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A bibliometric analysis of 50 years of worldwide research on statistical process control

Uma análise bibliométrica de 50 anos de pesquisa sobre controle estatístico de processo

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Abstract: An increasing number of papers on statistical process control (SPC) has emerged in the last fifty years, especially in the last fifteen years. This may be attributed to the increased global competitiveness generated by innovation and the continuous improvement of products and processes. In this sense, SPC has a fundamentally important role in quality and production systems. The research in this paper considers the context of technological improvement and innovation of products and processes to increase corporate competitiveness. There are several other statistical technics and tools for assisting continuous improvement and innovation of products and processes but, despite the limitations in their use in the improvement projects, there is growing concern about the use of SPC. A gap between the SPC technics taught in engineering courses and their practical applications to industrial problems is observed in empirical research; thus, it is important to understand what has been done and identify the trends in SPC research. The bibliometric study in this paper is proposed in this direction and uses the Web of Science (WoS) database. Data analysis indicates that there was a growth rate of more than 90% in the number of publications on SPC after 1990. Our results reveal the countries where these publications have come from, the authors with the highest number of papers and their networks. Main sources of publications are also identified; it is observed that the publications of SPC papers are concentrated in some of the international research journals, not necessarily those with the major high-impact factors. Furthermore, the papers are focused on industrial engineering, operations research and management science fields. The most common term found in the papers was cumulative sum control charts, but new topics have emerged and have been researched in the past ten years, such as multivariate methods for process monitoring and nonparametric methods.

Keywords: Statistical process monitoring; Statistical process control; Bibliometrics; Cienciometrics.

Resumo: *Um crescente número de trabalhos sobre controle estatístico do processo (CEP) emergiu nos últimos cinquenta anos e principalmente nos últimos quinze. Isso pode ser atribuído ao aumento da competitividade global gerada pela inovação e pela melhoria contínua de produtos e processos. Nesse sentido, o CEP tem um papel fundamental em sistemas de qualidade e de produção. A investigação deste artigo considera o contexto da melhoria tecnológica e de inovação de produtos e processos como forma de aumentar a competitividade das empresas. Existem várias outras técnicas e ferramentas estatísticas para auxiliar a melhoria contínua e inovação de produtos e processos, mas, apesar das limitações na sua utilização nos projetos de melhoria, há uma crescente preocupação sobre o uso do CEP. A diferença entre as técnicas de CEP ensinadas em cursos de engenharia e suas aplicações práticas para os problemas industriais é observada nas pesquisas empíricas; por esta razão, é importante identificar o que foi pesquisado e as tendências na pesquisa sobre CEP. O estudo bibliométrico é proposto neste sentido e usa para a investigação a base de dados Web of Science (WoS). A análise dos dados indica que houve uma taxa de crescimento de mais de 90% no número de publicações sobre CEP após 1990. Os resultados revelam a origem das principais*

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publicações, os autores com o maior número de artigos e suas redes. As principais fontes de publicações também são identificadas; observa-se que as publicações de artigos sobre CEP estão concentradas em algumas revistas científicas internacionais, não necessariamente aquelas com os maiores fatores de impacto. Além disso, os artigos estão concentrados no campo da engenharia industrial, pesquisa operacional e gestão. O termo mais comum encontrado nos artigos foi carta de controle de soma cumulativa, mas novos temas emergiram e foram pesquisados nos últimos dez anos, como métodos multivariados e não-paramétricos para monitoramento de processos.

Palavras-chave: *Monitoramento estatístico do processo; Controle estatístico do processo; Bibliometria; Cienciometria.*

1 Introduction

Monitoring and control plans, such as those in statistical process controls (SPC), are used during the planning and control phases of a process. Such plans can directly impact the efficiency and efficacy of the production; if these plans are poorly delineated, then they can compromise product quality and productivity (Duarte & Saraiva, 2008; Hoerl & Snee, 2010; Montgomery, 2013; Lim et al., 2014).

The SPC has intrinsic relationships with two important research areas: i) the continuous improvement of products and processes, upon which the theoretical bases are derived from quality management models known as Total Quality Management (TQM) and ii) quality engineering, in which propositions originating due to the statistical models used in quality assurance and because of the need to support decisions about processes by using SPC and Design of Experiments (DOE) methods. These two aspects have an impact on business competitiveness, especially in improving the industry productivity and quality of products (Xie & Goh, 1999; Bamford & Greatbanks, 2005; Sadikoglu & Zehir, 2010; Hoerl & Snee, 2010).

There are several books and papers on the use of statistical tools and technics for improving quality and productivity (Box et al., 1978; Chen, 1997; Xie & Goh, 1999; Jones et al., 2001; Montgomery & Runger, 2003; Bamford & Greatbanks, 2005; Ehie & Sheu, 2005; He & Grigoryan, 2005; Chakraborti, 2006; Triefenbach, 2008; Chakraborti et al., 2008; Hoerl & Snee, 2010; Boone & Chakraborti, 2011; Zhang et al., 2011; Oprime & Ganga, 2013; Montgomery, 2013; Bataineh & Al-Dwairi, 2012). Employees have started to join improvement groups, mainly through Kaizen programs, and they have been trained in statistical technics of quality monitoring and control. Such a trend shows the recognition of the importance of statistical tools and technics to solve practical problems. These changes have strongly influenced the dissemination of statistical technics in SPC research and applications.

Traditional SPC methods, which are based on univariate technics, are heavily taught in training programs that have been around since 1980. Following-up on these methods, numerous procedures for multivariate statistical quality control have been developed to simultaneously monitor several quality characteristics in a process. Although somewhat more challenging to implement, the multivariate SPC methods can promote a better understanding and control of the processes being monitored and, thus, seem to be more sensitive to special causes, which are not always easily detected while using univariate control technics (Epprecht et al., 2005; He & Grigoryan, 2005; Costa et al., 2009; Costa & Machado, 2011; Kim et al., 2014; Ferrer, 2014; García-Bustos et al., 2015; Siddiqui et al., 2015). This shows an evolution of the various development and use of SPC technics and their importance in applications.

However, it may be fair to say that the advances made in the academic research world of SPC methods have not yet been fully incorporated in the manufacturing best practices. This may be a result of: i) cultural paradigms; ii) the types of groups used to promote and improve the field of statistical quality control, such as task force and semi-autonomous groups; iii) governance within groups (centralized or decentralized, use of specific methods or routines and monitoring of activities); and iv) understanding and applying new technics and tools in the problem identification stage and solution (Juran & Gryna, 1991; Atkinson, 1994; Chapman & Hyland, 1997; Bond, 1999; Harrison, 2000; Bechet et al., 2000; Jabnoun, 2001; Hyland et al., 2003; Jager et al., 2004; Fryer et al., 2007; Marin-Garcia et al., 2008; Mahanti & Evans, 2012; Rantamäki et al., 2013; Sharma & Kharub; 2014; Lim et al., 2014).

By reviewing the literature, it is evident that many journals have recently presented studies that use SPC technics and focus on process improvement and continuous innovation (Imai, 1994; Prajogo & Sohal, 2001; Murray & Chapman, 2003; Konecny & Thun, 2009; Kim et al., 2012), as well as on organizational learning (Liyanage & Poon, 2002; O'Cass & Weerawardena, 2008; Omerzel & Antončič, 2008; Korakianiti & Rekkas, 2011; Ooi et al., 2012).

Significant advances can also be seen in the literature regarding the development of new methods and strategies for SPC, such as models for auto-correlated data and multivariate processes (Costa & Castagliola, 2011; Costa & Machado, 2011; Dokouhaki & Noorossana, 2013; Franco et al., 2014; Leoni et al., 2015), control charts allowing for varying the sampling interval and the sample size (Reynolds et al., 1988; Reynolds, 1996; Reynolds & Arnold, 2001; Lin & Chou, 2005; Castagliola et al., 2006; Wu et al., 2007; Lee, 2011;

Yang et al., 2012; Mahadik, 2013), improvement in the performance of control charts by double sampling (Costa & Castagliola, 2011; Teoh et al., 2015; Inghilleri et al., 2015), the design of control charts that minimize operational costs (Michel & Fogliatto, 2002; Celano et al., 2011; Lupo, 2014; Franco et al., 2014), the integration of statistical process control and automatic/engineering process control, avoiding over adjustement of the process (Holmes & Mergen, 2011; Siddiqui et al., 2015); application of the Bernoulli control charts in the field of medicine (Szarka & Woodall, 2011), application of SPC to image data (Megahed et al., 2011; Wells et al., 2013), and strategies for monitoring the variability of small batches (Celano et al., 2012; Castagliola et al., 2013).

Considering the complexity and the importance of SPC, we propose a thorough bibliometric analysis in order to better understand the research evolution over the last fifty years. Bibliometrics is an analysis tool based on empirical laws and principles and, with the passage of time, has become a generic and broad term in carrying out specific measurements in order to quantify the scientific and technological production data through publications of articles and/or patents (Okubo, 1997; Madani, 2015).

This paper has the following objectives that use bibliometrics: i) analyze the growth of the literature on SPC research in the scientific papers; ii) identify the main WoS categories in which publications can be classified and the main terms that are found; iii) recognize the leading authors in the research field and their proximity by publishing sources; iv) discover the main sources of publication; and v) determine networking and collaboration among authors and coutries. It is structured in five parts. The introduction sets out the objectives of the paper and then presents a summary of the research method. In the data analysis section, there are four subsections: i) analysis of the history of SPC publications; ii) most-cited terms and main WoS categories; iii) leading authors in the research field; iv) main souces and v) cooperation networks. A summary of the results found in the data analysis is given in Section 4. Finally, the conclusions are made in Section 5.

2 Method

The paper offers a bibliometric analysis of the international publications about SPC from 1956 to 2013 in the WoS data base. This study used advanced search methods to retrieve the search strings: "Statistical Process Control" or "Control Chart" or "SPC" or "Monitoring" or "Process Control". After the information extraction, keywords with typos were corrected, the same occurring with authors and countries, which required a significant effort in adjustments in the database; further, there was a standardization of terms. For example, the term CUSUM appeared as CUSUM TEST, CUSUM CHART, CUSUM CHART CONTROL, CONTROL CUMULATIVE CHART, among other citations.

The choice of the database WoS was made due to the fact that it is one of the best-known bibliographic databases in the world, as well as the fact that it contains thousands of journals that can be accessed. The publisher of WoS, Thomson Reuters, is well respected and WoS is one of the most used databases worldwide as a source for the construction of scientific production.

For the data analysis, two types of software were used: Vantage Point (i.e., software for the automatic analysis of bibliographic data, which allowed for the generation of lists, matrices, and networks of cooperation among authors and countries) and Statistica 11.0, which was used in exploratory multivariate analysis that was employed for clustering. The first step was to extract the title of selected publications from the WoS search, and each one was analyzed by reading its abstract to verify that the article contained applications or theoretical developments on the SPC topic.

Bibliometrics that is based on the three main laws was used for analysis (Ravichandra Rao, 1986; Guedes & Borschiver, 2005):

- Lokta Law: analyzes the number of publications and their frequency by individual authors within a specific theme. This analysis shows the contribution of authors to scientific or technological progress (scientific authors' productivity);
- Branford Law: analyzes the journals dispersion, focusing on journals that address a specific topic within the scientific research (journals' productivity);
- Zipt Law: establishes a constant relationship between the frequency of a word and the Word position in a ranking; based on the general principle of least effort, the words that require minimal effort appear more frequently in the text (words frequency).

Other concepts used by bibliometrics include the number of citations, the impact factor and the h-index. The number of citations may indicate the influence of a particular work on other researchers, demonstrate intellectual connections, and show that a small group of authors and publications has more influence in a subject (Guedes & Borschiver, 2005). Citation numbers establish the impact factor by measuring the importance and reputation of journals and authors (Garfield, 2006). The h-index can be calculated by the number of citations received by

articles from a particular journal or a particular author in the last two years divided by the total number of articles published in the same period (Garfield, 2006; Jones, 2003; Guedes & Borschiver, 2005). Another possibility, the h-index proposed by Hirsch (2005), is defined as the number of papers with the citation number ≥ h.

3 Results and discussion

3.1 SPC historical analysis

The search in the WoS database about SPC found 3,683 articles published from 1956 to 2013. Figure 1 shows the growth in the number of publications in the SPC literature. The highest number of publications was in 2013, with 343 records; 62.3% were published in the last ten years (2004 to 2013). From 1991 to 2013, 3,542 articles were published (96% of the records). The countries with the highest number of publications are the United States and the Republic of China (Figure 2), with 1,185 publications from the United States and 345 from China, together that is about 43% of the total number of publications.

Looking more closely, Figure 2 shows the strong growth of publications by Chinese researchers over the past decade, peaking in 2012 with 55 publications out of a total of 306, representing 17.97% of the publications for the year. The United States had 76 publications, 24.8% of the world records in the same year (2012). In 2013 the publications by United States researchers reached it's a peak with 100 articles published, clearly showing current interest in the topic.

Figure 3 shows the number of publications per country since 1956, as well as the 20 countries with the highest number of publications.

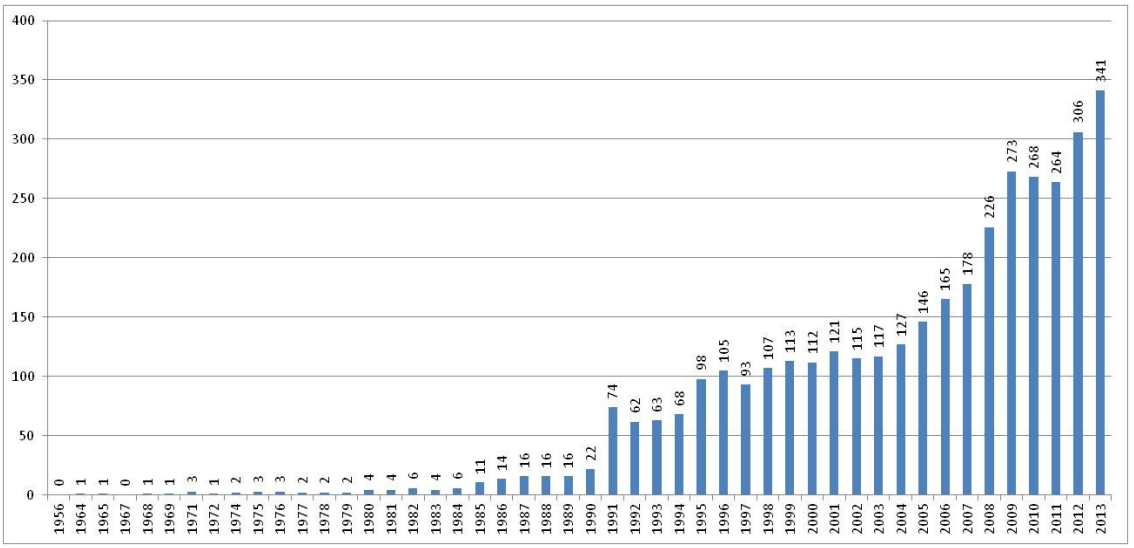

Figure 1. Total number of publications related to SPC.

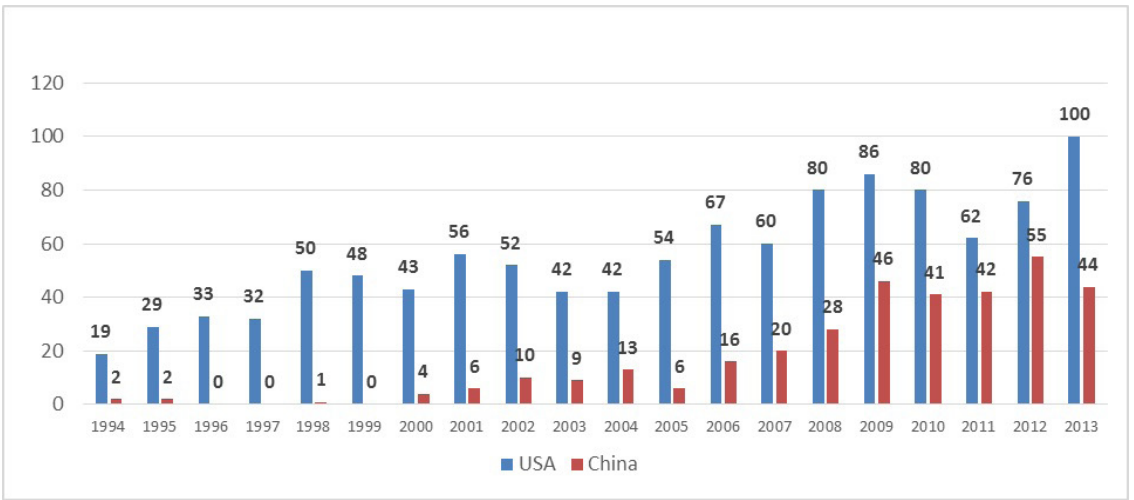

Figure 2. Number of publications related to SPC of the Republic of China and the United States.

It is interesting to note in Figure 3 that 3 (Taiwan, Singapore and South Korea) among the 10 countries with the highest number of publications in the area are countries that had a high growth rate and industrialization between 1960 and 1990, showing the importance of SPC to assist in the implementation of good manufacturing and control practices.

Six (China, Iran, India, Brazil, Turkey and Malaysia) of the 20 countries with the highest number of publications are considered to be developing countries, emphasizing the importance of SPC for industrial practice.

3.2 Most cited terms and main WoS categories

The topics that were surveyed about SPC are classified in the following WoS categories or fields, in order (Figure 4) are: Engineering, Mathematical; Operations Research & Management Science; Computer Science; Automation & Control Systems and Business & Economics. Engineering, Mathematical and Operations Research & Management Science have, in this period, 68.5% of the total number of papers. The articles are mainly classified in the Engineering

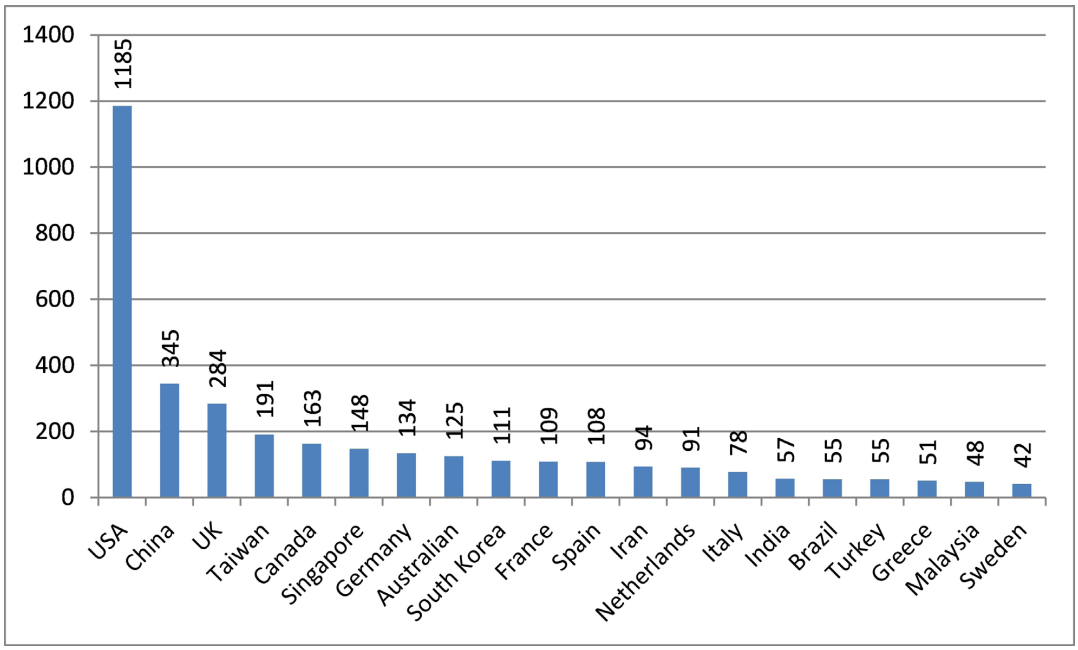

Figure 3. Number of SPC publications per country since 1956.

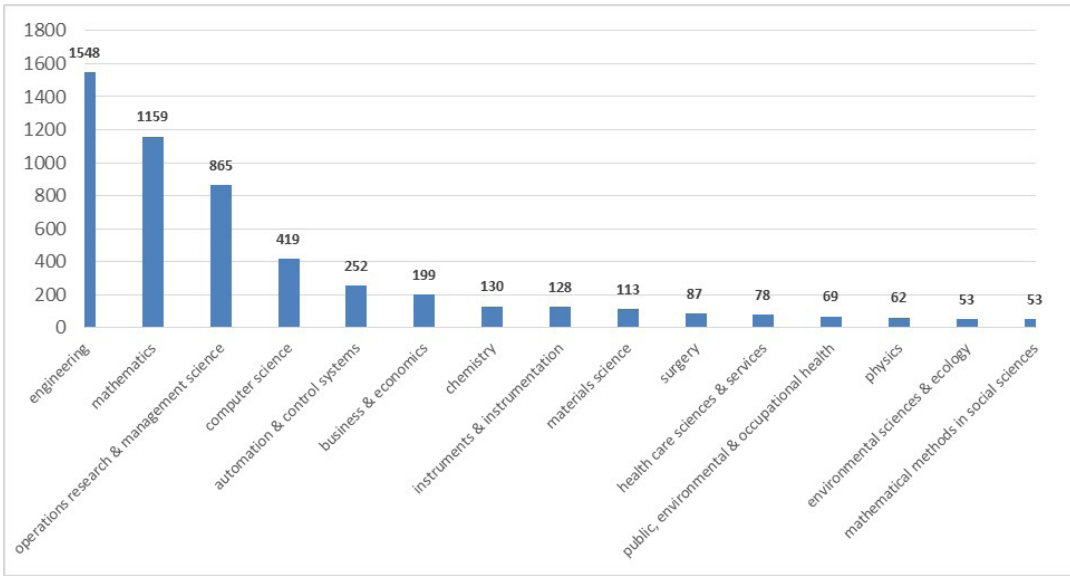

Figure 4. Main categories of SPC publications.

categoy (42.03%), showing that the papers present or deal with practical applications of SPC.

The main terms that occurred among the keywords of the SPC papers were identified and displayed in Figure 5. The terms are important because they indicate areas of research emphasis. Among these, the following keywords appear frequently: cumulative sum control charts (CUSUM), multivariate statistical process control, fault detection, exponentially weighted moving average (EWMA) and quality control. In addition, there are other areas that can be considered to be evolving and signify current areas of interest, such as low cost control charts, SPC applications in metrology, process capability analysis, and nonparametric methods.

3.3 Leading authors in the research field

Figure 6 shows the most productive authors in SPC from 1956 to 2013. Our results identify that the four most productive authors (i.e., Wu, Woodall, Reynolds and Runger) have 19.2% of the total publications of the 100 most productive authors. The leading authors have concentrated their publications in some particular journals; for example, Woodall, Reynolds and Runger have over than 37% of their publications in the *Journal of Quality Technology*.

Aiming to identify the proximity of the authors considering the source of the paper, the existence of four clusters is observed in Figure 7. It consists of the group of the 40 most productive authors, from 1956 to 2013. The analysis in Figure 7 was based on the main authors and the journals in which they

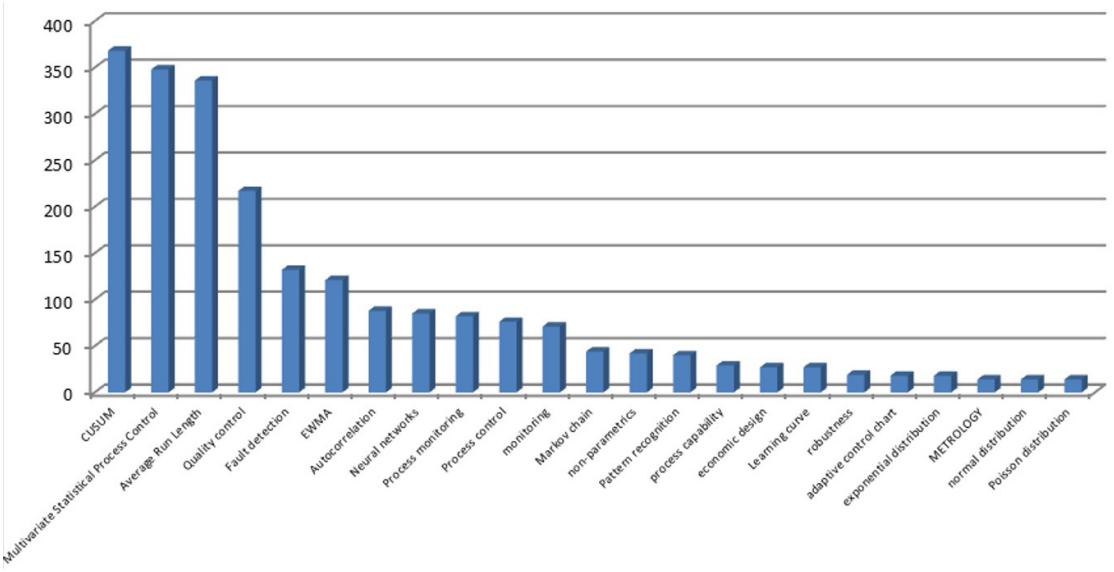

Figure 5. Principal terms found in the keywords.

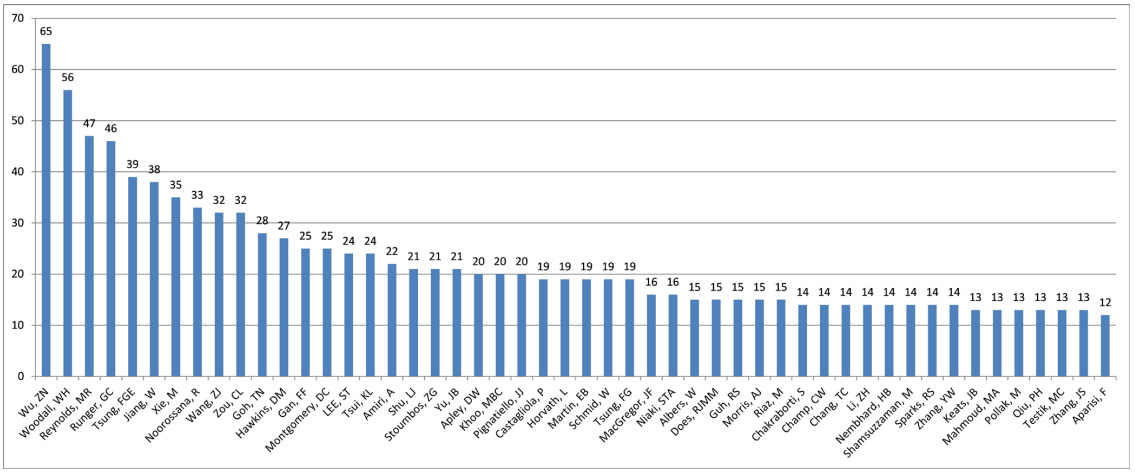

Figure 6. The most productive authors in SPC.

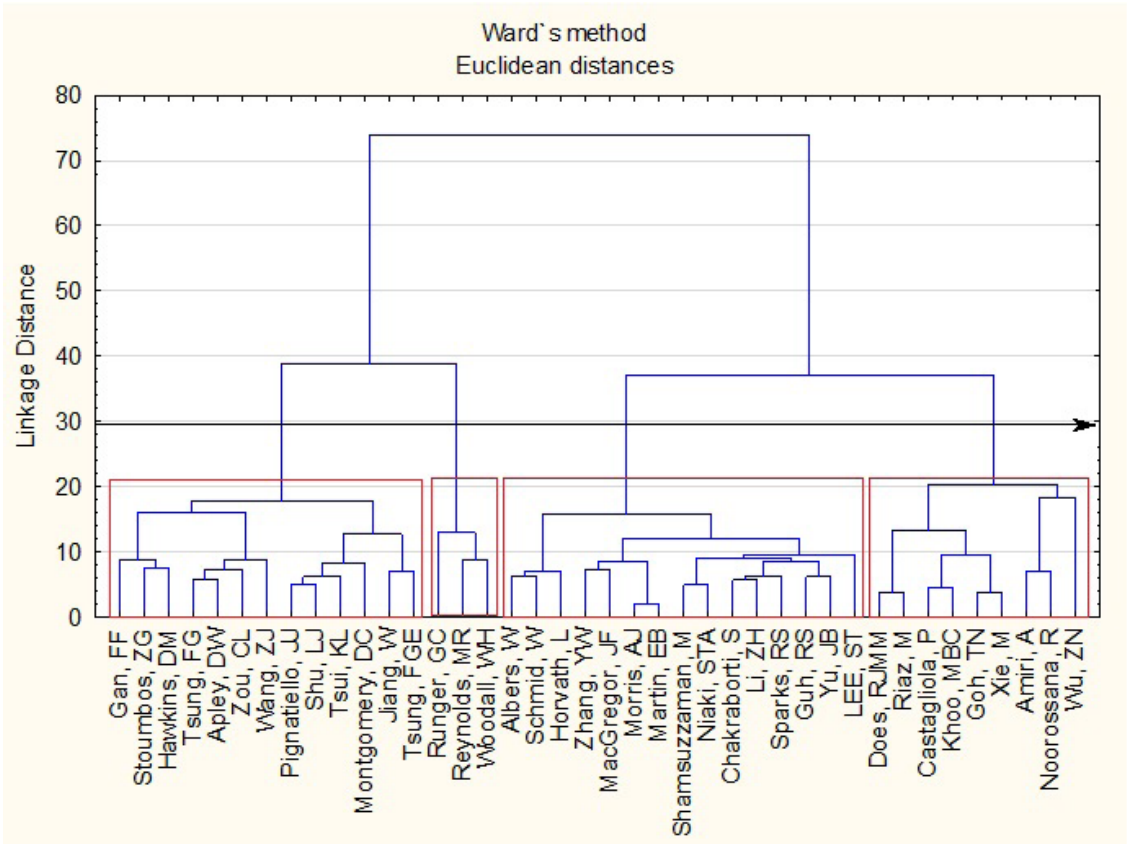

Figure 7. Most productive authors grouped by publication source.

published, and was then cross-checked for publication by different authors in the same journal. For the analysis, cases were the 40 most productive authors and the variables were the number of papers in the journals in which they publish. It was performed Ward's method of euclidean distance for analyzing the formed clusters, other methods were also tested, opting for the Ward's. The closer the authors are in the cluster analysis, the greater the tendency of publishing in the same journals.

Woodall, Runger and Reynolds are among the authors who published more articles in the area (Figure 6). Figure 7 indicates that all three are in the same cluster, indicating similarities among these authors in relation to the sources of publication. This is seen to be the most productive and the most-cited authors in recent years and have all published in similar publcations (journals). The same is not true for Wu, who, despite publishing a large number of articles, is distant from the other three authors based on the source of publication. The other 16 authors who publish more in the area are divided into clusters one and four, showing the trend of publishing in similar journals.

3.4 Main sources of publication

This analysis verifies the main sources of publication and can be seen in Figure 8 of the top 30 journals with publications on the topic of SPC, 1019 sources on the subject were found and these 30 journals are the sources of 44,3% of articles published on the topic. It should be noted that some publication sources, i.e. journals, such as the *Journal of Quality Technology*, *Quality and Realiability Engineering International*, *International Journal of Production Research*, *IIE Transactions* and *Communications in Statistics-Simulation and Computation*, are the top five sources of publications on the topic. Further, 20.1% of articles from 1956 to 2013 were published in these 5 major journals.

The WoS impact factor of the source of publications, which are measured by the number of citations, are shown in Table 1, the same table shows the h-index. Not all the information was available for all journals. The journals with the highest impact factor (*Annals of Statistics, Aiche Journal* and *Chenometrics and Intelligent Laboratory Systems*) appear in the twenty-third, twenty-second, and the eleventh position in relation to the number of published articles. Despite

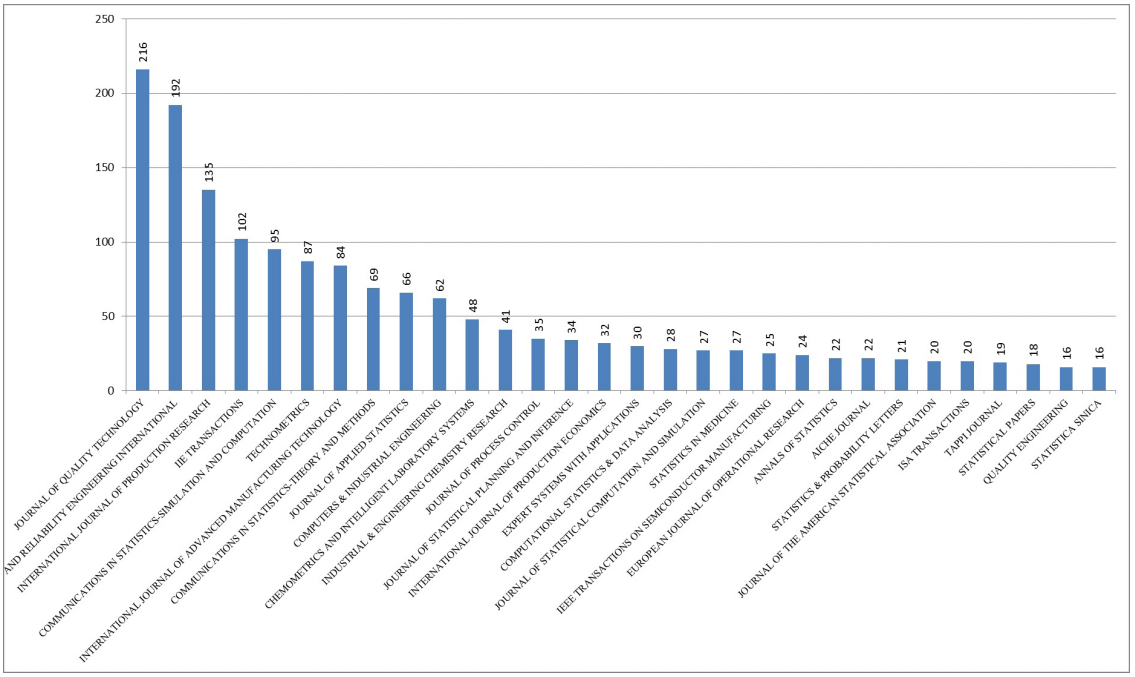

Figure 8. Top 30 journals with publications in SPC.

the high impact factor, these are not the journals with the highest number of publications in SPC.

Among the 10 journals with the highest number of articles published in the field, it may be noted that *Techmometrics*, *International Journal of Advanced Manufacturing Technology*, *Computers & Industrial Engineering* and *International Journal of Production Research* are the ones with a large number of published articles (sixth, seventh, tenth and third) and with higher impact factors (twelfth, thirteenth, fourteenth and fifteenth), and h-index values.

The journals with the highest impact factors among the 30 analyzed are: *Aiche Journal, Annals of Statistics, Chemometrics and Intelligent Laboratory Systems, ISA Transactions and Industrial & Engineering Chemistry Research*.

Regarding the h-index, the five journals with the highest rates are: *Annals of Statistics, Journal of Statistical Computation and Simulation, Technometrics, Chemometrics and Intelligent Laboratory Systems and International Journal of Production Research*. Two journals (*Annals Statistics and Chenometrics and Inteligent Laboratory Systems*) have both, one of the best impact factor and h-index of the sample analyzed; they are important sources of information on the subject for researches. Other sources have high levels of h-index and a large number of publications on SPC (for exemple, *International Journal of Production Research and Technometrics*)

This analysis allows researchers to identify the main sources of publications with a high impact factor, h-index and the number of publications for authors researching the topic or those who intend to publish on the subject.

A cluster analysis was also performed to verify the proximity of sources of publications to consider the authors who 'publish in the same journals' (see Figure 9). Was analyzed the number of articles published in each source by the fifty authors with the highest number of publications on SPC. The cases are the journals and variables are the number of publications of the fifty SPC main authors in these sources. The proximity of the sources shows that the same authors in the field of SPC publish in these sources.

It can be seen from Figure 9 that there are two main groups. The first group is formed by for of the six major journals in relation to the number of publications (the exception was *Communication in Statistics-Simulation* and *Computation* and *International Journal of Production Research*), authors who publish in one usually publish in the other. The other large group is formed by twenty-six other journals. The same thirty companies were used for cluster analysis. The analysis shows the publications trend in the field—that the main authors publish in a specific set of journals—typically in the first group, according to the cluster analysis. These are the primary sources of publications in the area.

In Figure 10 we show the growth in the number of publications in each journal over the last 50 years. The journal *Quality and Reliability Engineering International* should be highlighted for the growing number of published articles on SPC and for being

Table 1. Classification of main journals.

Number	# Records	Source	H-index	Impact Factor
1	216	JOURNAL OF QUALITY TECHNOLOGY	74	1.271
2	192	QUALITY AND RELIABILITY ENGINEERING INTERNATIONAL	29	0.994
3	135	INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	86	1.323
4	102	IIE TRANSACTIONS	68	1.064
5	95	COMMUNICATIONS IN STATISTICS SIMULATION AND COMPUTATION	33	0.288
6	87	TECHNOMETRICS	126	1.79
7	84	INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY	48	1.779
8	69	COMMUNICATIONS IN STATISTICS-THEORY AND METHODS	49	0.284
9	66	JOURNAL OF APPLIED STATISTICS	36	0.453
10	62	COMPUTERS & INDUSTRIAL ENGINEERING	62	1.69
11	48	CHEMOMETRICS AND INTELLIGENT LABORATORY SYSTEMS	94	2.381
12	41	INDUSTRIAL & ENGINEERING CHEMISTRY RESEARCH	-	2.235
13	35	JOURNAL OF PROCESS CONTROL	56	2.179
14	34	JOURNAL OF STATISTICAL PLANNING AND INFERENCE	52	0.598
15	32	INTERNATIONAL JOURNAL OF PRODUCTION ECONOMICS	75	2.081
16	30	EXPERT SYSTEMS WITH APPLICATIONS	69	1.965
17	28	COMPUTATIONAL STATISTICS & DATA ANALYSIS	58	1.151
18	27	JOURNAL OF STATISTICAL COMPUTATION AND SIMULATION	31	2.037
19	27	STATISTICS IN MEDICINE	146	0.713
20	25	IEEE TRANSACTIONS ON SEMICONDUCTOR MANUFACTURING	50	0.977
21	24	EUROPEAN JOURNAL OF OPERATIONAL RESEARCH	-	1.843
22	22	AICHE JOURNAL	-	2.581
23	22	ANNALS OF STATISTICS	162	2.442
24	21	STATISTICS & PROBABILITY LETTERS	45	0.531
25	20	ISA TRANSACTIONS	29	2.256
26	20	JOURNAL OF THE AMERICAN STATISTICAL ASSOCIATION	-	2.114
27	19	TAPPI JOURNAL	54	0.752
28	18	STATISTICAL PAPERS	18	0.82
29	16	QUALITY ENGINEERING	7	1.226
30	16	STATISTICA SINICA	55	0.355

one of the leading journals in relation to the number of articles published on the topic.

It is possible to see an upward trend in the number of publication in all of the five main journals from 1990 to 2009, thus showing the importance of the topic. It´s not possible to confirm if this trend continues in the 2010s, since the analysis was performed only for four years (2010-2013), but it is already possible to notice that the Quality and Reliability Engineering International journal has almost the same number of articles in four years that the previous decade (2000-2009).

Considering the fact that the 10 journals with the largest number of published papers on SPC contain 30.1% of all publications in the area, Table 2 shows what categories from WoS or research field articles are classified in each. For example, the *Journal of Quality Technology* classifies its publication in three different categories: Engineering, Industrial; Operations Research & Management Science and Statistics & Probability; because of this, the number of articles is repeated in each category. The same occurs for the journal *Quality and Reliability Engineering International*, that classifies its publication in three different categories: Engineering, Industrial; Operations Research & Management Science and Engineering, Multidisciplinary.

In absolute numbers, there is a greater occurrence of articles of SPC classified as Engineering, Industrial and Operations Research & Management Science

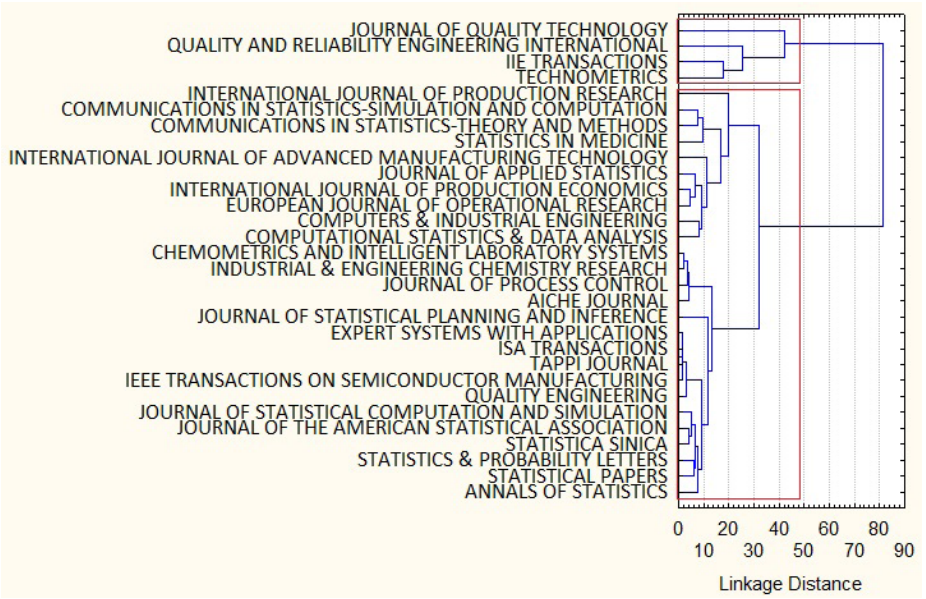

Figure 9. The most important sources grouped by authors' similarity.

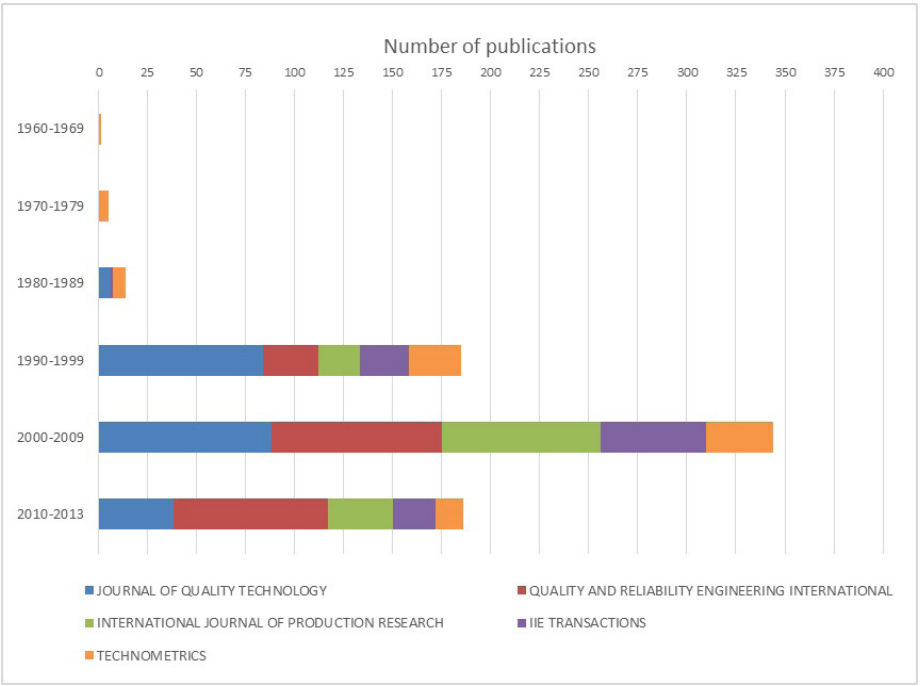

Figure 10. Annual publication by sources.

because of the journals in which they are published. A graph of the number of publications in the five main categories is shown in Figure 11. It is seen that the statistics and probability category has seen its ups and downs whereas the other categories all show an increasing trend. It appears that research and publications in SPC is trending more towards Engineering and Operations journals which focus more on practical and applied research.

3.5 Cooperation structure

The analysis of the co-authorship data by authors from different countries helps to identify and illustrate the knowledge network and the intellectual leverage generated by some authors with great international connections.

The network analysis was performed to identify the cooperation structure between 50 authors who produce the largest number of publications in SPC,

Table 2. Classification of journals in the main categories of WoS.

Journal	Web of Science Categories						
	Engineering, Industrial	**Operations Research & Management Science**	**Statistics & Probability**	**Engineering, Manufacturing**	**Engineering, Multidisciplinary**	**Automation & Control Systems**	**Computer Science, Interdisciplinary Applications**
JOURNAL OF QUALITY TECHNOLOGY	216	216	216				
QUALITY AND RELIABILITY ENGINEERING INTERNATIONAL	192	192			192		
INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	135	135		135			
IIE TRANSACTIONS	102	102					
COMMUNICATIONS IN STATISTICS-SIMULATION AND COMPUTATION			95				
TECHNOMETRICS			87				
INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY				84		84	
COMMUNICATIONS IN STATISTICS-THEORY AND METHODS			69				
JOURNAL OF APPLIED STATISTICS			66				
COMPUTERS & INDUSTRIAL ENGINEERING	62						62
Total	707	645	533	219	192	84	62

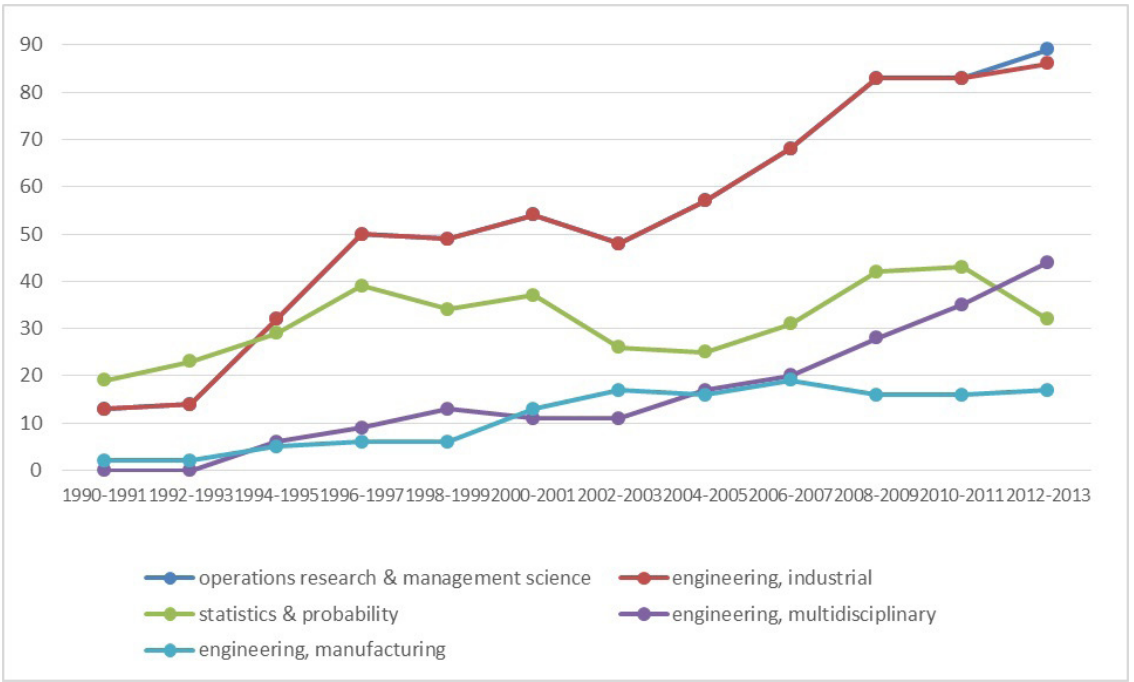

Figure 11. Evolution of numbers of publications by WoS categories.

considering the connections between countries and North American states. Figure 12 summarizes this analysis, identifying seven networks of cooperation, especially the cooperation between the Chinese and American authors, and others (e.g., USA-Germany, USA-South Korea, USA-India, France-Italy, France-Malaysia and Netherlands-Belgium). This analysis is important because it shows the network of cooperation between countries and the dissemination of knowledge, and researchers from some countries have not yet established significant international partnerships, such as Greece, Portugal and even Brazil.

Figure 13 shows the network among the authors, i.e, the relations between the co-authors of the papers, the focus being on the connection among the individual researchers. Figure 13 displays the network of cooperation between the 50 leading authors, thus showing that, as a form of cooperation between countries, some authors have a network of more contacts, thus influencing other authors who work together. The authors who publish more in the field (Wu, Woodall, Reynolds, Runger and Tsung), have a high level of contact with others, thus strengthening the network of publications.

4 Discussion

The United States and China are the two countries that stood out with the highest number of published articles on SPC over the last decade; Chinese production has increased substantially since 2000. The five countries with the highest number of publications since 1956, in order, are the United States, China, the United Kingdom, Taiwan and Canada. Several countries among the twenty with the highest number of publications on SPC had a high rate of industrialization between 1960-1990 or are developing countries, showing the connection and importance of the topic for researchers and industrial applications.

The analysis of the number of publications on the subject during the time investigated showed that there is an increasing trend in the number of published articles, thus showing the growth of SPC research and that SPC is an important and current topic.

The scientific production in the area of SPC has grown by 65.5% in the last ten years. It is concentrated in the fields of Engineering, Mathematics and Operations Research & Management Science. The most commonly used terms found in the database in the period surveyed were: CUSUM, Multivariate Statistical Process Control, Average Runs Length (ARL) and Quality Control. Other topics with lower absolute numbers of records, but equally important, were Economic Design, Process Capability, Pattern Recognition and Non-Parametric Analysis. The analysis of the key terms can identify search trends, as some of them have already been heavily exploited and others seem to be indicating trends for future research.

The bibliometric analysis also allowed the identification of the main authors of the area (Wu, Woodall, Reynolds, Runger and Tsung) and the proximity between them regarding the sources of publication. It should be noted that the *Journal of*

Quality Technology, Quality and Realiability Engineering International, *International Journal os Production Research*, *IIE Transactions* and *Communications in Statistics-Simulation and Computation* are the top five sources of number of publications on the SPC topic. We also observed the journals with the highest impact factor and h-index.

The top journals that publish SPC research focus on Engineering, Industrial; Operations Research & Management Science, Statistics & Probability, but

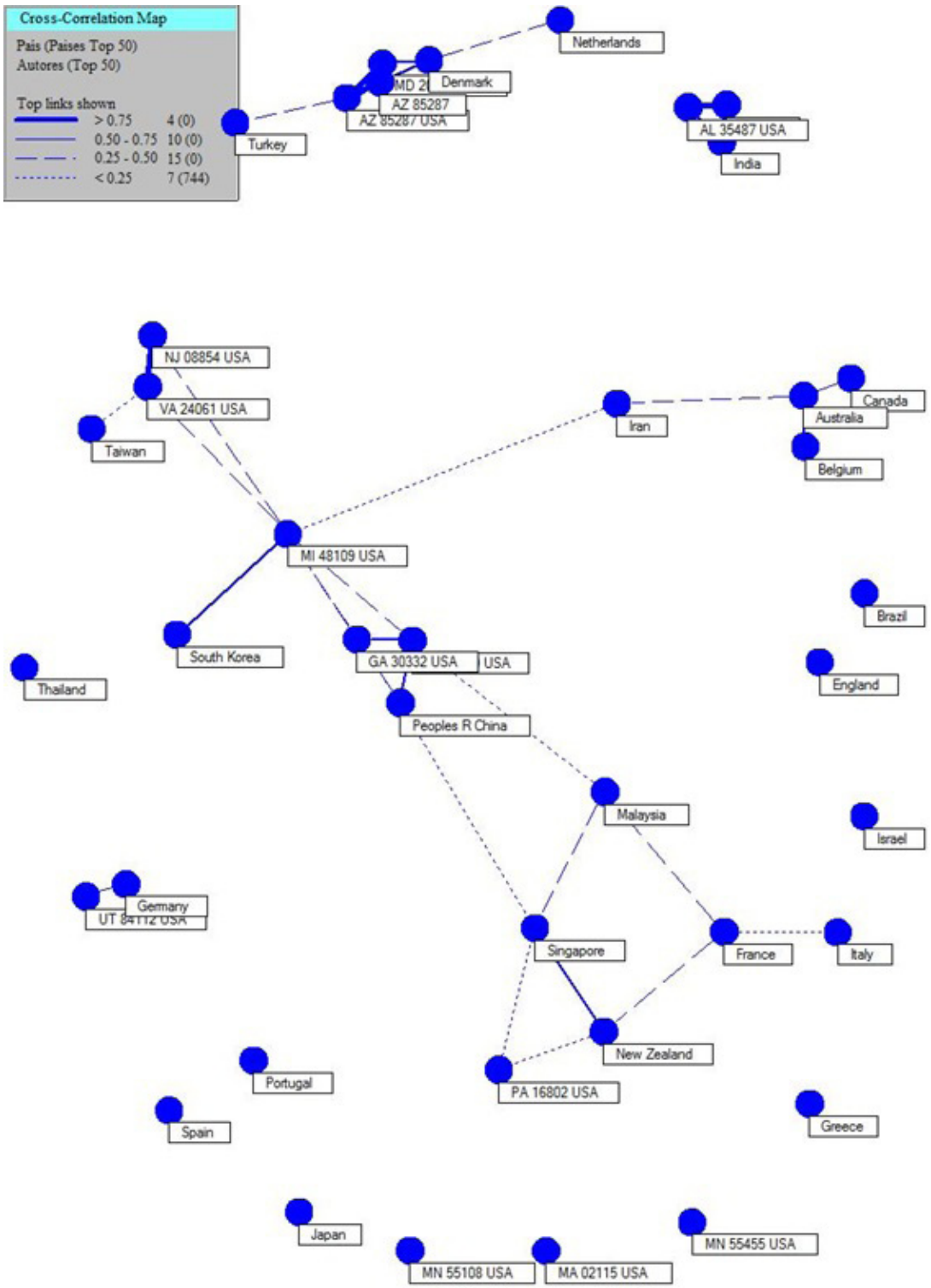

Figure 12. General structure for cooperation.

there was a decrease in the number of publications in the last category over the years. The concentration of publications in the Engineering and Operations Research categories shows the applied nature of SPC research. The use of cluster analysis made it possible to identify the closeness among the journals because of publication by the same authors in these different sources.

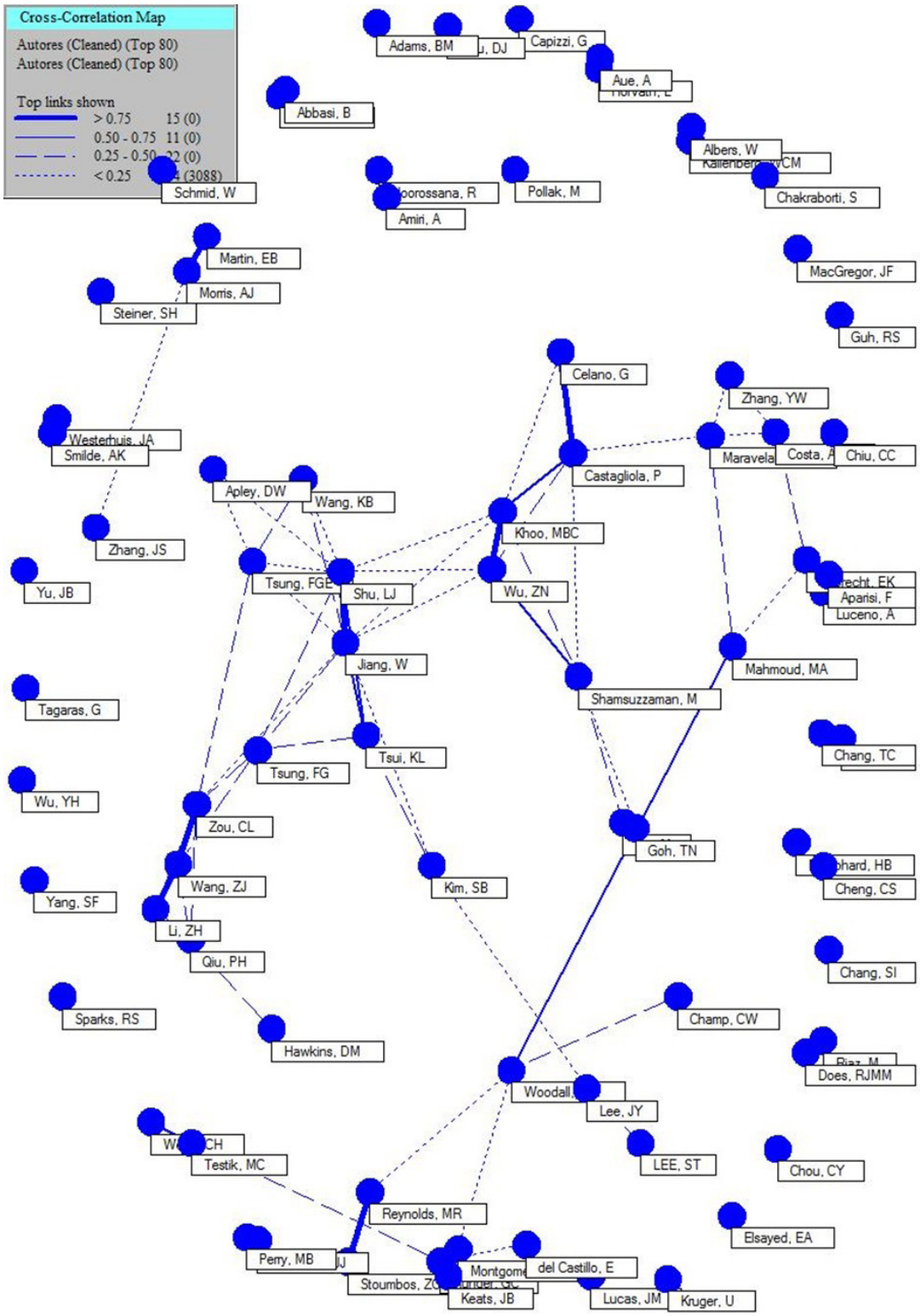

Figure 13. Network among authors.

The final analysis involved the creation of cooperation networks between the countries and between the authors, thus enabling the identification of the knowledge network and important links between and among these networks.

5 Conclusion

SPC continues to be an important area of research for the Engineering, Operations Research and Management Science sectors. For this reason, the number of published articles on SPC has grown in recent years. However, some research topics, such as ARL, were already well explored, opening space for topics such as multivariate statistical control. Incentives for research on emerging topics on SPC, such as non-parametric methods, can be achieved by encouraging other researchers to work on the subject and thus form productive networks.

There are leading countries in this type of publication, such as the United States. More recently, China have increased their academic outputs, but the production remains still small compared to that of United States.

The most productive authors publish in the same sources (journals) and have a strong research network. The most productive authors also have strong affinities and are distinguished from other clusters of researchers who publish in different journals. The collaboration network is also strong for countries with the highest number of publications, therefore showing the importance of forming collaborative networks and knowledge dissemination pathways.

This paper chronicles identifies the growth of publications in the various areas of SPC research and the main sources of English language publications. It also surveys major terms, countries that have the highest number of publications on the subject and cooperation networks between the leading authors and between countries. A bibliometric analysis of SPC is important because it provides an overview of the research arena, main sources and authors to indentify current research and future trends for SPC.

References

Atkinson, C. (1994). Continuous Improvement: the ingredients of change. *International Journal of Contemporary Hospitality Management*, 6(2), 6-8. http://dx.doi.org/10.1108/09596119410052017.

Bamford, D. R., & Greatbanks, R. W. (2005). The use of quality management tools and techniques: a study of application in everyday situations. *International Journal of Quality & Reliability Management*, 22(4), 376-392. http://dx.doi.org/10.1108/02656710510591219.

Bataineh, O., & Al-Dwairi, A. (2012). Integrated SPC-based scheme utilising variable control charts and Cpm ratio to improve manufacturing quality of empty hard gelatin capsules. *International Journal of Productivity and Quality Management*, 9(3), 332-351. http://dx.doi.org/10.1504/IJPQM.2012.046366.

Bechet, A. J., Wainwright, C. E. R., & Bance, D. (2000). Implementing an industrial continuous improvement system: a knowledge management case study. *Industrial Management & Data Systems*, 100(7), 330-338. http://dx.doi.org/10.1108/02635570010349113.

Bond, T. C. (1999). The role of performance measurement in continuous improvement. *International Journal of Operations & Production Management*, 19(12), 13-18. http://dx.doi.org/10.1108/01443579910294291.

Boone, J. M., & Chakraborti, S. (2011). Two simple Shewhart-type multivariate nonparametrics control charts. *Applied Stochastic Models in Business and Industry*, 28(2), 130-140. http://dx.doi.org/10.1002/asmb.900.

Box, G. E. P., Hunter, W. G., & Hunter, J. S. (1978). *Statistics for experimenters* (pp. 510-539). New York: Wiley.

Castagliola, P., Celano, G., & Fichera, S. (2006). Evaluation of the statistical performance of a variable sampling interval R EWMA control chart. *Quality Technology & Quantitative Management*, 3(3), 307-323. http://dx.doi.org/10.1080/16843703.2006.11673117.

Castagliola, P., Celano, G., Fichera, S., & Nenes, G. (2013). The variable sample size t control chart for monitoring short production runs. *International Journal of Advanced Manufacturing Technology*, 66(9-12), 1353-1366.

Celano, G., Castagliola, P., & Trovato, E. (2012). The economic performance of a CUSUM control chart for monitoring short production runs. *Quality Technology & Quantitative Management*, 9(4), 329-354. http://dx.doi.org/10.1080/16843703.2012.11673297.

Celano, G., Castagliola, P., Trovato, E., & Fichera, S. (2011). The economic performance of the Shewhart *t* chart. *Quality and Reliability Engineering International*, 28(2), 159-180. http://dx.doi.org/10.1002/qre.1222.

Chakraborti, S. (2006). Parameter estimation and design considerations in prospective applications of the $\bar{X}$ chart. *Journal of Applied Statistics*, 33(4), 439-459. http://dx.doi.org/10.1080/02664760500163516.

Chakraborti, S., Human, S. W., Graham, M. A., & Phase, I. (2008). Statistical process control charts: an overview and some results. *Quality Engineering*, 21(1), 52-62. http://dx.doi.org/10.1080/08982110802445561.

Chapman, R. L., & Hyland, P. W. (1997). Continuous improvement strategies across selected Australian manufacturing sectors. *Benchmarking for Quality Management & Technology*, 4(3), 175-188. http://dx.doi.org/10.1108/14635779710181415.

Chen, G. (1997). The mean and standard deviation of the run length distribution of $\bar{X}$ charts when control limits are estimated. *Statistica Sinica*, 7, 789-798.

Costa, A. F. B., & Castagliola, P. (2011). Effect of measurement error and autocorrelation on the X-bar

chart. *Journal of Applied Statistics*, 38(4), 661-673. http://dx.doi.org/10.1080/02664760903563627.

Costa, A. F. B., & Machado, M. A. G. (2011). Variable parameter and double sampling Xbar charts in the presence of correlation: the Markov chain approach. *International Journal of Production Economics*, 130(2), 224-229. http://dx.doi.org/10.1016/j.ijpe.2010.12.021.

Costa, A. F. B., Magalhães, M. S., & Epprecht, E. (2009). Monitoring the process mean and variance using synthetic control chart with two-stage testing. *International Journal of Production Research*, 47(18), 5067-5086. http://dx.doi.org/10.1080/00207540802047098.

Dokouhaki, P., & Noorossana, R. (2013). A Copula Markov CUSUM chart for monitoring the bivariate auto□correlated binary observations. *Quality and Reliability Engineering International*, 29(6), 911-919. http://dx.doi.org/10.1002/qre.1450.

Duarte B. P. M., & Saraiva P. M. (2008). An optimization-based approach for designing attribute acceptance sampling plan. *International Journal of Quality & Reliability*, 25(8), 824-841. http://dx.doi.org/10.1108/02656710810898630.

Ehie, I., & Sheu, C. (2005). Integrating six sigma and theory of constraints for continuous improvement: a case study. *Journal of Manufacturing Technology Management*, 16(5), 542-553. http://dx.doi.org/10.1108/17410380510600518.

Epprecht, E. K., Costa, A. F. B., & Mendes, F. C. T. (2005). Gráficos adaptativos de controle por atributos e seu projeto na prática. *Pesquisa Operacional*, 25(1). 113-134. http://dx.doi.org/10.1590/S0101-74382005000100007.

Ferrer, A. (2014). Latent structures-based multivariate statistical process control: a paradigm shift. *Quality Engineering*, 26(1), 72-91. http://dx.doi.org/10.1080/08982112.2013.846093.

Franco, B. C., Celano, G., Castagliola, P., & Costa, A. F. B. (2014). Economic design of Shewhart control charts for monitoring autocorrelated data with skip sampling strategies. *International Journal of Production Economics*, 151, 121-130. http://dx.doi.org/10.1016/j.ijpe.2014.02.008.

Fryer, K. J., Antony, J., & Douglas, A. (2007). Critical success factors of continuous improvement in the public sector. *The TQM Magazine*, 9(5), 497-517. http://dx.doi.org/10.1108/09544780710817900.

García-Bustos, S., Aparisi, F., & Epprecht, E. K. (2015). Optimal EWMA of linear combination of Poisson variables for multivariate statistical process control. *International Journal of Production Research*, 53(14), 4141-4159.

Garfield, E. (2006). Citation indexes for science. A new dimension in documentation through association of ideas. *International journal of epidemiology*, 35(5), 1123-1127.

Guedes, V. L. S., & Borschiver, S. (2005). Bibliometria: uma ferramenta estatística para a gestão da informação e do conhecimento, em sistemas de informação, de comunicação e de avaliação científica e tecnológica. In *Anais do VI Encontro Nacional de Ciência da Informação* (pp. 1-18). Salvador: ICI/UFBA.

Harrison, A. (2000). Continuous improvement: the trade-off between self management and discipline. *Integrated Manufacturing Systems*, 11(3), 180-187. http://dx.doi.org/10.1108/09576060010320416.

He, D., & Grigoryan, A. (2005). Multivariate multiple sampling charts. *IIE Transactions*, 37(6), 509-521. http://dx.doi.org/10.1080/07408170490507837.

Hirsch, J. E. (2005). An index to quantify an individual's scientific research output. *Proceedings of the National Academy of Sciences of the United*, 102(46), 16569-16572.

Hoerl, R. W., & Snee, R. (2010). Statistical thinking and methods in quality improvement: a look to the future. *Quality Engineering*, 22(3), 119-129. http://dx.doi.org/10.1080/08982112.2010.481485.

Holmes, D. S., & Mergen, A. E. (2011). Using SPC in conjunction with APC. *Quality Engineering*, 23(4), 360-364. http://dx.doi.org/10.1080/08982112.2011.602941.

Hyland, P. W., Soosay, C., & Sloan, T. R. (2003). Continuous improvement and learning in the supply chain. *International Journal of Physical Distribution & Logistics Management*, 33(4), 316-335. http://dx.doi.org/10.1108/09600030310478793.

Imai, M. (1994). *Kaizen: a estratégia para o sucesso competitivo* (5th ed.). São Paulo: IMAM.

Inghilleri, R., Lupo, T., & Passannanti, G. (2015). An effective double sampling scheme for the c control chart. *Quality and Reliability Engineering International*, 31(2), 205-216. http://dx.doi.org/10.1002/qre.1572.

Jabnoun, N. (2001). Values underlying continuous improvement. *The TQM Magazine*, 13(6), 381-387. http://dx.doi.org/10.1108/09544780110406137.

Jager, B., Minnie, C., Jager, J., Welgemoed, M., Bessant, J., & Francis, D. (2004). Enabling continuous improvement: a case study of implementation. *Journal of Manufacturing Technology Management*, 15(4), 315-324. http://dx.doi.org/10.1108/17410380410535017.

Jones, A. W. (2003). Impact factors of forensic science and toxicology journals: what do the numbers really mean? *Forensic Science International*, 133(1-2), 1-8. http://dx.doi.org/10.1016/S0379-0738(03)00042-2. PMid:12742682.

Jones, L. A., Rigdon, S. E., & Champ, C. W. (2001). The performance of exponentially weighted moving average charts with estimated parameters. *Technometrics*, 43(2), 156-167. http://dx.doi.org/10.1198/004017001750386279.

Juran, J. M., & Gryna, F. M. (1991). *Controle da qualidade handbooks*. São Paulo: Makron Books.

Kim, D. Y., Kumar, V., & Kumar, U. (2012). Relationship between quality management practices and innovation.

Journal of Operations Management, 30(4), 295-315. http://dx.doi.org/10.1016/j.jom.2012.02.003.

Kim, J., Al-Khalifa, K. N., Jeong, M. K., Hamouda, A. M. S., & Elsayed, E. A. (2014). Multivariate statistical process control charts based on the approximate sequential χ 2 test. *International Journal of Production Research*, 52(18), 5514-5527. http://dx.doi.org/10.1080/00207543.2014.917212.

Konecny, P. A., & Thun, J.-H. (2009). Do it separately or simultaneously - an empirical analysis of a conjoint implementation of TQM and TPM on plant performance. *International Journal of Production Economics*. http://dx.doi.org/10.1016/j.ijpe.2010.12.009.

Korakianiti, E., & Rekkas, D. (2011). Statistical thinking and knowledge management for quality-driven design and manufacturing in pharmaceuticals. *Pharmaceutical Research*, 28(7), 1465-1479. http://dx.doi.org/10.1007/s11095-010-0315-3. PMid:21161338.

Lee, P. H. (2011). Adaptive R charts with variable parameters. *Computational Statistics & Data Analysis*, 55(5), 2003-2010. http://dx.doi.org/10.1016/j.csda.2010.11.026.

Leoni, R. C., Costa, A. F. B., & Machado, M. A. G. (2015). The effect of the autocorrelation on the performance of the T 2 chart. *European Journal of Operational Research*, 247(1), 155-165. http://dx.doi.org/10.1016/j.ejor.2015.05.077.

Lim, S. A. H., Antony, J., & Albliwi, S. (2014). Statistical Process Control (SPC) in the food industry – a systematic review and future research agenda. *Trends in Food Science & Technology*, 37(2), 137-151. http://dx.doi.org/10.1016/j.tifs.2014.03.010.

Lin, Y., & Chou, C. (2005). On the design of variable sample size and sampling intervals charts under non-normality. *International Journal of Production Economics*, 96(2), 249-261. http://dx.doi.org/10.1016/j.ijpe.2004.05.001.

Liyanage, S., & Poon, P. S. (2002). Technology and innovation management learning in the knowledge economy: a techno-managerial approach. *Journal of Management Development*, 22(7), 579-602. http://dx.doi.org/10.1108/02621710310484740.

Lupo, T. (2014). Economic design approach for an SPC inspection procedure implementing the adaptive C chart. *Quality and Reliability Engineering International*, 30(4), 545-558. http://dx.doi.org/10.1002/qre.1507.

Madani, F. (2015). 'Technology Mining' bibliometrics analysis: applying network analysis and cluster analysis. *Scientometrics*, 105(1), 323-335. http://dx.doi.org/10.1007/s11192-015-1685-4.

Mahadik, S. (2013). Variable sample size and sampling interval (x)over-bar charts with runs rules for switchingbetween sample sizes and sampling interval lengths. *Quality and Reliability Engineering International*, 29(1), 63-76. http://dx.doi.org/10.1002/qre.1293.

Mahanti, R., & Evans, J. R. (2012). Critical success factors for implementing statistical process control in the software industry. *Benchmarking: An International Journal*, 19(3), 374-394. http://dx.doi.org/10.1108/14635771211244309.

Marin-Garcia, J. A., Val, M. P., & Martin, T. B. (2008). Longitudinal study of the results of continuous improvement in an industrial company. *Team Performance Management*, 14(1/2), 56-6. http://dx.doi.org/10.1108/13527590810860203.

Megahed, F. M., Woodall, W. H., & Camelio, J. A. (2011). A review and perspective on control charting with image data. *Journal of Quality Technology*, 43(2), 83-98.

Michel, R., & Fogliatto, F. S. (2002). Projeto econômico de cartas adaptativas para monitoramento de processos. *Gestão & Produção*, 9(1), 17-31. http://dx.doi.org/10.1590/S0104-530X2002000100003.

Montgomery, C. D., & Runger, G. C. (2003). *Estatística aplicada e probabilidade para engenheiros* (2nd ed.). São Paulo: LTC.

Montgomery, D. C. (2013). *Introduction to statistical quality control* (7th ed., 754 p.). New York: John Wiley & Sons.

Murray, P., & Chapman, R. (2003). From continuous improvement to organizational learning: developmental theory. *The Learning Organization*, 10(5), 272-282. http://dx.doi.org/10.1108/09696470310486629.

O'Cass, A., & Weerawardena, J. (2008). Examining the role of international entrepreneurship, innovation and international market performance in SME internationalization. *European Journal of Marketing*, 43(11/12), 1325-1348. http://dx.doi.org/10.1108/03090560910989911.

Okubo, Y. (1997). *Bibliometric indicators and analysis of research systems : methods and examples*. Paris: Organisation for Economic Co-operation and Development.

Omerzel, D. G., & Antončič, B. (2008). Critical entrepreneur knowledge dimensions for the SME performance. *Industrial Management & Data Systems*, 108(9), 1182-1199.

Ooi, K. B., Lin, B., Teh, P. L., & Chong, A. Y. L. (2012). Does TQM support innovation performance in Malaysia's manufacturing industry? *Journal of Business Economics and Management*, 13(2), 366-393. http://dx.doi.org/10.3846/16111699.2011.620155.

Oprime, P. C., & Ganga, G. M. D. (2013). A framework for continuous inspection plans using multivariate mathematical methods. *Quality and Reliability Engineering International*, 29, 1446-1446.

Prajogo, D. I., & Sohal, A. S. (2001). TQM and innovation: a literature review and research framework. *Technovation*, (21), 5329-5558.

Rantamäki, J., Tiainen, E. L., & Kässi, T. (2013). A case of implementing SPC in a pulp mill. *International Journal of Lean Six Sigma*, 4(3), 321-337. http://dx.doi.org/10.1108/IJLSS-05-2013-0029.

Ravichandra Rao, I. K. (1986). *Métodos quantitativos em biblioteconomia e ciência da informação*. Brasília: ABDF.

Reynolds, A. R. Jr (1996). Variable-sampling-interval control charts with sampling at fixed times. *IIE Transactions*, 26(6), 497-510. http://dx.doi.org/10.1080/07408179608966297.

Reynolds, A. R. Jr, & Arnold, J. C. (2001). EWMA control charts with variable sample sizes and variable sampling intervals. *IIE Transactions*, 33(6), 511-530. http://dx.doi.org/10.1080/07408170108936850.

Reynolds, A. R., Amim, R. W., Arnold, J. C., & Nachlas, J. A. (1988). Charts With Variable Sampling Intervals. *Technometrics*, 30(6), 181-192.

Sadikoglu, E., & Zehir, C. (2010). Investigating the effects of innovation and employee performance on the relationship between total quality management practices and firm performance: An empirical study of Turkish firms. *International Journal of Production Economics*, 127(1), 13-26. http://dx.doi.org/10.1016/j.ijpe.2010.02.013.

Sharma, R., & Kharub, M. (2014). Attaining competitive positioning through SPC–an experimental investigation from SME. *Measuring Business Excellence*, 18(4), 86-103. http://dx.doi.org/10.1108/MBE-10-2013-0050.

Siddiqui, Y. A., Saif, A. W. A., Cheded, L., Elshafei, M., & Rahim, A. (2015). Integration of multivariate statistical process control and engineering process control: a novel framework. *International Journal of Advanced Manufacturing Technology*, 78(1-4), 259-268. http://dx.doi.org/10.1007/s00170-014-6641-6.

Szarka, J. L. 3rd, & Woodall, W. H. (2011). A review and perspective on surveillance of bernoulli processes. *Quality and Reliability Engineering International*, 27(6), 735-752. http://dx.doi.org/10.1002/qre.1256.

Teoh, W. L., Khoo, M. B., Castagliola, P., & Chakraborti, S. (2015). A median run length-based double-sampling $\bar{X}$ chart with estimated parameters for minimizing the average sample size. *International Journal of Advanced Manufacturing Technology*, 80(15), 411-426. http://dx.doi.org/10.1007/s00170-015-6949-x.

Triefenbach, F. (2008). *Design of experiments: the D-optimal approach and its implementation as a computer algorithm* (Bachelor's thesis). UMEA University, UMEA.

Wells, L. J., Megahed, F. M., Niziolek, C. B., Camelio, J. A., & Woodall, W. H. (2013). Statistical process monitoring approach for high-density point clouds. *Journal of Intelligent Manufacturing*, 24(6), 1267-1279. http://dx.doi.org/10.1007/s10845-012-0665-2.

Wu, Z., Zhang, S., & Wang, P. (2007). CUSUM scheme with variable sample sizes and sampling intervals for monitoring the process mean and variance. *Quality and Reliability Engineering International*, 23(2), 157-170. http://dx.doi.org/10.1002/qre.782.

Xie, M., & Goh, T. N. (1999). Statistical techniques for quality. *The TQM Magazine*, 11(4), 238-241. http://dx.doi.org/10.1108/09544789910272913.

Yang, M., Wu, Z., Lee, K. M., & Khoo, M. B. (2012). The X control chart for monitoring process shifts in mean and variance. *International Journal of Production Research*, 50(3), 893-907. http://dx.doi.org/10.1080/00207543.2010.539283.

Zhang Y., Castagliola, P., Wu, Z., & Chong, M. K. B. (2011). The variable sampling interval xbar chart with estimated parameters. *Accepted for Publication in Quality and Reliability Engineering International*, 28(1), 19-34. http://dx.doi.org/10.1002/qre.1209.