in this context. Callahan & Griffen (2003) documented the use of *I-MR* chart in the emergency department (ED) to monitor the door-to-reperfusion time for patients with acute myocardial infarction. Door-to-reperfusion time is the delay between the arrival of a patient in an emergency department with an acute myocardial infarction and the restoring of the patient's blood flow to an organ or tissue with intervention. The control charts helped the ED to identify and eliminate the special cause of variation, thus helped them reduce the door-to-reperfusion time. Howard *et al.* (2018) presented the use of *u*-chart to monitor adverse events in an emergency department as a trigger tool to identify adverse events and to measure the rate of adverse events over time. Walley *et al.* (2006) used *Xbar* chart to monitor the percent of patients treated and admitted, transferred or discharged in 4 hours or less in the emergency department. Welch & Dalto (2011) used the *Xbar* chart to track the door-to-physician times in the emergency departments of two community hospitals.

The use of control charts for operational decision-making is not limited to the department of emergency alone; one can also find instances where control charts were used in the hospital administration department. Canel *et al*. (2010) used *c*-chart to monitor the days to completion for the assembled records post improvement initiatives at the administration department of the hospital. In order to meet the standard assembly record completion times, set by the Joint Commission on the Accreditation of Healthcare Organization, the improvement team implemented a process redesign, and an after *c*-chart showed that the redesign effort was successful. Robinson & Neyens (2017) described the use of *u*-charts for monitoring harm and no-harm events at the hospital and department level.

As for the type of charts used in operational decision-making, the use of *p*-chart is the highest followed by the *u*-chart and Run chart, as shown in Figure 2.7. The high usage of *p*-charts can be attributed to the fact there are indeed a number of operational variables which are binomial in nature such as the number of falls in a month for a hospital, the proportion of hospital acquired infections and so on. The second highest usage of u-chart can be employed to monitor variables such as the number of medication errors or the number of harmful events, which are frequently analyzed events in a hospital.

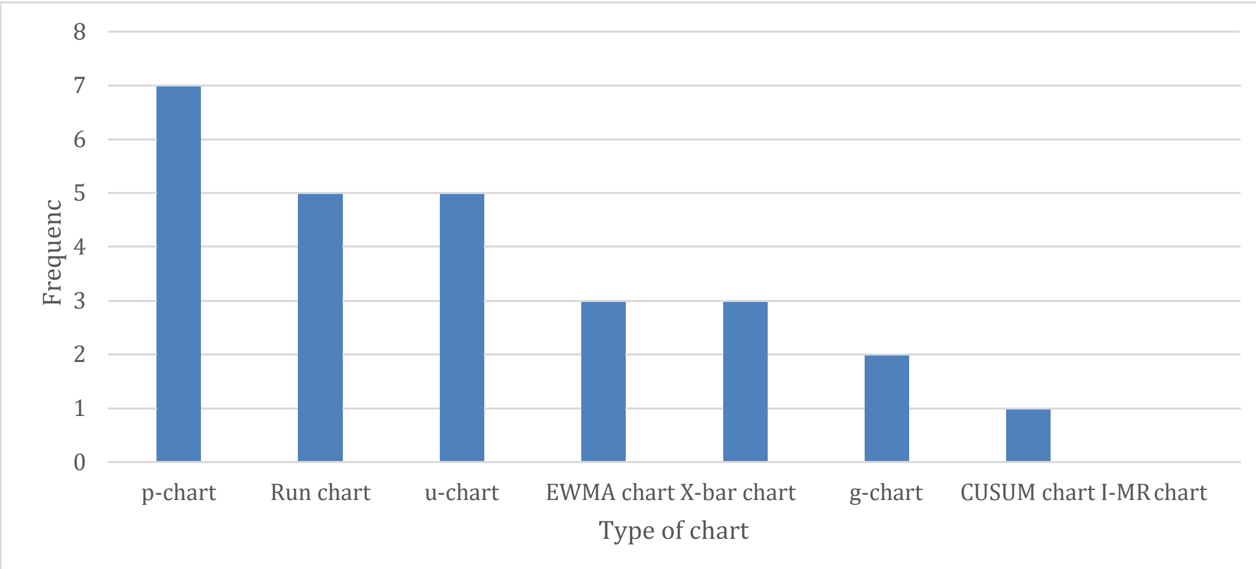


**Figure 2.7 Frequency of Control Chart Types Used in Operational Studies**

## 2.3. Framework for the deployment of control charts in the operational sector

The literature provided a foundation to build a framework for the use of control charts particularly for operational decision-making. First, the studies pertaining to operational decision-making were divided based on the metrics targeted. The metrics, which are defined below, were quality, volume, financial, and utilization.

***Volume metrics:*** This is used when one has to measure a parameter such as the flow of patients in a hospital setting which comprises variables like the number of patients visiting a particular department and the number of inbound referrals if any.

***Utilization metrics:*** This metric is employed when the utilization of doctors or the department is of concern. Examples are appointments completed per doctor in the hospital, total number of surgeries performed by a surgeon in a month, appointments scheduled vs. appointments fulfilled department wise in a hospital.

***Quality metrics***: This metric typically comes into picture when the parameters of interest include employee satisfaction rate, readmission rates for patient with severe conditions, number of clinical errors over a period of time, length of stay, wait time for patients and so on.

***Financial metrics:*** This is a measure that encompasses items such as revenue generation per doctor, per department, the expenses incurred per doctor, per department or special medical instruments needed. It also signals to the lost opportunities of revenue generations such as appointment cancellations due to the patients not showing up and outbound referrals due to the dearth of the specialized services.

In order to further understand the nature of operational decision-making and its impact on control chart selection it was necessary to analyze and find out the importance of the metrics pertaining to operational decision-making. It should be noted that there were instances where more than one metric was targeted in a single study and, in that case, both metrics were extracted and included in the analysis. For instance, one study discussing the usage of control charts to assess surgeries completed per surgeon also considered the financial costs associated with surgeon spending extra time in an operating theater, thereby targeted the utilization metric as well as the financial metric (Maruthappu *et al.,* 2013). Figure 2.8 depicts the percentage distribution of the aforementioned metrics targeted in the studies which were in the operational decision-making domain. Quality metric was the leading metric with about 50% which was then followed by the financial metric at 25%. The utilization and the volume metrics were appeared in about 14% and 11% of the studies respectively. The results were especially affirmative of the notion that for the healthcare managers, improving quality in the delivery of the healthcare processes is the objective of the utmost importance. Also, as healthcare managers they are tasked with ensuring the delivery of the quality services at a reasonable cost, which the financial metric being the second most targeted metric in the studies.

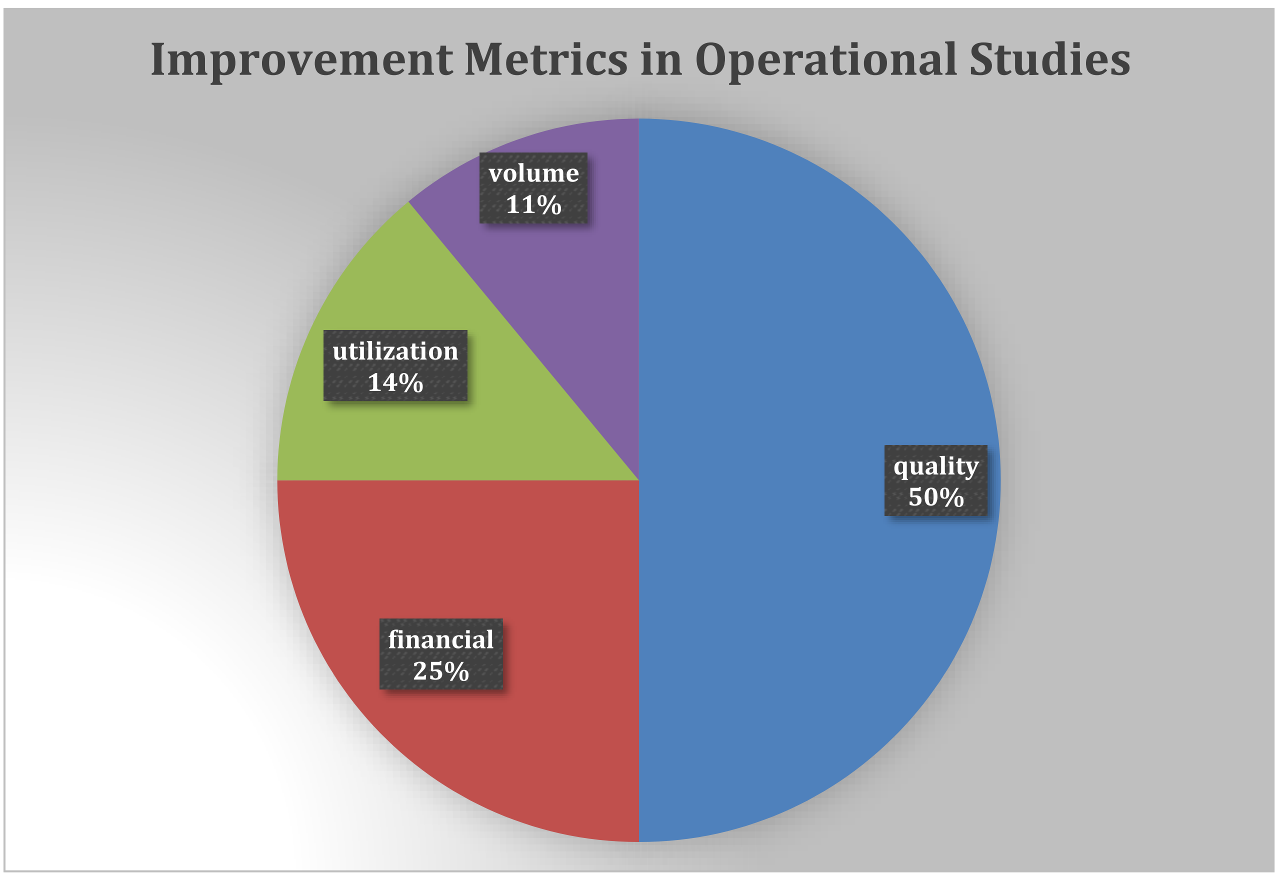


**Figure 2.8 Percent Share of the Metrics Targeted in the Selected Studies**

While a single study does not provide concrete steps on how to generalize the use control charts in operations studies, the collection of them provide sufficient material to construct a guideline. Such a guideline would have the following benefits:

- It would lessen the chance for the managers of selecting an inappropriate control chart
- It would help them in prioritizing the monitoring process as a whole. For instance, if the managers are specifically dealing with plummeting revenue for a hospital, they would know exactly where to start i.e., monitoring the variables associated with the financial metric or if the hospital has been getting complaints with respect to the delivery of the care then they would know the variables associated with the quality metric should be monitored at first
- Due to such prioritization, they could save on significant amount of time at the start of their improvement project
- Important caveats listed in the guideline will ensure that the appropriate control limits are chosen along with the suggested control chart. This may reduce the risk of false negatives associated with variables critical to the safety of the patient
- Also, the guidelines would help the healthcare managers in streamlining their projects as they can choose from the multiple scenarios listed in the guidelines and choose the control charts accordingly

The section below describes the guideline developed based on the literature findings as well as the knowledgebase on Quality Control methods, particularly control chart theory and practice.

### 2.3.1 Guidelines

Table 2.5 depicts the proposed framework to be used when control charts are deployed in the operational decision-making domain. Like all improvement projects, healthcare managers must start with defining the purpose for carrying out the quality improvement initiative and the goals to be achieved. For instance, a healthcare manager might consider decreasing the wait times for patients in a particular hospital department as the project's purpose and the goal might be the quantifiable reduction in percentage the improvement team is aiming to achieve. The next step involves considering the project scope; in the wait time example this might include defining the study area such as singular department of the hospital or the entire hospital. The project scope is important because the type of control charts to use may change depending on the project scope. For instance, if one is monitoring the number of infections acquired from a department like cardiology as opposed to the entire hospital, then it may happen that the chance of infection was rare in cardiology and thus one had to use a $g$-chart to monitor the number of days between infections. But when monitoring for an entire hospital it may turn out to be a fairly common phenomenon and thus one had to use a $u$-chart or $c$-chart depending on the procedures carried out. After the scope is decided upon, the important operational characteristics of the department should be identified, and the metrics involved are selected. An example of operational characteristics may be assessing how much the particular department in question directly relates to patient safety. This can be best explained by the nature of emergency department which witnesses a lot of critical patients and thus can be categorized under the department that has a direct relation to patient safety. Before the healthcare managers can select the type of control charts, they need to make sure the prerequisites are satisfied prior to implementation of the control charts. For instance, if they are dealing with the selection of subgroups then they need to make sure that the time interval between selected subgroups is constant thereby ensuring the selected subgroups are created under identical set of circumstances which is extremely important for the accuracy of the results generated. Also, when dealing with large amounts of data, one should follow good sampling practices like selecting data randomly and in a way which is truly representative of the larger population in order to avoid bias. Limaye *et al.* (2008) & Morton *et al.* (2001) state that when it comes to the minimum number of samples for generating a control chart a minimum of 20 samples is recommended. Next, the healthcare manager can focus on the type of control chart that ought to be selected for the process monitoring. This depends on the type of data involved: attribute or variable. Depending on the data type and the type of distribution it follows, the manager can select the appropriate control chart. If the process to be monitored directly relates to patient safety, then it is better to set the control limits at 2 standard deviations from the mean instead of the conventional 3 standard deviations. The reasoning behind this is it would be acceptable to spend resources to investigate for false alarms than to not be signaled and resulting in possible patient harm. After the process is plotted on a control chart, out of control points should be investigated if there are any. The manager should ensure that appropriate action is taken to eliminate the special cause variation and then once again plot the control chart to ensure whether the new limits indicate a stable process after the elimination of special cause of variation. For long-term success, the management along with the hospital staff should also ensure that the new changes that were made are being sustained to keep the new process in control.

**Table 2.5 Framework for Deployment of Control Charts**

<table>
<tr><th colspan="3">CONTROL CHART SELECTION</th></tr>
<tr><td colspan="3">PREREQUISITES:<br><br>General:<br>• Make sure the data source is authentic<br>• Ensure there are no missing values<br>• Identify the variable to be monitored and ensure that one is dealing with a single variable at a time<br><br>For data collection:<br>• Obtain at least 20 data points in order to have enough confidence in the control limits generated for determining special cause<br>• Gather data over time and sort them in time order so that the control chart generated will truly be able to plot process variation over time<br>• Ensure that subgrouping is done at the start and not the end of process in order to make sure that the conservation of time sequence is followed properly<br>• Ensure that the observations taken in time sequence are not correlated, i.e. the readings taken are independent of each other in order to not violate the basic assumption of control charts</td></tr>
<tr><th>STEP</th><th>ITEMS TO ADDRESS</th><th>CONSIDERATIONS</th></tr>
<tr><td>1. Identify the study goals</td><td colspan="2">• Is your improvement efforts related to quality, cost, productivity, or profitability?<br>○ Quality -> Go to Quality Metrics section<br>○ Cost -> Go to Financial Metrics section<br>○ Productivity > Go to Utilization Metrics section<br>○ Profitability -> Go to Volume and Financial Metrics section</td></tr>
<tr><td>Identify the study metrics</td><td>• Quality Metrics: If your Quality Metric appears on the list provided in the next column, review the section for that particular metric provided in Section 2.3.1.1/Table 2.6<br>• If your metric is not listed:<br>○ Review the general implementation section 2.3.5</td><td>Quality Metrics:<br>• Length of Stay<br>• Door-to-Reperfusion Time<br>• Surgical Infections<br>• Hospital Readmissions<br>• Harm and Non-harm events<br>• Monthly surgical complication rate<br><br>Continuous vs. Attribute Metrics:<br>• Continuous: The metrics which can be measured on a continuum or scale and can have almost any numeric value fall under the category of continuous metrics. For instance, the temperature of a patient's body measured by the doctor is an example of continuous</td></tr>
</table>

| | | |
|---|---|---|
| | | metric<br>• *Attribute:* The metrics which can be classified and counted fall under the category of attribute metrics. For example, if counting the number of hospital-acquired infections in a month is an area of interest, then it happens to be of attribute nature. |
| | • **Financial Metrics**: If your Financial Metric appears on the list provided in the next column, review the section for that particular metric provided in Section 2.3.1.2/Table 2.7<br>• If your metric is not listed, review Section 2.3.5 | **Financial Metrics:**<br>• Revenue generation per doctor<br>• Expenses incurred per department<br>• Number of appointment cancellations |
| | • **Utilization Metrics**: If your Utilization Metric appears on the list provided in the next column, review the section for that particular metric provided in Section 2.3.1.3/Table 2.8<br>• If your metric is not listed, review Section 2.3.5 | **Utilization Metrics:**<br>• Number of total surgeries performed<br>• Number of appointments completed by a doctor<br>• Daily nurse workload ratio |
| | • **Volume Metrics**: If your Volume Metric appears on the list provided in the next column, review the section for that particular metric provided in Section 2.3.4<br>• If your metric is not listed, review Section 2.3.1.4/Table 2.9 | **Volume Metrics:**<br>• Number of patients visiting a department<br>• Number of completed patient records |
| **2.** Select control limits | • Is the variable to be monitored has a direct relation with patient safety? | **Directly relates to patient safety:** Set the limits at **±2** standard deviations from the mean<br><br>**Doesn't directly relate to patient safety:** Set the limits at **±3** standard deviations from the mean |

The flowchart which summarizes the information in the table is provided in Figure 2.9

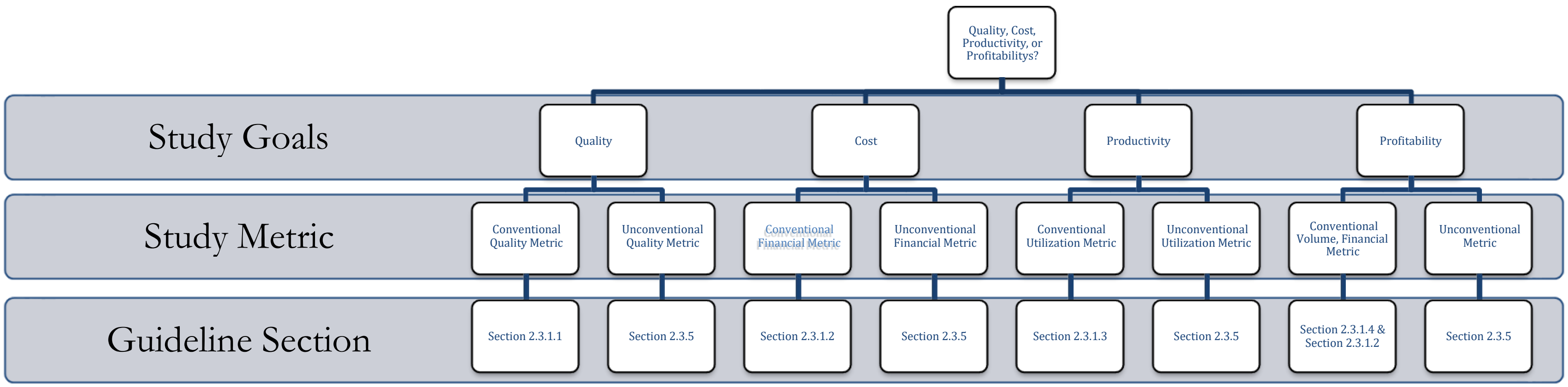


**Figure 2.9 Flowchart for Selection Guidelines**

### 2.3.1.1 Quality Metric

Table 2.6 helps the user to understand the quality metrics including the nature of the data associated with the metric, the type of control chart that one should use when dealing with different scenarios associated with that particular metric and also additional items to consider if there is any.

**Table 2.6 Variables Associated with the Quality Metric**

| Quality Metric and its nature | Scenario | Suggested Control Charts | Additional Considerations |
|---|---|---|---|
| ***Length of Stay (LoS)*** for patients admitted in a hospital<br><br>Nature: Variable type | If monitoring individual patient LoS | *I-MR* chart | |
| ***Door-to-reperfusion time*** or ***wait times*** for patients<br><br>Nature: Variable type | If monitoring individual patient wait times | *I-MR* chart | • If the wait time monitored occurs in a setting that directly relates to patient safety such as in an emergency department, then preferably **use ±2 standard deviations** from the mean when setting up the control limits for the chart.<br>• If that is not the case, then use the conventional ±3 standard deviations from the mean when plotting the control limits for the chart |
| ***Number of surgical infections*** or the ***rate of surgical infections*** | If monitoring the total number of surgical infections per month or a chosen time period in a hospital and the number of surgical procedures per month are constant | *c*-chart | If the number of surgical infections in a hospital happen to be a rare phenomenon, then it is advised to use ***g*-chart** and monitor the number of days between hospital infections as opposed to the number of |

| | | | |
|---|---|---|---|
| Nature: Attribute type | | | infections. |
| | If monitoring the average number of surgical infections and the number of surgical procedures performed per month or the chosen time period are not constant | *u*-chart | |
| ***Number of hospital readmissions***<br>Nature: Attribute type | If monitoring the number of hospital readmissions monthly, or yearly and there is a non-constant number of discharges during the months or the time period selected | *p*-chart | |
| | If monitoring the number of hospital readmissions monthly and there is a constant number of discharges during the months or the time period selected | *np*-chart | |
| ***Number of harm events and no-harm events***<br>Nature: Attribute type | If monitoring the number of harm events per 1000 patient days per week | *u*-chart | |
| | If monitoring the number of non-harm events per 1000 patient days per week | *u*-chart | |
| ***Monthly complication rate for surgery***<br>Nature: Attribute type | If monitoring the proportion of monthly complications that have taken place in a surgical department | *p*-chart | If one is interested in the different types of complications that occurred during any given surgery, then a ***U*-chart** should be used to monitor the average number of complications per surgical procedure. |

### 2.3.1.2 Financial Metric

Table 2.7 helps the user to understand the financial metrics including the nature of the data associated with the metric, the type of control chart that one should use when dealing with different scenarios associated with that particular metric and also additional items to consider if there is any.

**Table 2.7 Variables Associated with the Financial Metric**

| Financial Metric and its nature | Scenario | Suggested Control Charts | Additional Considerations |
|---|---|---|---|
| ***Revenue generated per doctor***<br><br>Nature: Variable Type | If monitoring how much individual doctor contributes to the department or a hospital in terms of revenue generation | *I-MR* chart | |
| | If monitoring how much a group of doctors between 2 and 10 contributes in terms of revenue generation | *Xbar* & *R* chart | |
| | If monitoring how much a group of doctors more than 10 contributes in terms of revenue generation | *Xbar* & *S* chart | |
| ***Expenses incurred per department each month in a hospital***<br><br>Nature: Variable Type | If monitoring the total costs incurred per department in a hospital or monitoring the total costs for the entire hospital for any given time period | *I-MR* chart | |
| ***Number of appointment cancellations for the hospital in a month***<br><br>Nature: Attribute Type | If monitoring the total number of appointment cancellations each month for a hospital | *p*-chart | If the number of appointment cancellations happens to be a rare phenomenon, one can instead monitor the number of days between the appointment cancellations and use a ***g*-chart** for this purpose |

### 2.3.1.3 Utilization Metric

Table 2.8 helps the user to understand the utilization metrics including the nature of the data associated with the metric, the type of control chart that one should use when dealing with different scenarios associated with that particular metric and also additional items to consider if there is any.

**Table 2.8 Variables Associated with the Utilization Metric**

| Utilization Metric and its nature | Scenario | Suggested Control Charts | Additional Considerations |
|---|---|---|---|
| ***Number of total surgeries performed***<br><br>Nature: Attribute type | If monitoring the total number of surgeries performed by each surgeon in a month or any given time period | *I-MR* chart | |
| | If monitoring the total number of surgeries performed in a department in a month or any given time period | *Xbar* & *R* chart | Usually, the number of surgeons in a department are likely to fall between 2 & 10. In a situation where the number of surgeons exceed 10 one should use ***X-bar* & *S* chart** |
| ***Number of appointments completed by a doctor in a department***<br><br>Nature: Attribute type | If monitoring the number of patients seen by a doctor in a department either weekly or monthly or for any time period | *p*-chart | |
| ***Daily nurse workload ratio***<br><br>Nature: Variable type | If monitoring the daily workload ratio of the nurses or in other words patients to nurse ratio in a ward | *I-MR* chart | The ratio is usually obtained by dividing the number of patient hours to the number of nurse hours available |

### 2.3.1.4 Volume Metric

Table 2.9 helps the user to understand the volume metrics including the nature of the data associated with the metric, the type of control chart that one should use when dealing with different scenarios associated with that particular metric and also additional items to consider if there is any.

**Table 2.9 Variables Associated with the Volume Metric**

| Volume Metric and its nature | Scenario | Suggested Control Charts | Additional Considerations |
|---|---|---|---|
| ***Number of patients visiting a department in a day or in a month***<br>Nature: Attribute type | If monitoring the patient flow to a department in a day or in a month in order to understand the load each department handles | $c$-chart | |
| ***Number of completed records in a hospital***<br>Nature: Attribute type | If monitoring the proportion of completed patient records in a day or in a month | $p$-chart | |

### 2.3.5 Further Guidelines

- If the variable is of continuous nature but the individual data points are to be monitored, then use: ***I-MR*** **chart**
- If the variable is of continuous nature but the data consists of subgroups from size 2 to 10 then use: ***X-bar*** **&** ***R*** chart
- If the variable is of continuous nature but the data consists of subgroups with sizes exceeding 10 then use: ***X-bar*** **&** ***S*** chart
- If the variable is of attribute nature, and the data is binary then use: ***P*****-chart**
- If the variable is of attribute nature but has the possibility of having multiple opportunities per unit, then use: ***U*****-chart** or ***C*****-chart**
- If the variable is of attribute nature but can be categorized as a rare event, then use: ***G*****-chart**

Figure 2.10 summarizes the control chart selection process in general.

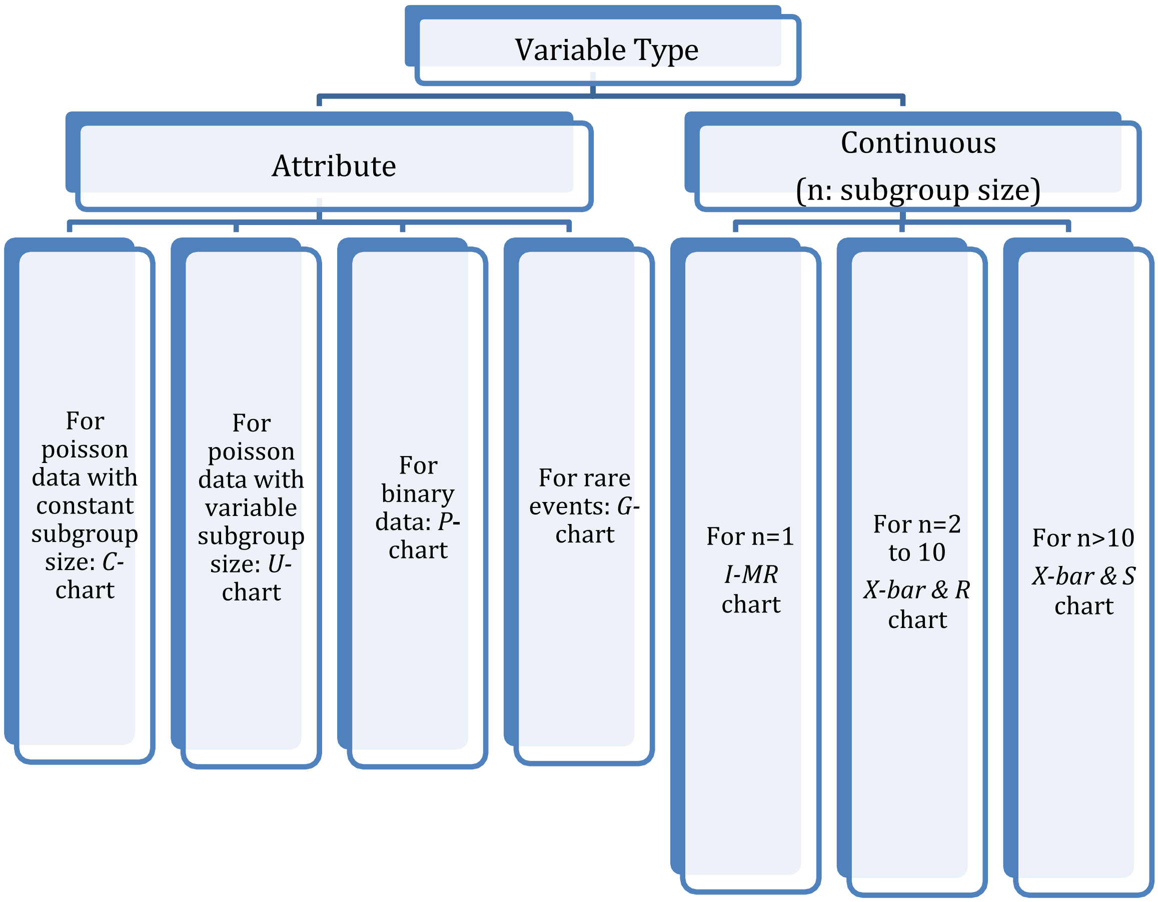


**Figure 2.10 Control Chart Selection Decision Tree**

### 2.3.6 Key Success Factors for Effective Implementation

Like any other process improvement initiative there are certain factors that are instrumental to the success of the quality improvement project. With regards to healthcare, the healthcare managers should make sure that the data collected and reported by the hospital staff is authentic. There are certain methodological criteria with regards to the construction of control charts which should be followed by the healthcare managers in order to minimize the risks of Type-I and Type-II errors. A research article by Koetsier et al. (2012) indicated that it would be advisable to use 10-35 data points and the control limits at ± 3 standard deviations from the mean to mitigate the risks of Type-I and Type-II errors. They further recommended that positive data with a skewed distribution should undergo the logarithmic transformations prior to construction of control charts instead of setting the lower control limit to zero to tackle the issue. There also needs to be adequate efforts from the management side in order to make sure that the suggested changes by the healthcare managers are enforced in a proper manner (Suman & Prajapati, 2018). Often times, the lack of training for the hospital staff and lack of management support for improvement initiatives results in the failure of effective control charts implementation (Suman & Prajapati, 2018). It is also very important to make sure that the hospital staff is being informed about the goals and implications of the project in order to make them understand that the improvement project being carried out does not have mass layoffs as one of its consequences. This would make them more cooperative and their assistance could prove to be very useful in the improvement project.

# 3. CASE STUDY

## 3.1. Description of the case and data set

Although, we did witness monitoring the number of hospital acquired infections in a hospital from a clinical perspective in one of our studies, this variable is important for healthcare managers as well. Since the healthcare managers are dealing with diverse problem areas in a healthcare setting, tracking the number of hospital acquired infections most certainly can be associated with them as a part of their quality improvement initiative. In order to understand how the proposed methodology can be implemented for quality and process improvement in healthcare from an operational perspective, a dataset consisting of surgical site infections of all the hospitals in the state of California was used. This dataset was obtained from the website HealthData.gov. The data source consisted of the following information: the facility (hospital) name, the state where the facility was located, the type of surgical procedure carried out, the total number of surgical procedures and the total number of surgical site infections associated with the procedure and the corresponding year in which they occurred. A sample view of the public data is provided in Appendix I.

The first step of methodology involves defining the nature of the project and its scope. The data selected was about the number of surgical site infections for all colon surgeries per year at a particular hospital from the year 2013 to 2019. The second step involves understanding the type of metric being targeted. The metric in the selected data set is a quality metric as surgical site infections is considered to be one of the crucial quality indicators of a hospital when it comes to risk-free delivery of care. The next step involves understanding the nature of data. The number of surgical site infections is an attribute data type since it is a count variable; and it follows binomial distribution since there are only two possible outcomes arising out of the situation, where the patient did contract a surgical site infection, or the patient did not contract a surgical site infection. The next step guides to the selection of control charts. Since the data involved is of attribute type, follows a binomial distribution and does not have a constant subgroup size (ie. the yearly count of surgical procedures does not remain constant), p-type control chart for monitoring the number of surgical site infection is the appropriate control chart for this study. The procedure for selecting an appropriate control chart using the proposed framework is summarized in Figure 3.1.

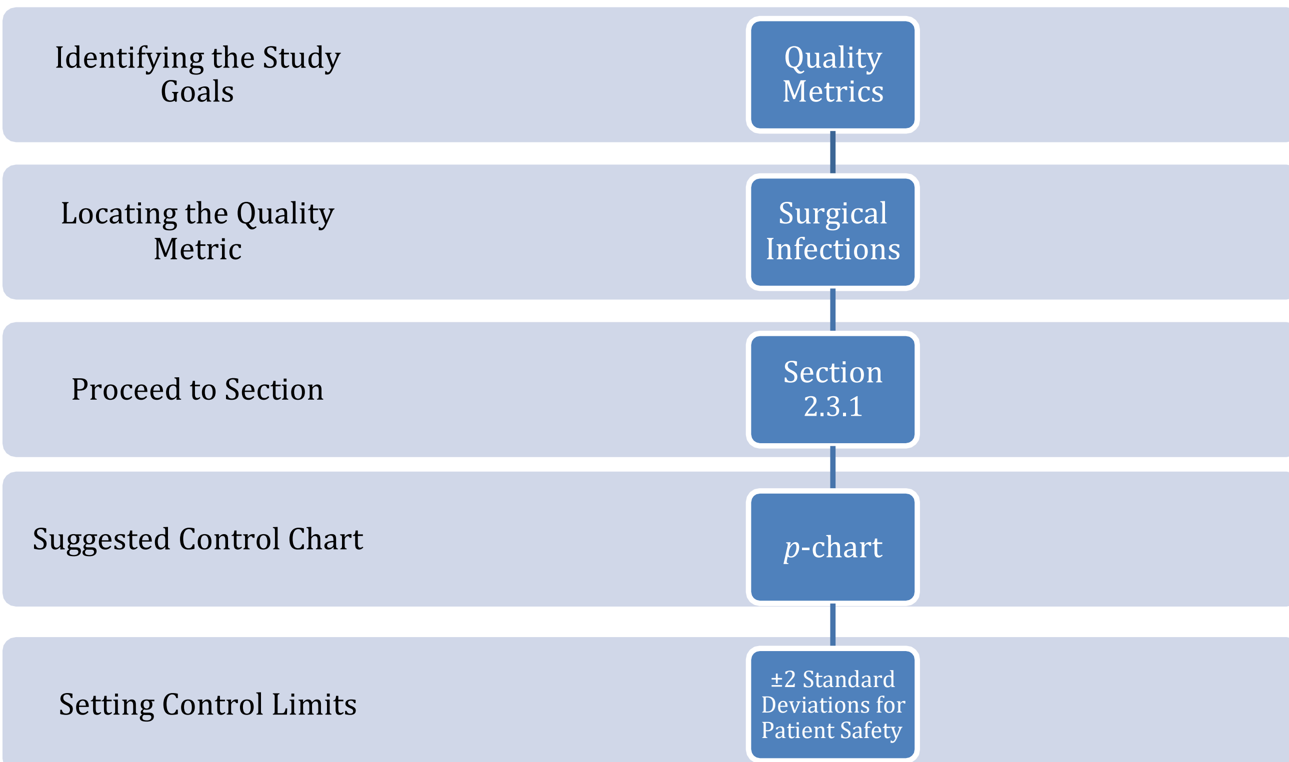


**Figure 3.1 Flowchart for Control Chart Selection Process**

The table 3.1 shows the data used for the study and includes the number of surgical site infection count as well as the yearly total number of colon surgical procedures carried out from the year 2013 to the year 2019.

**Table 3.1 Yearly Surgical Site Infection (SSI) count and total surgical procedures**

| Year | Surgical procedure Count | Surgical site infection (SSI) count |
|---|---|---|
| 2013 | 622 | 24 |
| 2014 | 684 | 35 |
| 2015 | 610 | 23 |
| 2016 | 611 | 23 |
| 2017 | 590 | 20 |
| 2018 | 655 | 26 |
| 2019 | 615 | 17 |

### 3.2. Control Chart implementation using the proposed framework

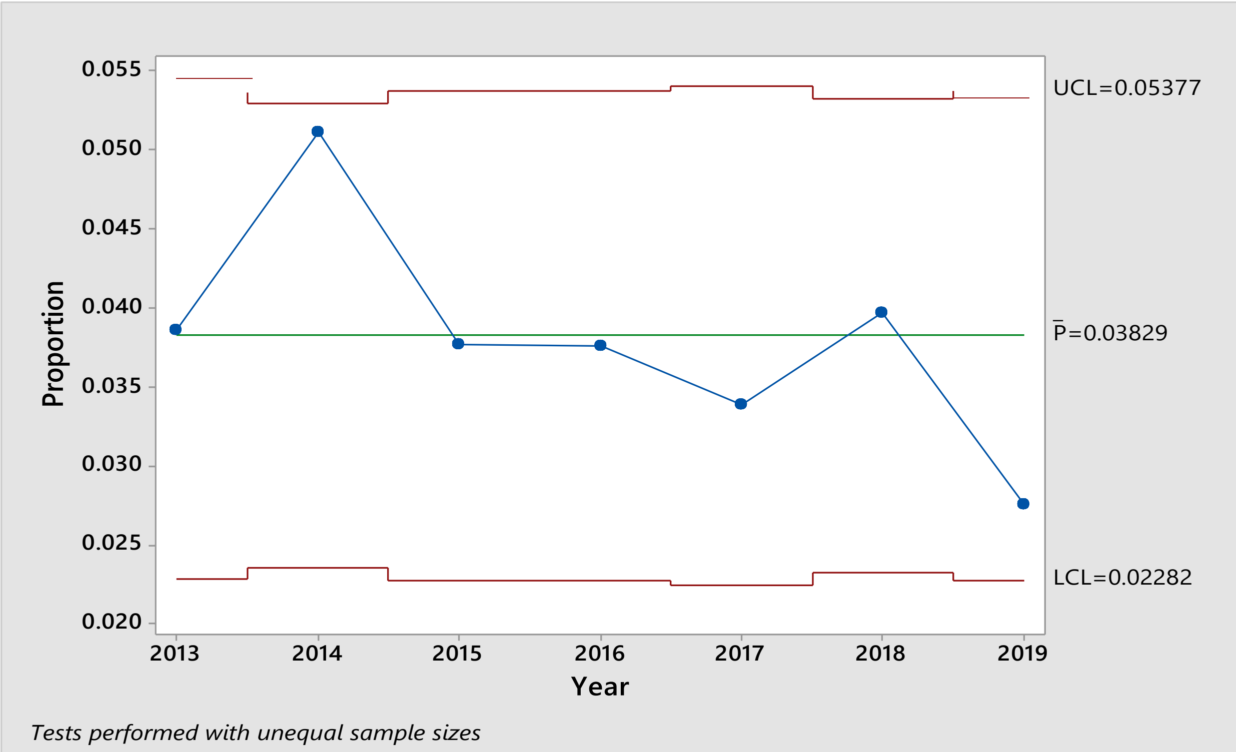


**Figure 3.2 Proportion of surgical site infections for colon surgery by the year**

The *p*-type control chart in figure 3.2 shows 7 data points with each data point corresponding to the data in table 3.1. The control limits are set at ± 2 standard deviations from the mean since the metric monitored is directly related to patient safety. Low surgical site infection rate since is an indicator of good quality of the surgical procedure carried out in a hospital. Contrary to the popular notion that the data points falling outside either of the control limits indicates unstable process, here if any point falls outside the lower control limit (LCL) it is actually a sign of good quality however the point falling outside the upper control limit (UCL) is not desirable and it is indicator of poor quality for the hospital. In this case, the data point for the year 2014 seems to be an unfavorable data point as it is very close to UCL. Although it is not an out of control data point we can state that the SSI rate of colon surgery for the hospital was high in the year 2014 relatively and an investigation would be beneficial. In this manner, the healthcare managers of a particular hospital can utilize control charts to track the surgical site infection (SSI) rate of their hospital and compare it with the yearly data if available to see which years were a sign of good and bad performance with respect to surgery.

# 4. FINDINGS & DISCUSSION

## 4.1. Role of control charts in operational decision-making

Healthcare industry like any other industry aims at delivering quality services to its customers at a reasonable cost. But the aspects of quality and safety are so much intertwined in the healthcare sector that it becomes instrumental for the hospitals to adopt a safety-first approach while simultaneously looking for ways to save the financial resources as well. It is estimated that medication errors in the United States alone cost around 21 billion dollars and impacted approximately 7 million patients annually (Silva & Krishnamurthy, 2016). Looking at such data compels us to monitor the quality metric for the hospital at a priority. If such types of quality metrics are closely monitored and dealt with appropriately then it will save a lot of financial resources for the hospital as well. However, it is also important to deal with the factors that have a direct impact on the profit-making ability of the organization. Like every other organization, hospitals require large capital to function smoothly. This is why monitoring the financial metrics and the variables associated with them are extremely important too. The expenses generated per department versus the costs incurred for its functioning are an indicator of the profitability of the department and can influence certain decisions pertaining to its functioning or even the closure of such a department. Similarly, the revenue brought in by a doctor versus the cost incurred for the doctor is also very important variable to monitor when dealing with the financial metric. Albeit this being said, it also depends on the scenario when we are talking about the key metrics involved as they can change depending on the scope of the improvement project. For instance, if the healthcare organization is specifically interested in understanding the requirements of hospital staff, then in this case the key metric to be monitored would be the utilization metric as opposed to quality metric. As the goal of the improvement project changes, the key metric(s) also change and that is the reason it is extremely important to understand the specifics of the improvement project. Therefore, as the nature of the project changes the key metrics that should be monitored also are subject to change. Control charts help to monitor such key performance metrics which are important for the fulfillment of the objectives set by the hospital and hence turn out to be beneficial for looking at trends, analyzing the success of the intervention strategy in the past if any, and also testing the efficacy of the changes implemented by the quality improvement team.

### 4.2. Further potential areas for deployment of control charts for operational decision-making

There are still some areas in healthcare which have the potential to employ control charts for monitoring variables related to quality improvement, but they remain unexplored as we could not find evidence of their documentation in the literature. One of the potential areas is monitoring patient satisfaction rating where the control charts can be used for tracking patient satisfaction ratings on a scale of 1 to 10. Since the patient satisfaction is considered to be one of the most important aspects when it comes to measuring the quality of care being provided, the control charts can be used to track the ratings of patients before treatment as well as after treatment. This would enable the quality improvement team to focus on the problem area specifically since before treatment, it is usually the administration department that is responsible for handling and preparing the necessary documentation and after treatment would be determined by the quality of care provided by the doctors and nurses and the follow-up provided by them if any. This type of patient satisfaction tracking can be used department wise in a hospital for best results since it will help the managers to pinpoint the problem area as well as the entities associated with it. Another area where the control charts can be employed is for tracking variable overhead costs. When it comes to tracking the expenses for a hospital using control charts it can be beneficial to track variable overhead costs separately using control charts. Since the variable costs include healthcare worker supplies, patient care supplies, diagnostic and therapeutic supplies and medications, tracking these would give a clearer picture for the healthcare managers to narrow down the problem areas if any and channelize the available resources efficiently. Another area where there is significant potential to use control charts is the emergency department. Although the existing literature shows that the control charts are being used to track the number of visits to an emergency department but there seems to be no evidence of tracking the nature of conversion of these visits i.e., the number of emergency visits which converted in hospitalization, admission to critical care unit or discharged immediately after providing the necessary care. The importance of tracking this kind of conversions is that this will assist the improvement managers to optimize patient flow for the other departments that might get involved and also might be helpful when they are concerned with reducing wait times in the emergency department.

### 4.3. Control charts as a standalone tool for quality improvement

During our systematic literature review we found that at times the control charts are used in conjunction with the other tools under the umbrella of Six Sigma or Lean Six Sigma methodologies and sometimes as a standalone tool in quality improvement initiatives. To gauge the capabilities of control charts as a standalone tool, the selected studies were further analyzed .

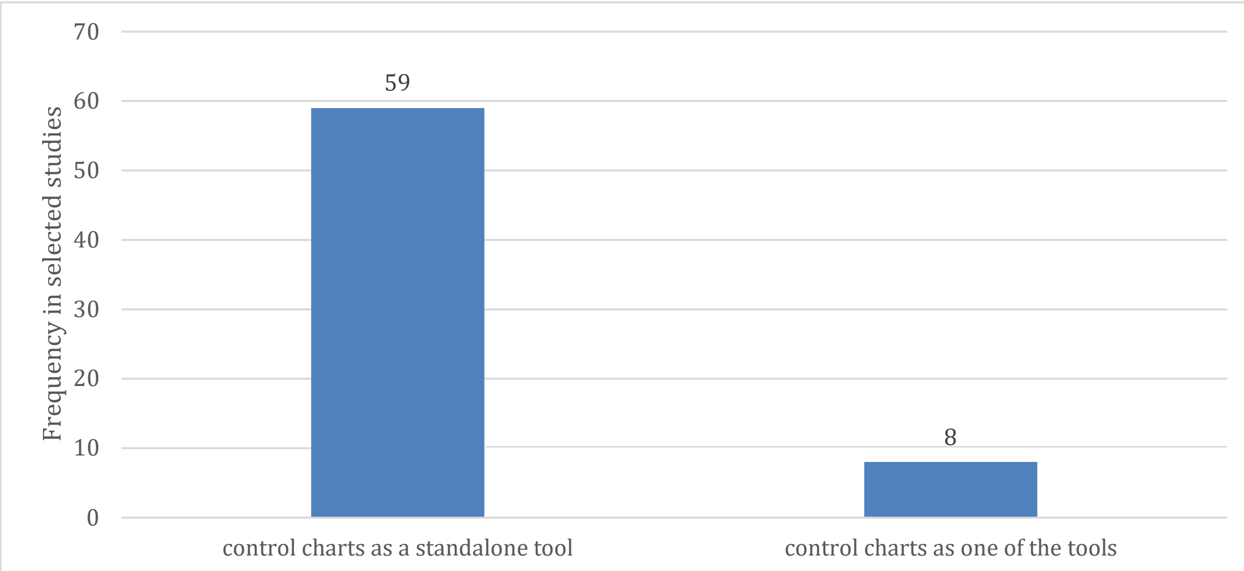


**Figure 4.1 Frequency of Types of Control Charts Usage**

Figure 4.1 shows that about only 12% of the total studies used control charts in conjunction with other tools. This gives us significant evidence to conclude that control charts have the ability to function as a standalone tool when it comes to quality improvement in healthcare.

# 5. CONCLUSION

Control charts are being deployed in clinical decision-making and operational decision-making domains in healthcare for quality improvement purposes. Since the healthcare managers are typically tasked with the operational decision-making in a hospital there was a need to assess the content of literature available regarding the deployment of control charts in a hospital setting for operational decision-making purposes. A current limitation in the literature is that it is focused only on the outcome of the control charts after their application in a healthcare setting. But it does not always specify the decision-making domain associated with it, the metrics targeted when monitoring a certain key performance indicator or the reason behind the selection of the type of control chart used. In order to tackle these issues, in this study a framework was developed and prescribed guidelines for assisting the healthcare managers in selecting appropriate control charts according to the different possible scenarios that one may encounter when it comes to the operational decision-making domain were provided. The findings are compelling enough to conclude that control charts have a large potential when it comes to the application of it in other operational areas and also has the capacity to perform as a standalone tool.

## 5.1. Limitations

While the proposed guidelines were constructed without considering a particular geographical location, the majority of studies came from the U.S. making the proposed framework somewhat specific to the U.S. healthcare industry. Therefore, if the proposed framework is to be implemented outside U.S. healthcare, it might require amends due to cultural differences that may exist. The hospital selected for the purpose of case study does not supplement with the data about the ramifications of the surgical site infections recorded. For instance, it is very much possible that in a particular year, the number of surgical site infections recorded were significant but overall, they were less life threatening. On the contrary, there can also be a year where although the surgical site infections were less in number, but they proved to be life threatening. This information is important for the improvement team, as this will help them in deciding the future course of action. Also, the availability of just seven data points casts a significant doubt over the accuracy of the result obtained and thereby the analysis too.

### 5.2. Future Work

There is a need for further research to assess the extent of training when it comes to understanding in the field of the basics of control charts Six Sigma required by the hospital staff in order to help the improvement team with regards to data collection, resources required for the project and in ensuring the project is running according to the schedule. There is also a need for actual implementation of the proposed framework to deeply understand the potential barriers in an actual setting if any and also to facilitate the implementation of proposed guidelines in the thesis.

# APPENDIX I

| A | B | C | D | L | M | N | O | P | Q | R |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | State | HAI | Operative_Procedure | Procedure_Count | Infection_Count | SIR | Comparisc | SIR 95% CI | SIR 95% CI | Notes |
| 2013 | California | SSI | Abdominal hysterectomy | 42 | 0 | | | | | â€ See data dictionary |
| 2013 | California | SSI | Bile Duct, Liver or Pancreatic surgery | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Cesarean section | 214 | 1 | 1.17 | No Differe | 0.03 | 6.49 | â€ See data dictionary |
| 2013 | California | SSI | Colon surgery | 68 | 2 | 1.1 | No Differe | 0.19 | 3.65 | â€ See data dictionary |
| 2013 | California | SSI | Gallbladder surgery | 249 | 0 | 0 | No Differe | 0 | 2.77 | â€ See data dictionary |
| 2013 | California | SSI | Gastric surgery | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Hip prosthesis | 118 | 0 | 0 | No Differe | 0 | 1.91 | â€ See data dictionary |
| 2013 | California | SSI | Laminectomy | 20 | 0 | | | | | â€ See data dictionary |
| 2013 | California | SSI | Open reduction of fracture | 105 | 2 | 1.42 | No Differe | 0.24 | 4.7 | â€ See data dictionary |
| 2013 | California | SSI | Rectal surgery | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Spinal Fusion | 24 | 0 | | | | | â€ See data dictionary |
| 2013 | California | SSI | Appendix surgery | 242 | 1 | 0.93 | No Differe | 0.05 | 4.59 | â€ See data dictionary |
| 2013 | California | SSI | Exploratory laparotomy | 251 | 3 | 2.02 | No Differe | 0.51 | 5.49 | â€ See data dictionary |
| 2013 | California | SSI | Knee prosthesis | 247 | 0 | 0 | No Differe | 0 | 1.53 | â€ See data dictionary |
| 2013 | California | SSI | Refusion of spine | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Small bowel surgery | 43 | 0 | 0 | No Differe | 0 | 1.96 | â€ See data dictionary |
| 2013 | California | SSI | Thoracic surgery | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Vaginal hysterectomy | 140 | 1 | 1.01 | No Differe | 0.03 | 5.6 | â€ See data dictionary |
| 2013 | California | SSI | Abdominal hysterectomy | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Cesarean section | 410 | 0 | 0 | No Differe | 0 | 4.58 | |
| 2013 | California | SSI | Colon surgery | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Gallbladder surgery | 25 | 0 | | | | | |
| 2013 | California | SSI | Appendix surgery | 45 | 0 | | | | | |
| 2013 | California | SSI | Exploratory laparotomy | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Small bowel surgery | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Vaginal hysterectomy | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Abdominal Aortic Aneurysm Repair | | | | | | | ~ See Data Dictionary |
| 2013 | California | SSI | Abdominal hysterectomy | 107 | 1 | 1.24 | No Differe | 0.03 | 6.9 | |

| A | B | C | D | H | I | J | K | L | M | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | State | HAI | Operative_Procedure | Procedure | Infection_Count | Predicted_Infection_Count | SIR | Comparisc | SIR_CI_95 | SIR_CI_ |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Abdominal hysterectomy | 51 | 1 | 0.4 | 2.49 | No Differe | 0.06 | 13. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Colon surgery | 71 | 3 | 1.59 | 1.89 | No Differe | 0.48 | 5. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Gallbladder surgery | 228 | 0 | 0.32 | 0 | No Differe | 0 | 11. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Gastric surgery | 11 | 0 | 0.22 | 0 | No Differe | 0 | 16. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Hip prosthesis | 161 | 1 | 1.31 | 0.77 | No Differe | 0.04 | 3. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Laminectomy | 81 | 1 | 0.41 | 2.45 | No Differe | 0.06 | 13. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Open reduction of fracture | 113 | 1 | 0.9 | 1.11 | No Differe | 0.03 | 6. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Rectal surgery | 12 | 0 | 0.2 | | | | |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Spinal fusion | 78 | 0 | 0.69 | 0 | No Differe | 0 | 5. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Appendix surgery | 133 | 1 | 1.01 | 0.99 | No Differe | 0.05 | 4. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Bile duct, liver or pancreatic surgery | 12 | 0 | 0.41 | 0 | No Differe | 0 | 8. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Exploratory laparotomy | 251 | 1 | 1.57 | 0.64 | No Differe | 0.03 | 3. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Knee prosthesis | 370 | 0 | 2.38 | 0 | No Differe | 0 | 1. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Refusion of spine | 1 | 0 | 0.01 | | | | |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Small bowel surgery | 27 | 3 | 0.34 | 8.75 | Higher* | 1.8 | 25. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Thoracic surgery | 31 | 0 | 0.18 | | | | |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Vaginal hysterectomy | 141 | 0 | 1.18 | 0 | No Differe | 0 | 2. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Abdominal hysterectomy | 22 | 0 | 0.21 | 0 | No Differe | 0 | 17. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Cesarean section | 432 | 0 | 0.77 | 0 | No Differe | 0 | 4. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Exploratory laparotomy | 37 | 0 | 0.21 | 0 | No Differe | 0 | 1 |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Small bowel surgery | 1 | 0 | 0.02 | | | | |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Vaginal hysterectomy | 16 | 0 | 0.16 | | | | |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Abdominal hysterectomy | 13 | 0 | 0.08 | | | | |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Colon surgery | 15 | 1 | 0.31 | 3.22 | No Differe | 0.08 | 17. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Gallbladder surgery | 91 | 0 | 0.12 | | | | |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Gastric surgery | 3 | 0 | 0.04 | | | | |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Appendix surgery | 123 | 2 | 1.45 | 1.38 | No Differe | 0.23 | 4. |
| 2015 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Bile duct, liver or pancreatic surgery | 1 | 0 | 0.04 | | | | |

SSI_2015

| A | B | C | I | J | K | L | M |
|---|---|---|---|---|---|---|---|
| Year | State | HAI | Operative_Procedure | Procedure_Count | Infections_Reported | Infections_Predicted | SIR |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | | 1832 | 11 | 8.64 | 1.27 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Abdominal aortic aneurysm repair | 4 | 0 | 0.03 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Appendix surgery | 103 | 0 | 0.35 | 0 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Bile duct, liver or pancreatic surgery | 34 | 1 | 0.28 | 3.64 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Cardiac surgery | 37 | 0 | 0.11 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Coronary bypass,chest and donor incisions | 75 | 1 | 0.47 | 2.14 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Coronary bypass,chest incision only | 1 | 0 | 0.01 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Gallbladder surgery | 186 | 0 | 0.54 | 0 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Colon surgery | 72 | 4 | 1.6 | 2.5 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Cesarean section | 561 | 0 | 0.54 | 0 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Open reduction of fracture | 164 | 1 | 1.08 | 0.92 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Gastric surgery | 30 | 0 | 0.29 | 0 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Hip prosthesis | 111 | 3 | 0.75 | 3.98 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Hysterectomy,abdominal | 6 | 0 | 0.03 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Knee prosthesis | 113 | 0 | 0.46 | 0 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Kidney surgery | 7 | 0 | 0.02 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Ovarian surgery | 12 | 0 | 0.01 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Pacemaker surgery | 95 | 0 | 0.18 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Rectal surgery | 11 | 0 | 0.08 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Small bowel surgery | 54 | 1 | 1.01 | 1 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Spleen surgery | 7 | 0 | 0.04 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Thoracic surgery | 56 | 0 | 0.13 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Hysterectomy, vaginal | 2 | 0 | 0.01 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Exploratory abdominal surgery (laparotomy) | 91 | 0 | 0.63 | 0 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | | 3999 | 10 | 19.33 | 0.52 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Abdominal aortic aneurysm repair | 1 | 0 | 0.01 | |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Appendix surgery | 165 | 0 | 0.55 | 0 |
| 2018 | California | Healthcare Associated Infection, Surgical Site Infections (SSI) | Bile duct, liver or pancreatic surgery | 21 | 0 | 0.23 | 0 |

| A | B | D | E | J | K | L | M | N | O | P |
|---|---|---|---|---|---|---|---|---|---|---|
| Year | State | HAI | Operative_Procedure | Procedure_Count | Infections_Reported | Infections_Predicted | SIR | SIR_CI_95 | SIR_CI_95 | Comparis |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA | 682211 | 3643 | 4303.43 | 0.85 | 0.82 | 0.87 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Abdominal aortic aneurysm repair | 361 | 1 | 2.46 | 0.41 | 0.02 | 2.01 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Appendix surgery | 30509 | 74 | 119.62 | 0.62 | 0.49 | 0.77 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Bile duct, liver or pancreatic surgery | 7939 | 196 | 209.76 | 0.93 | 0.81 | 1.07 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Cardiac surgery | 13217 | 35 | 51.34 | 0.68 | 0.48 | 0.94 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Cesarean section | 123006 | 188 | 214.71 | 0.88 | 0.76 | 1.01 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Colon surgery | 29467 | 633 | 751 | 0.84 | 0.78 | 0.91 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Coronary bypass, chest and donor incisions | 13893 | 77 | 104.98 | 0.73 | 0.58 | 0.91 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Coronary bypass, chest incision only | 1635 | 7 | 10.91 | 0.64 | 0.28 | 1.27 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Exploratory abdominal surgery (laparotomy) | 44627 | 233 | 252.21 | 0.92 | 0.81 | 1.05 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Gallbladder surgery | 51081 | 161 | 193.15 | 0.83 | 0.71 | 0.97 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Gastric surgery | 21046 | 114 | 147.58 | 0.77 | 0.64 | 0.92 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Heart transplant | 409 | 2 | 5.62 | 0.36 | 0.06 | 1.18 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Hip prosthesis | 46600 | 259 | 290.18 | 0.89 | 0.79 | 1.01 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Hysterectomy, abdominal | 24396 | 134 | 171.99 | 0.78 | 0.66 | 0.92 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Hysterectomy, vaginal | 4294 | 18 | 24 | 0.75 | 0.46 | 1.16 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Kidney surgery | 7684 | 34 | 25.36 | 1.34 | 0.94 | 1.85 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Kidney transplant | 2376 | 9 | 14.35 | 0.63 | 0.31 | 1.15 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Knee prosthesis | 57496 | 215 | 219.23 | 0.98 | 0.86 | 1.12 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Laminectomy | 29523 | 106 | 103.67 | 1.02 | 0.84 | 1.23 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Liver transplant | 847 | 25 | 41.11 | 0.61 | 0.4 | 0.89 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Open reduction of fracture | 37153 | 258 | 273.65 | 0.94 | 0.83 | 1.06 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Ovarian surgery | 18335 | 11 | 13.33 | 0.83 | 0.43 | 1.43 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Pacemaker surgery | 19539 | 40 | 34.15 | 1.17 | 0.85 | 1.58 | Same |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Rectal surgery | 6032 | 39 | 103.02 | 0.38 | 0.27 | 0.51 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Small bowel surgery | 25174 | 420 | 511.35 | 0.82 | 0.75 | 0.9 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Spinal fusion | 42127 | 281 | 323.74 | 0.87 | 0.77 | 0.97 | Better |
| 2019 | California | Surgical Site Infections (SSI) | STATE OF CALIFORNIA POOLED DATA - Spleen surgery | 1879 | 22 | 11.57 | 1.9 | 1.22 | 2.83 | Worse |

# REFERENCES


Austin M., Gibb K., Milos N., Scott D. & Raborn G. (2002). Understanding Variation in Revenue and Expenses. *Healthcare Financial Management, 70-73.*

Benneyan J., Lloyd R. & Plsek P. (2003). Statistical Process Control as Tool for research and healthcare improvement. *BMJ Quality & Safety, 12, 458-464.*

Benneyan J. (2001). Number-Between G-type Statistical Quality Control Charts for Monitoring Adverse Events. *Health Care Management Science, 4, 305-318.*

Boepple J. (2015). Using Control Charts in a Healthcare Setting. *American Societyfor Quality, 1-6.*

Bonetti P., Waeckerlin A., Schuepfer G. & Frutiger A. (2000). Improving Time Sensitive Processes in the Intensive Care Unit: The Example of Door to Needle Time in Acute Myocardial Infraction. *International Journal for Quality in Healthcare, 12, 311–317.*

Callahan C. & Griffen D. (2003). Advanced Statistics: Applying Statistical Process Control Techniques to Emergency Medicines: A Primer for Providers. *Academic Emergency Medicine, 10, 883– 890.*

Canel C., Mahar S., Rosen D. & Taylor J. (2008). Quality Control Methods at a Hospital. *International Journal of Health Care Quality Assurance, 23(1), 59-71.*

Centers for Disease Control and Prevention. (2009). *National Center for Health Statistics*. Retrieved from: https://www.cdc.gov/nchs/fastats/health-expenditures.html

Chassin R. & Loeb M. (2011). The Ongoing Quality Improvement Journey: Next Stop, High Reliability. *Health Affairs, 30(4), 559–568*.

Chien T., Chou M., Wang W., Tsao L. & Lin W. (2012). Intraclass Reliability for Assessing How Well Taiwan Constrained Hospital Provided Medical Services Using Statistical Process Control Chart Techniques. *BMC Health Services Research, 12, 67–76.*

Choi J., Ensafi S., Chartier L. & Praet O. (2017). A Quality Improvement Initiative to Decrease the Rate of Solitary Blood Cultures in the Emergency Department. *Academic Emergency Medicine, 24, 1080-1087.*

Coory M., Duckett S. & Baker K. (2008). Using Control Charts to Monitor Quality of Hospital Care with Administrative Data. *International Journal for Quality in Health Care, 20(1), 31-39.*

Curran E., Harper P., Loveday H., Gilmour H., Jones S., Benneyan J., Hood J. & Pratt, R. (2008). Results of a Multicenter Randomised Controlled Trial of Statistical Process Control Charts and Structured Diagnostic Tools to Reduce Ward-Acquired-Methicillin Resistant Staphylococcus Aureus: the chart project. *Journal of Hospital Infection 70, 127–135*

Duclos A. & Voirin N. (2010). The P Control Chart: A Tool for Care Improvement. *International Journal for Quality in Healthcare, 22(5), 402–407.*

Eisenstein E. & Bethea C. (1999). The Use of Patient Mix-Adjusted Control Charts to Compare In-Hospital Costs of Care. *Healthcare Management Science, 2, 193-198.*

Fretheim A. & Tomic O., (2015). Statistical Process Control and Interrupted Time Series: A Golden Opportunity for Impact Evaluation in Quality Improvement. *BMJ Quality and Safety, 24, 748-752.*

Gabbay U. & Bukchin M. (2009). Does Daily Nurse Staffing Match Ward Workload Variability? Three Hospital Experiences. *International Journal of Health Care Quality Assurance, 22, 625–641.*

Gan F. & Tan T. (2010). Risk-Adjusted Number-Between Failures Charting Procedures for Monitoring a Patient Care Process for Acute Myocardial Infarctions. *Health Care Management Science, 13, 222-233.*

Grant P. & Kim A. (2007). Infection Control Consultation in a 150-Bed Acute Care Hospital: Making this Unobserved and Unmeasured Critical Job Function Visible. *American Journal of Infection Control, 35, 401–406.*

Grigg O., Farewell V. & Spieglhalter D. (2003). Use of Risk-Adjusted CUSUM and RSPRT Charts for Monitoring in Medical Contexts. *Statistical Methods in Medical Research, 12, 147-170.*

Gustafson T. (2000). Practical Risk Adjusted Quality Control Charts for Infection Control. *American Journal of Infection Control, 28, 406-414.*

Hanslik T., Boelle P. & Flahault A., (2001). The Control Chart: an Epidemiological Tool for Public Health monitoring. *Public Health, 115,* 277-281.

Henry J. Kaiser Family Foundation. (2006). Snapshots: Comparing Projected Growth in Health Care Expenditure and the Economy. Retrieved from: *https://www.kff.org/health-costs/issue-brief/snapshots-comparing-projected-growth-in-health-care-expenditures-and-the-economy/.*

Howard I., Pillay B. Castle N., Shaikh L., Owen R. & Williams D., (2018). Application of the Emergency Medical Services Trigger Tool to Measure Adverse Events in Pre-Hospital Emergency Care: A Time Series Analysis. *BMC Emergency Medicine, doi: 10.1186/s12873-018-0195-0*

Jones M. & Steiner S. (2012). Assessing the Effect of Estimation Error on Risk-Adjusted CUSUM Chart Performance. *International Journal for Quality in Healthcare, 24, 176–181*

Kaminsky F., Maleyeff J. & Mullins D. (1998). Using SPC to Analyse Measurements in Healthcare Orgainsations. *Journal of Industrial Engineering and Management, 18, 36–46.*

Keller D., Stulberg J., Lawrence J., Samia H. & Delaney C. (2015). Initiating Statistical Process Control to Improve the Quality Outcomes in Colorectal Surgery. *Surgical Endoscopy, 29, 3559–3564*

Koetsier A., Veer S., Jager K., Peek N. & Keizer F. (2012). Control Charts in Healthcare: Quality Improvement. *Methods of Information in Medicine, 51, 189-198.*

Lawson E., Hall B., Esnaola N. & Clifford K. (2012). Identifying Worsening Surgical Site Infection Performance: Control Charts Versus Risk-Adjusted Rate Outlier Status. *American Journal of Medical Quality, 27(5), 391-397.*

Lee R., Kim K., Cho S., Lim S., Shim J., H.D. Huh & Lee S. (2017). Statistical Process Control Analysis for Patient Quality Assurance of Intensity Modulated Radiation Therapy. *Statistical Methods in Medical Research, 71, 717–721.*

Levett J. & Carey R. (1999). Measuring for Improvement: From Toyota to Thoracic Surgery. *Interactive Cardiovascular and Thoracic Surgery, 68(2), 353-358.*

Lighter D. & Tylkowski C. (2004). Using Control Charts to Track Physician Productivity. *The Physician Executive, 53-57.*

Limaye S., Mastrangelo C. & Zerr D. (2008). A Case Study in Monitoring Hospital Associated Infections with Count Control Charts. *Quality Engineering, 20, 404–413.*

Maruthappu M., Carty M., Lipsitz S., Wright J., Orgill D. & Duclos A. (2014). Patient- and Surgeon-Adjusted Control Charts for Monitoring Performance. *BMJ Open, doi: 10.1136/bmjopen-2013-004046.*

Mazloum M., Alsadat R., Bardan S., Shamah, M., Eltayeb F., Marie A., Dakkak A., Betelmal I., Kherallah M. (2012). Use of Ventilator Associated Pneumonia Bundle and Statistical Process Control Chart to Decrease VAP rate in Syria. *Journal of Quality Technology, 2, 79–83.*

Mezzenga E., D'Errico V., Sarnelli A., Strigari L., Menghi E., Marcocci F., Bianchini D. & Benassi M. (2016). Preliminary Retrospective Analysis of Daily Tomotherapy Output Constancy Checks Using Statistical Process Control. *PLOS One, 11, 1–12*.

Minne L., Eslami S., Keizer N., Jonge E., Rooij S. & Hanna A. (2012). Statistical Process Control for Validating a Classification Tree Model for Predicting Mortality-A novel Approach Towards Temporal Validation. *Journal of Biomedical Informatics, 45, 37–44.*

Mohammed M. (2004). Using Statistical Process Control to Improve the Quality of Healthcare. *BMJ Quality & Safety, 13, 243–245*

Moran J. & Solomon P. (2013). Statistical Process Control of Mortality Series in the Australian and New Zealand Intensive Care Society (ANZICS) Adult Patient Database: Implications of Data Generating Process. *BMC Health Services Research, 13, 66–78.*

Morton A., Whitby M., McLaws M., Dobson A., McElwain S., Looke D., Stackelroth J. & Sartor A. (2001). The Application of Statistical Process Control Charts to the Detection and Monitoring of Hospital-Acquired Infections. *Journal of Quality in Clinical Practice 21, 112-117.*

Mosher H., Lose D., Leslie R., Pennathur P. & Kaboli P. (2015). Aligning Complex Processes and Electronic Health Record Templates: A Quality Improvement Intervention on Inpatient Interdisciplinary Rounds. *BMC Health Services Research, doi: 10.1186/s12913-015-0932-y*

Neuburger J., Walker K., Sherlaw-Johnson C., Meulen J. & Cromwell D. (2017). Comparison of Control Charts for Monitoring Clinical Performance Using Binary Data. *BMJ Quality & Safety, 26, 919-928.*

Norton P., Murray M., Doupe M., Cummings G., Poss J., Squires J., Teare G. & Estabrooks C. (2014). Facility Versus Unit Level Reporting of Quality Indicators in Nursing Homes When Performance Monitoring is the Goal. *BMJ Open, doi:10.1136/bmjopen-2013- 004488.*

Noyez L. (2009). Control Charts, CUSUM Techniques and Funnel Plots. A Review of Methods for Monitoring Performance in Healthcare. *Interactive CardioVascular and Thoracic Surgery, 9, 494-499.*

Oguntunde P., Odetunmibi O. & Oluwadare O. (2015). Comparative Study of the Use of Statistical Process Control in Monitoring Healthcare Delivery. *International Journal of Quality and Reliability Management, 14, 154–158*

Pagel C., Ramnarayan P., Ray S. & Peters M. (2016). Development and Implementation of a Real Time Statistical Control Method to Identify the Start and End of Winter Surge in Demand for Pediatric Intensive Care. *European Journal of Operational Research, 26, 847–858.*

Prajapati D. & Singh S. (2016). Determination of Level of Correlation for Products of Pharmaceutical Industry by Using Modified Chart. *International Journal of Quality & Reliability Management, 33, 724– 746.*

Prajapati D. (2016). Correlation Level Among the Observations for a Pharmaceutical Industry Using X Chart With Economics. *International Journal of Quality & Reliability Management, 19, 277–300.*

Quesenberry C. (2000). Statistical Process Control Geometric G Chart for Nosocomial Infection Surveillance. *American Journal of Infection Control, 28, 314–320* .

Robinson S., Neyens D. & Diller T. (2017). Applied Use of Safety Event Occurrence Control Charts of Harm and Non-Harm Events: A Case Study. *American Journal of Medical Quality, 32, 285-291*

Rosenbluth G., Garritson S., Green A., Milev D., Vidyarthi A., Auerbach A. & Baron R. (2016). Achieving Hand Hygiene Success With a Partnership Between Graduate Medical Education, Hospital Leadership, and Physicians. *American Journal of Medical Quality, 31(6), 577-583.*

Salinas M., Lopez M., Flores E., Gutierrez M., Lugo J. & Uris J. (2009). Three Years of Preanalytical Errors: Quality Specifications and Improvement Through Implementation of Statistical Process Control. *Scandinavian Journal of Clinical & Laboratory Investigation, 69(8), 822-826.*

Sanghangthum T., Suriyapee S., Srisatit S. & Pawlicki T. (2012). Statistical Process Control Analysis for Patient-Specific IMRT and VMAT QA. *Journal of Radiation Research, 54, 546–552.*

Schmidtke K., Watson D. & Vlaev I. (2016). The Use of Control Charts by Laypeople and Hospital Decision-Makers for Guiding Decision Making. *The Quarterly Journal of Experimental Psychology, 70, 1114-1128*

Schrem H., Schneider V., Kurok M., Goldis A., Kaltenborn A., Gwinner W., Barthold M., Liebeneiner J., M. Winny M. & Kleine M. (2016). Independent Pre-Transplant Recipient Cancer Risk Factors after Kidney Transplantation and the Utility of G-chart Analysis for Clinical Process Control. *PLOS One, 11, 1–17.*

Silva B. & Krishnamurthy M. (2016). The Alarming Reality of Medication Error: A Patient Case and Review of Pennsylvania and National Data. *Journal of Community Hospital Medicine Perspectives, 6(4).*

Silvester K., Harriman P., Walley P. & Burley G. (2013). Does Process Flow Make a Difference to Mortality and Cost? An observational Study. *International Journal of Health Care Quality Assurance, 27(7), 616-632.*

Silwa M & Kane J. (2011). Service Quality Measurement: Appointment Systems in UK GP Practices. *International Journal of Health Care Quality Assurance, 24(6),441-452.*

Smith I., Gardner M., Garlick B., Brighouse R., Cameron J., Lavercombe P., Mengersen K. & Rivers J. (2013). Performance Monitoring in Cardiac Surgery: Application of Statistical Process Control to a Single Site Data. *American Journal of Medical Quality, 22, 634–641.*

Suman G. & Prajapati D. (2018). Control Chart Applications in Healthcare: A Literature Review. *International Journal of Metrology and Quality Engineering, 9, 1-5.*

Taner M. (2013). Application of Six Sigma Methodology to a Cataract Surgery Unit. *International Journal of Health Care Quality Assurance, 26(8), 768-785.*

Tennant R., Mohammed M.A., Coleman J. & Martin U., (2007). Monitoring Patients Using Control Charts: Systematic Review. *International Journal for Quality in Health Care, 19(4),* 187-194.

Thor J., Lundberg J., Ask J., Olsson J., Carli C., Harenstam K. & Brommels M. (2007). Application of Statistical Process Control in Healthcare Improvement: A Systematic Review. *BMJ Quality & Safety, 16, 387-399.*

Walley P., Sylvester K. & Mountford S. (2006). Health-care Process Improvement Decisions: A Systems Perspective. *International Journal of Health Care Quality Assurance, 19(1), 93-104.*

Waterhouse M., Smith I., Assareh H. & Mengersen K. (2010). Implementation of Multivariate Control Charts in a Clinical Setting. *International Journal for Quality in Healthcare, 22, 408–414.*

Welch S. & Dalto J. (2011). Improving Door-to-Physician Times in 2 Community Hospital Emergency Departments. *American Journal of Medical Quality, 26(2), 138-144.*

Wiemken T., Furmanek S., Carrico R., Mattingly W., Persaud A., Guinn B., Kelley R. & Ramirez J. (2016). Process Control Chart in Infection Prevention: Make it Simple to Make it Happen. *American Journal of Infection Control, 45, 216–221.*

Woodall W., Fogel S. & Steiner S. (2015). The Monitoring and Improvement of Surgical-Outcome Quality. *Journal of Quality Technology, 47(4), 383-399.*