A road map for the implementation of statistical control charts for the monitoring and prevention of hospital infections

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Abstract: Healthcare-associated infections (HAI) are a significant burden globally, with millions of patients affected each year. Healthcare-related infections are infections that arise in a patient during the course of care in a hospital or other care facility, which were not present or incubating at the time of admission. Among the member states of the European Union, Italy is one of the countries that is most affected by the circulation of multi-resistant microorganisms, attributable to an improper use of antibiotics and a lack of effective measures to prevent the transmission of infections. In most Italian hospitalization facilities, clinical and organizational procedures have already been implemented regarding the prevention of HAIs, however no systematic surveillance of processes with statistical control tools has yet been introduced. The purpose of the research is to outline which kind of control chart can be used in the healthcare sector and for which type of parameters (clinical and environmental one). This article analyzes the literature by analyzing the application of control charts in the healthcare sector. The limits of applicability of such kind of tools are then highlighted. According to the authors, the use of monitoring tools such as control charts would allow a significant reduction of the HAIs. The surveillance implemented through the use of control charts, in the context of infection prevention, could create the basis for activating immediate preventive actions (eg. example in case of epidemics) and directs health policies. Finally, surveillance should generate data that can be used in some way to improve the quality of care. The choice of the most effective chart to use is often essential to avoid overestimating or underestimating the control variable under consideration. Finally, this paper defines a possible road map for the implementation of control charts in monitoring hospital infections in a middle size Italian hospital.

Keywords: HAI, hospital infections, statistical control chart, infection control

I. INTRODUCTION

The World Health Organization indicates Infections Related to Healthcare as the most frequent adverse event during the provision of health services and services, with a progressing epidemiological trend and a significant clinical and economic impact with a consequent increase in costs direct and indirect, due to an extension of the length of hospitalization, long-term disability and mortality [1].

In Italy, every year, about 5-8% of hospital patients contract HAI (Infections Related to Assistance) or ICA as an Italian acronym, determined by AR (Antimicrobial Resistance) or MDR (Multi-Drug Resistance) microorganisms. There are 450-700 thousand cases: 1 patient out of 15 contracts an infection during hospitalization, 1 in 100, on the other hand, contracts it in home care. Also in Italy, deaths caused by ICA are estimated to be around 10 thousand per year. From the point of view of the economic impact, AR is estimated to cost Italy 13 billion dollars, between now and 2050, for new and further hospitalizations and in social and health facilities, as well as for the repercussions in terms of direct costs and indirect (social costs) [2].

Although today there is still no widespread use of statistical control charts applied to nosocomial infections, these tools, applied in other health fields, has already allowed the achievement of surprising results such as a reduction in mortality rates, in the length of hospitalizations, in the number of complications, in the percentage of errors [3].

The present study outlines how the statistical control charts can be applied to HAIs, by monitoring the appropriate risk factors, in order to prevent the number of HAI cases and reduce the directly attributable mortality rate.

The paper provides a preliminary overview of the main types of hospital infections in order to also frame the associated risk factors. An analysis of the literature is then presented by investigating the studies conducted and the application of statistical control charts in the health sector. The limits of applicability of this tool will be highlighted, such as the long times necessary to reach a sample size sufficient to establish the state of the process and the concomitant difficulty in monitoring rare low-frequency events such as infections. The choice of the paper to be used based on the situation to be monitored was found to be of considerable importance in order to avoid overestimating or underestimating a given process under consideration. Finally, an implementation road map will be proposed taking as a reference case study a medium-sized Italian hospital, that has made available to the authors some data and information useful for finalizing the research.

II. HOSPITAL INFECTIONS

Hospital-acquired infections are infectious diseases that arise during hospitalization, or in some cases after the patient has been discharged, and that were neither clinically manifest nor incubating at the time of admission to the hospital [4]. Such infections, also known as nosocomial infections, can occur 48 hours after hospital admission, up to three days after discharge, up to thirty days after an operation, and of course in healthcare settings where the patient was admitted for reasons other than the infectious cause [5-6].

People at risk of contracting a hospital infection are therefore mainly patients but, with less frequency, also hospital staff, volunteer assistants, students and trainees.

According to the first global report of the World Health Organization of 2011 [1], in Europe each year ICAs cause 16 million additional days of hospitalization, 37,000 attributable deaths and 110,000 deaths for which the infection is a contributing cause. Considering only direct costs, moreover, every year the expenditure caused by these types of infections amounts to 7 billion euros.

According to data released in 2021 by EPI-CENTRO [7], Institute of Epidemiology for Public Health of the Istituto Superiore di Sanità (ISS), hospital infections are associated to four main localizations that account for approximately 80 % of all observed infections:

- The urinary tract
- Surgical wounds
- Respiratory system
- Systemic infections (sepsis, bacteremia).

There are several factors that could increase the probability of incurring in a hospital infection such as the duration of hospitalization, the use of invasive instruments and the inappropriate use of broad-spectrum antibiotics for prophylactic and therapeutic purposes, which selects the emergence of antibiotic-resistant strains [6]. This last aspect is of considerable importance because although handwashing has been shown to prevent more than 25% of infections, as most bacteria are carried from the healthcare worker to the patient [8], appropriate antibiotic use is extremely important. Resorting to potent antibiotics when even a more common one would suffice, results in increased selection of multi-resistant bacteria in the hospital healthcare environment, increasing the risk of lethal infections sustained by bacteria, resistant to all available antibiotics [9].

Surveillance of hospital infections must therefore be constant and at the appearance of suspicious signs and symptoms it is necessary to intervene with the search for the site of infection, establish its cause and remove the suspicious devices.

In the United States, the Study on the Efficacy of Nosocomial Infection Control (SENIC) demonstrated that by adopting effective control programs, up to 35% of the overall hospital infections can be prevented [10].

The data that emerges clearly from the study of the European Center for Infectious Diseases [11] is that today in Italy the probability of contracting infections during hospitalization is about 6%, with 530 thousand cases each year, data that put Italy in last place among all countries in Europe. The number of nurses and physicians in charge of infection control is insufficient (medians: 3 and 1 FTE staff per thousand beds) and in any case lower than the European average of 4 nurses and 1.44 physicians. This staffing deficit, and the consequent lack of infection control programs, which is being addressed by the Ministry of Health's National Plan to Combat Antimicrobial Resistance (PNAR) 2017-2020, has been shown to be associated with an increased risk of ICA. For example, audits have been found to be the intervention that has shown the greatest effectiveness, but only 53.6% of hospitals implement them for at least one area of infectious risk and less than 9% throughout the hospital. Facility indicators reported an average of 0.67 FTE (Full Time Equivalent) antimicrobial stewardship staff across hospitals, which means 1.68 staff per thousand beds, thus with at least 50% of hospitals enrolled without such support.

III. THE CONTROL CHARTS IN THE HEALTHCARE SECTOR

Statistical control charts, the main tool of SPCs, being commonly used for monitoring of ongoing processes and for continuous improvement of them, have received in the last thirty years more and more interest regarding their application to the health care field, turning at first the analysis to the laboratory level and later applying them to the health care and hospital field having patient care as the ultimate goal.

Gaurav Suman and DeoRaj Prajapati from the Indian Department of Mechanical Engineering (Punjab Engineering College) in 2018 published an article [3] showing how control charts have been used in the scientific literature in the healthcare sector worldwide, analyzing a number of aspects of them. In fact, they highlighted that control charts are mostly applied at the departmental level and, to date, the departments that have made most use of them are surgery and epidemiology. This is followed by the emergency department, radiology, administrative department, pharmacy and finally cardiology.

To date the countries that have implemented them most are the United States of America, Australia and England. In England, however, although it ranks third, control charts have been used with greater continuity, highlighting the gaps that other countries still have in implementing them.

Finally, the authors have highlighted how, depending on the data collection process implemented, two types of application of control charts can be distinguished. If an analysis is carried out starting from data from the past, the study is retrospective; if, on the other hand, data are collected by closely observing the process under analysis, the study is longitudinal. They outline that until now there are more retrospective studies, but in the future, it is desirable to implement more longitudinal studies as they allow to have a clearer idea and vision of the current situation of the processes.

Yee Kam et al. in 2021 perform a study of the application of control charts in monitoring healthcare performance [12]. The Authors illustrate some examples implemented by the National Health Service (NHS) in England. They used a XmR control chart to monitor the response time of the ambulance and to assess how the process has changed with the introduction of a new set of ambulance guidelines and a new triage system. A U chart was chosen to keep track of the rate of adverse events events per incident related to medical devices or equipment. A retrospective study was conducted from January 2009 to June 2012. There were a total of 130,512 adverse events with medical devices, with a total incident of 4,328,100 for this period. Investigation on points fall outside the control limits allowed to identify special causes (for instance a malfunction of the external pacemaker) and to suggest actions to prevent the recurrence of similar events.

The case studies show how a control chart can help the healthcare organizations to choose the right and proper improvement plan–whether to detect and remove special causes of variation to bring the process back into the state of control (when the process is out of control) or to make more effort to enhance the fundamental process and to redesign the process in the desired direction (when the process is in control). Besides, the control chart can also be used as a simple tool to keep track of whether the improved process is maintained over time. Thus, a control chart helps visualize the efficacy of the current process performance, taking more statistical rigor to the act of making critical decisions and ensuring the consistency of process improvements over time.

The control charts can help healthcare institutions to avoid wasted investments and resources in any changes that have no effective impact on performance improvement.

IV. CONTROL CHARTS APPLIED TO INFECTIONS CONTROL

Although the literature highlights the achievement of interesting results with control chart application also in the healthcare sectors, today there is still no widespread use of these statistical tools applied to nosocomial infections.

Certainly, a first obstacle can be represented by the availability of data and the sampling methods required by the control charts. To assess that a process is under statistical control, at least 25 subgroups would need to be collected and analysed [13], a requirement that could have significant implications for how data should be collected and analysed by healthcare organizations presumably quality oriented. Even using traditional quarterly data, for example, one might still have to wait a minimum of 6 or 7 years to determine whether the critical process being examined is stable or contains anomalies. For this reason, it is generally recommended to use smaller, more frequent subsets of data over time [14].

The authors analyzing the literature found different types of control charts applied to the surveillance of nosocomial infections.

Standard approaches for the application of SPC to nosocomial infections are the use of control charts of type p or u, which are used, respectively, to study the fraction or mean number of patients who contract a particular type of infection in a given reporting period. A p chart, based on a binomial distribution, is used when the data collected are the number of events with one or more infections. In contrast, the u-type card, based on a Poisson distribution, would be more appropriate if each event (e.g., patient, reporting period, etc.) were considered as an area of opportunity for which theoretically more than one infection could occur and for which multiple occurrences are counted [15-17].

It should be emphasized that small subsets of data distributed according to a binomial or Poisson distribution in no way invalidate np, p, c, or u control charts, a concept that is sometimes not conveyed. These charts are based on a Poisson or binomial distribution and not on a normal distribution, however one should be careful and consider the sensitivity and specificity of any chart. For this reason, probability bounds are often preferred over k- sigma bounds (where k is usually equal to 3).

Another possible application of control charts is to track the number of events (e.g., surgeries or other procedures) that occur between specific outcomes (e.g., a particular type of infection), rather than tracking the number of infections that occurred per month. This type of metric has been proposed in the healthcare literature due to its ease of use, conceptual appeal, almost immediate data availability, more timely feedback, and low infection rates. An example of such an application is to keep track of the number of days between the occurrence of one Clostridium difficile infection and another thanks to the almost immediate availability of the individual's observations and the ease of use with which non-technical staff can implement this measure. The advantage of such a chart is that it is easy to calculate and can therefore be updated in real time in the hospital, without knowing the most appropriate census or denominator (which in the case of the example just cited referring to Clostridium difficile is assumed to be more or less constant or at most vary only slightly) [18-19]. A traditional approach in high-quality processes in other industries sometimes is to monitor the number of cases that occur among outcomes of concern, such as the number of manufactured items or financial transactions that can be counted among nonconforming parts or data errors, respectively.

A. Control charts applied to HAIs: two illustrative case studies

To date, control charts have not yet been particularly used for the prevention and control of hospital infections. Some critical issues are related to the availability and the low frequency of data to be monitored, as detailed in the previous paragraph. However, among the few studies currently implemented and the various potential pilot studies, this study illustrate below a series of explanatory examples that can give an idea of the potential, usefulness and effectiveness that tools such as control charts possess.

<u>SSI: Surgical Site Infections</u>

The case study shown below is a hypothetical application of control charts to SSIs proposed by J.C Benneyan et al. in 2012 [20].

An interdisciplinary team sought to reduce the postoperative surgical site infection (SSI) rate for selected surgical procedures. Instead of aggregating SSIs to calculate a week/month infection rate, the control chart graphically represents the number of surgeries among the occurrences of infection (Figure 1). This representation allows the statistical significance of each occurrence of an infection to be assessed rather than having to wait until the end of a week/month before the data can be analyzed. This ability to immediately evaluate data greatly increases the potential timeliness of the analysis

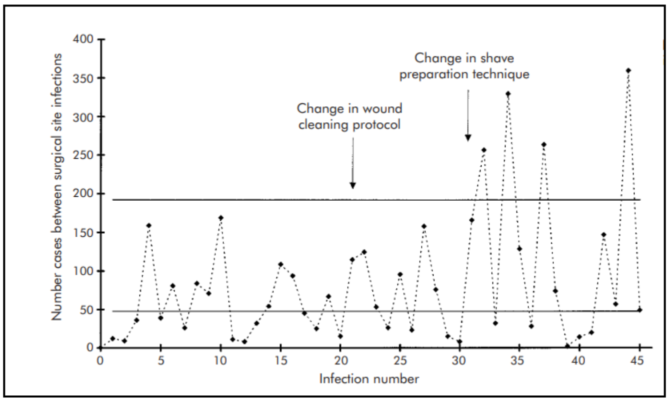

Fig. 1. Control chart for surgical site infections [20]

A first possible intervention suggested by the team was to test a change in the postoperative wound cleaning protocol. However, as is evident from the analysis of the control chart, this type of intervention did not appear to have any type of impact on reducing infection rates. The results obtained by reading the chart prevented, nonetheless, additional resources and time from being invested by the team in implementing a change that was ineffective for the hospital.

After further brainstorming and literature reviews, the team decided to take action by modifying the shaving preparation technique to prepare the surgical site prior to surgery. A new shave preparation protocol was used for several months, and the control chart in Figure 1 highlights the improvement this change brought about. The SSI rate went from about 2.1% to 0.9% (for this type of graph, the average SSI rate is the reciprocal of the center line: 1/47 = 2.1% versus 1/111 = 0.9%). Thus, note that on this type of graph, the data plotted above the UCL indicate an improvement, as an increase in the number of surgeries among SSIs equals a decrease in the SSI rate.

Monitoring of bacteremia

The National Institute for Cancer Research (IST), Genoa, Italy in 2012 chose to adopt a systematic approach based on process monitoring to generate continuous process improvement [21]. The tool chosen to keep under control the clinical outcomes, which represent the direct consequence/effects of the services provided by the professionals involved in the healthcare provision, was the control card.

Therefore, the goal was to implement a tool that could identify adverse events through constant monitoring and timely information return of the performance provided that deserved to be better studied.

The population that was involved included all patients hospitalized from 2006 until March 2011 at the Department of Integrated Surgical Oncology and Integrated Medical Oncology.

The variables monitored for patient safety were falls, bacteremia, and pressure injuries (Ldp). A survey form was defined to collect these events, and the events detected by monitoring were represented on a monthly time scale.

To represent these phenomena, attribute control charts known as U-Charts were used because they allow the number of adverse events to be monitored against the number of opportunities.

This chart, in fact, highlights the expected average value of the probability of adverse events occurring for the number of opportunities examined in the period observed. The x-axis is calibrated in units of time, whereas the y-axis shows the number of events per average number of patients or relative frequency. The center line (LC) represents the mean of all relative frequency values while the control limits, lower (LCI) and upper (LCS), identify the area within which the process relative frequency is under control. The LCS varies according to the number of patients present in the month examined (subgroup).

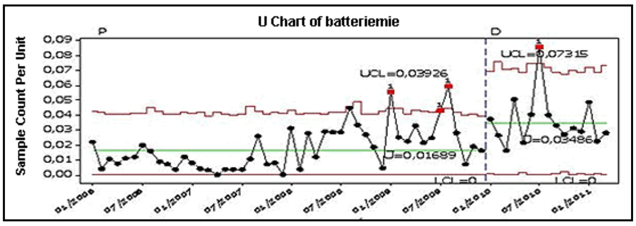

Fig. 2. Monitoring of bacteremia before (P) and after (D) [21]

The control charts used for analysis are separated into two distinct phases (Figure 2), corresponding to the period before (before, P) and after (after, D) the operator training and the event reporting awareness efforts. As a consequence of the P period, the procedures governing the processes involved were re-evaluated. For some phenomena, the Root cause analysis technique was employed in order to identify possible variables on which to act in order to activate improvement projects.

The limitation of this project, however, is that the small sample size of adverse events has determined a different start for the monitoring for each variable. The population involved was chosen not by statistical sampling, but randomly with respect to the presence in the institution in the month considered and no exclusion criteria were defined because it was considered that all patients had an equal chance of experiencing an adverse event.

Catheterization-associated urinary tract infections

In 2017, the American Journal of Infection Control published an article [22] on the application of control charts to several critical processes in the care setting using simulated data. Specifically, as illustrated in Figure 3, it proposes the use of a u-type control chart to monitor catheterization-associated urinary tract infections.

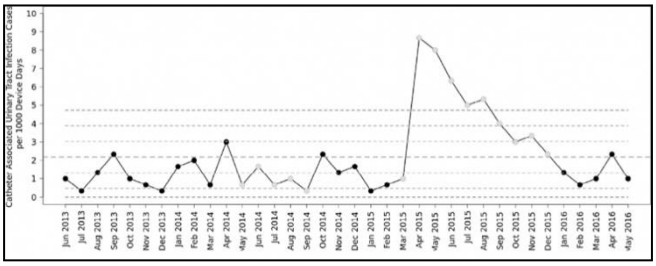

Fig. 3. Process control u chart for catheter-associated urinary tract infection surveillance [22]

By mapping the number of catheterization-associated urinary tract infections over 1000 days of in situ device, distributed according to a Poisson distribution, this chart allowed the presence of special causes of variability over months to be detected. Between May and September 2014, 4 out of 5 points were below the limit set at - 1 sigma, suggesting special cause variation leading to lower disease rates than previous data. Even between March and December 2015, the process exhibited anomalies as all four Western electric rules first published in 1856 were met, bringing the process under review out of statistical control.

V. A ROAD MAP FOR INFECTIONS MONITORING BY MEANS OF CONTROL CHARTS

After analyzing the applications found in the literature, the Authors tried to define a road map for the implementation of control charts for hospital infection surveillance for a medium-sized Ligurian hospital intending to undertake an improvement policy in the control and prevention of nosocomial infections. As specified in Section III there are two possible types of approaches in applying control charts. If the data are collected and analysed only at a later date, the study is defined as retrospective. If, on the other hand, the data acquisition process is on line real time, the analysis falls into the category of longitudinal studies. According to the literature reviewed, the best type of study to pursue is the longitudinal one, as it allows the collection of more organic and focused data on the process under investigation. To date, however, there is a prevalence of retrospective studies, as they require less effort and cost, therefore, although the effectiveness achieved through a longitudinal study is greater.

The Authors propose for the hospital a first pilot study of retrospective type on historical data related to infections in order to identify firstly the most recurrent types of infections and to detect special causes of variation that have determined abnormal increases or decreases of the infections rate.

In addition, this preliminary retrospective study is helpful to understand on which parameters it is more effective to implement a longitudinal study. Moreover, it would allow to calculate, based on the history, the control limits related to the incidence / 100 patients per type of infection in the different departments. This calculation is very important if you want to implement new procedures/protocols and you want to test their effectiveness in terms of reduction of HAIs.

Once the retrospective study has been conducted, it is necessary to select the parameters of interest and, depending on the typology of data selected, the most suitable control chart will be identified.

According to a study conducted in 2018 [22], the most frequent infections in Liguria are urinary tract infections (21.5%) followed by pneumonia (19%) and bloodstream infections (14.2%). Finally, gastrointestinal and surgical site infections amount to 12% and 9.5%, respectively.

One could then make a chart for each type of infection mentioned and use the charts to monitor the totality of infections in each of the hospital wards, establishing the natural variability of the as is situation. Proceeding in this way, the charts could then be used on one hand to test the effectiveness of new procedures and protocols implemented for the containment of infections, and on the other hand to have a temporal view of the occurrence of HAIs in the various departments and then trying to trace the causes that determine any growth trends. By mapping the number of patients infected, by at least one ICA, the control charts that could be used are np or p.

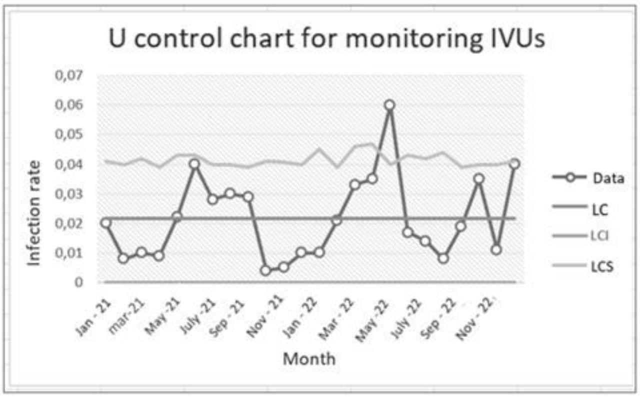

Fig. 4. A u-chart for monitoring IVUs (made from hypothetical data)

Urinary tract infections (UTIs) or IVUs as an Italian acronym are predominantly associated with invasive procedures on the urinary tract and 75-80% of UTIs are associated with bladder catheter use and the percentage of hospitalized patients wearing a catheter, at any given time during their hospitalization, is 12-16%. Therefore, the main risk factor for developing a UTI is the duration of catheterization, accompanied by other risk factors such as female sex and old age. In fact, the risk of developing bacteriuria increases from 3 to 7% for each day of catheterization. In the proposed example, illustrated in Figure 4, a reference period of two years is considered, and in each month the rate of infection occurring per unit is mapped, given by the ratio between the cases of UTI of the month and the sample size of the month itself.

Hospital-acquired pneumonias, the most frequent infections after urinary tract ones, are the infections associated with the highest costs and the highest proportion of deaths due to infection. The costs generated by a single episode of nosocomial pneumonia are estimated in the U.S. at approximately $5,000, with an impact on the overall cost of hospitalization between 5% and 10% depending on the department.

Finally, among the most frequent hospital infections in Liguria surgical site infections should be considered too. The risk of developing a surgical site infection depends on several factors such as patient characteristics, characteristics of the operation, duration of preoperative hospitalization and adoption or not of preventive measures. Patient characteristics that increase the risk of infection are numerous, including age (people in the extreme ages, infants or elderly, are more susceptible), the presence of co-morbidities, malnutrition, and obesity. Surgeries involving the intestinal, respiratory, or urinary tract are at increased risk of infection, given the higher degree of endogenous contamination, and the risk also increases with the duration of the surgery and the type of surgical technique employed. It would also be useful to implement Studies using control charts also for this type of infection. For example, for a cardiac surgery department one might decide to monitor for a time interval of one year the number of surgical site associated ICAs occurring each month on a sample of patients, taken by implementing subgroup sampling. In this case the most suitable chart for the study is the control chart of type c. If, on the other hand, we decide to consider the entire population of patients admitted every month to the cardiac surgery ward, the number of patients enrolled in the study would vary from month to month and therefore the control chart to be used would be the chart of type u. This use of the chart would allow us to assess the trend of ICA over time for each ward and eventually correlate abnormalities with known risk factors or it could also allow us to identify risk factors not yet known to be present in that time interval.

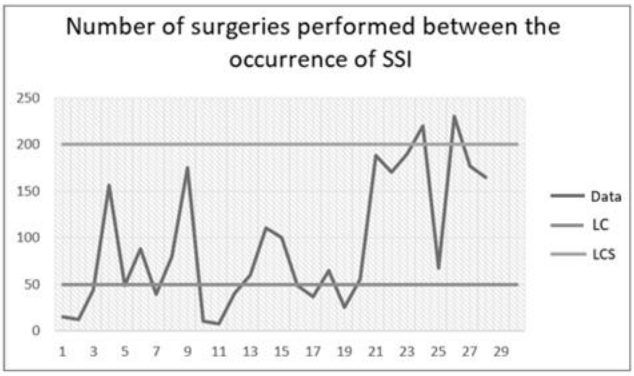

Fig. 5. A g-chart to track the number of surgeries performed between the occurrence of SSI (made with hypothetical data)

A further proposed application of control charts to SSIs (Surgical Site Infections) is illustrated in Figure 5. The g-chart created is used to track the number of surgeries that are performed by the hospital between the consecutive occurrence of an infection.

Finally, further effective applications of control charts trying to contain the number of ICAs within a hospital could be to monitor clinical parameters of patients or environmental parameters such as proper hand hygiene and to monitor cases of Clostridium difficile infection per 1000 patient days. Such applications would be implemented based on what has already been done and reported in 2017 by the American Journal of Infection Control [22].

The Authors summarized all the statistical analysis proposed in a road map in order to prioritize interventions (Figure 6).

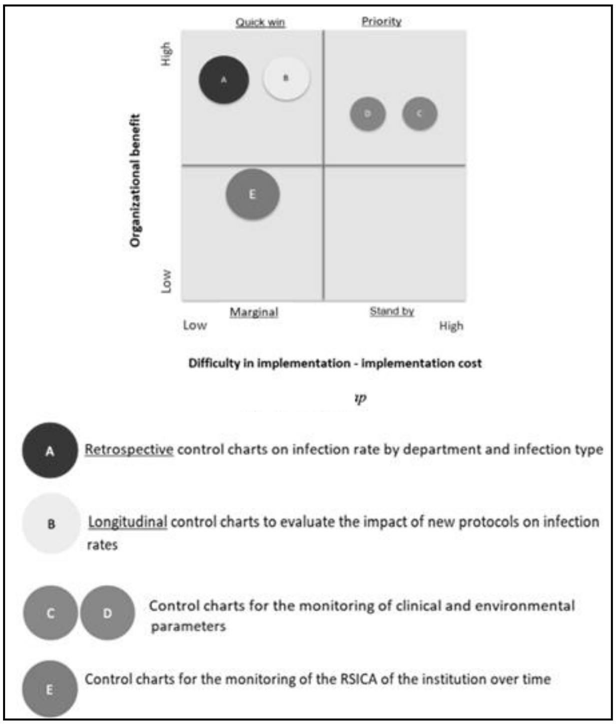

Fig. 6. The proposed Road map

VI. CONCLUSION

Considering that currently in Italy there is an incidence of Care-Related Infections equal to 450,000 - 700,00 and that, among the member states of the European Union, Italy is one of the countries that stands out for the circulation of multi-resistant microorganisms attributable to an intemperate use of antibiotics and a lack of application of effective measures to prevent the transmission of infections, the use of tools such as control charts would allow an overall improvement of health care. Being a commonly used tool for monitoring processes in progress and for their continuous improvement, control charts have received in the last thirty years more and more interest in their application to the health care field, turning at first the analysis at the laboratory level and then applying them to the health care and hospital having as ultimate goal the patient care. However, although there are many case studies in the literature, few of them are aimed at the reduction and prevention of ICA in hospitals. For this reason, to accompany the procedures already in use in a hospital, a first conduction of retrospective studies could be implemented, summarized in a road map to prioritize interventions. In the wake of the few studies implemented, the proposal is to establish per department and per specific type of infection to that department the limits of control, in order to establish the natural variability of the as is situation so that at a later time the control charts could be used to test the effectiveness of new protocols/procedures implemented by the institution for infection containment.

Based on regional data, a hospital could also monitor the overall performance of its facility relative to its healthcare competitors through the temporal analysis of the standardized infection ratio proposed by Alisa. Risk factors such as hand hygiene and the presence of Clostridium difficile, although it would be appropriate to monitor them, currently require a complex data collection and sampling process, which I therefore suggest should be implemented through control charts in the hopefully near future. Once consolidated the use of Shewart's control charts through retrospective studies, following what is proposed on the basis of case studies already reported in the literature, the hospital could implement a longitudinal study to monitor, in a more correct and sophisticated way, what is the current situation at the hospital itself, so that following a logic of continuous improvement tries to get better and better results in the prevention and containment of costs and deaths due to ICA.

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