DETECTING THE HISTORICAL ROOTS OF TRIBOLOGY RESEARCH: A BIBLIOMETRIC ANALYSIS

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ABSTRACT

In this study, the historical roots of tribology (a sub-field of mechanical engineering and materials science) are investigated using a newly developed scientometric method called "Referenced Publication Years Spectroscopy (RPYS)". The study is based on cited references (n=577,472) in tribology research publications (n=24,086). The Science Citation Index – Expanded (SCI-E) is used as data source. The results show that RPYS has the potential to identify the important publications: Most of the publications which have been identified in this study as highly cited (referenced) publications are landmark publications in the field of tribology.

INTRODUCTION

New research usually evolves on the basis of previous investigations and discussions among the experts in a specific scientific community. Although there are many differences between the theories about scientific development (see e.g. Popper, 1961 and Kuhn, 1962), the relationship of current research to past literature always plays a significant role: knowledge cannot be acquired without the references to the past (Marx and Bornmann 2014). Although the past literature plays a significant role in every research field, their importance is seldom studied using scientometric techniques and data. Thus, Marx et al. (2014) introduced the method "Referenced Publication Years Spectroscopy (RPYS)" to reveal the important historical publications in a research field. The RPYS is able to identify the historical roots of research fields and can quantify their citation impact on current research. The method is based on analyzing the frequencies with which references are cited in the publications of a specific research field in terms of the publication years of the cited references. According to Marx and Bornmann (2014), RPYS can not only be applied to the identification of historical roots, but also to unveil scientific legends in a scientific field.

This study is intended to identify the historical roots of the tribology research from the perspective of the cited references. The term *tribology* was coined by Jost (1966) deriving from the Greek word *tribos* (or *triben*) means rubbing. Tribology is the science and technology of two interacting surfaces in relative motion and of related subjects and practices. Tribology is a multidisciplinary field which incorporates a number of disciplines, including mechanical engineering, material science, mechanics, surface chemistry, and surface physics. According to a report of the South African Institute of Tribology, tribology is a property of matter or the second most important field of study of material property after that of gravity.

METHODOLOGY

The results of the RPYS for the tribology field is based on the Science Citation Index - Expanded (SCI-E, Thomson Reuters). The study is mainly concerned with the analysis of the referenced publication years (RPYs) and especially with the analysis of early publications cited particularly frequently as the historical roots of tribology research. In order to analyze the RPYs, the following steps have been employed with the program *rpys.exe* (see http://www. leydesdorff.net/software/rpys/ and Bornmann et al. in press).

- The 1st step is to select the publications on tribology in the SCI-E database and to extract all bibliographical records.

- The 2nd step is to extract all references from the records using *rpys.exe* and to identify the most important historical RPYs for the tribology research field.

- The 3rd step is to identify the most important publications in specific RPYs using the program *yearcr.exe*. The program *RefMatchCluster.jar* has been employed to aggregate cited references across misspellings and variants.

- The 4th step is to establish the frequency distribution of cited references over the RPYs and to determine the publications cited most frequently in early RPYs.

The publications on tribology were selected in the SCI-E database by searching in the title, abstract, author keywords and keywords plus fields with the following keywords (date of search: May 2015): **tribolog* OR "tribosyst*" OR "tribo-syst*" OR "tribo-chem*" OR "tribochem*" OR "tribotechn*" OR "tribo-physi*" OR "tribophysi*"* (Elango et al. 2015; Elango et al. in press). An overview of the data set used in this study is provided in Table 1.

Table 1 – General overview of the data set used	
Item	**#**
Number of publications	24086
Period of publication	1953-2014
Number of cited references	577472

Based on the SCI-E input data (publications on tribology), *rpys.exe* generates two output files: *rpys.dbf* contains the number of cited references per referenced publication RPY. *median.dbf* contains the deviation of the number of cited references in each RPY from the median for the number of cited references in the two previous, the current, and the two following RPYs [t - 2; t - 1; t; t + 1; t + 2]. Both files are used in Excel for drawing a spectrogram and heat map.

Bornmann et al. (in press) recommend to calculate quantile values in order to compare the importance of different RPYs. For the calculation, the formula given by Hazen (1914) is employed:

$$\text{Quantile} = ((i-0.5)/n * 100),$$

Where i is the rank of a specific RPY (years are ranked in decreasing order by their number of cited references) and n the total number of RPYs. The quantile values are available in *median.dbf* generated by *rpys.exe*. The higher the quantile value for a specific RPY, the most frequently referenced literature (cited) from that RPY (compared to other RPYs).

RESULTS

The distribution of the number of references cited in the tribology literature is presented in Figure 1. The most frequently cited RPY is 2000, showing the strong contemporary relevance of this research field. Figure 2 shows the heat map based on quantiles for the RPYs. The figure reveals that the most frequently cited RPYs spread between 1999 and 2006. However, some

RPYs in the early years seem to be important too (e.g. 1805 or 1882). In order to receive an overview of the history in tribology, we limited the RPYs to the period between 1801 and 1965. The term "tribology" was introduced by Jost (1966), so that the year 1966 which might be seen as the starting point of the modern tribology research.
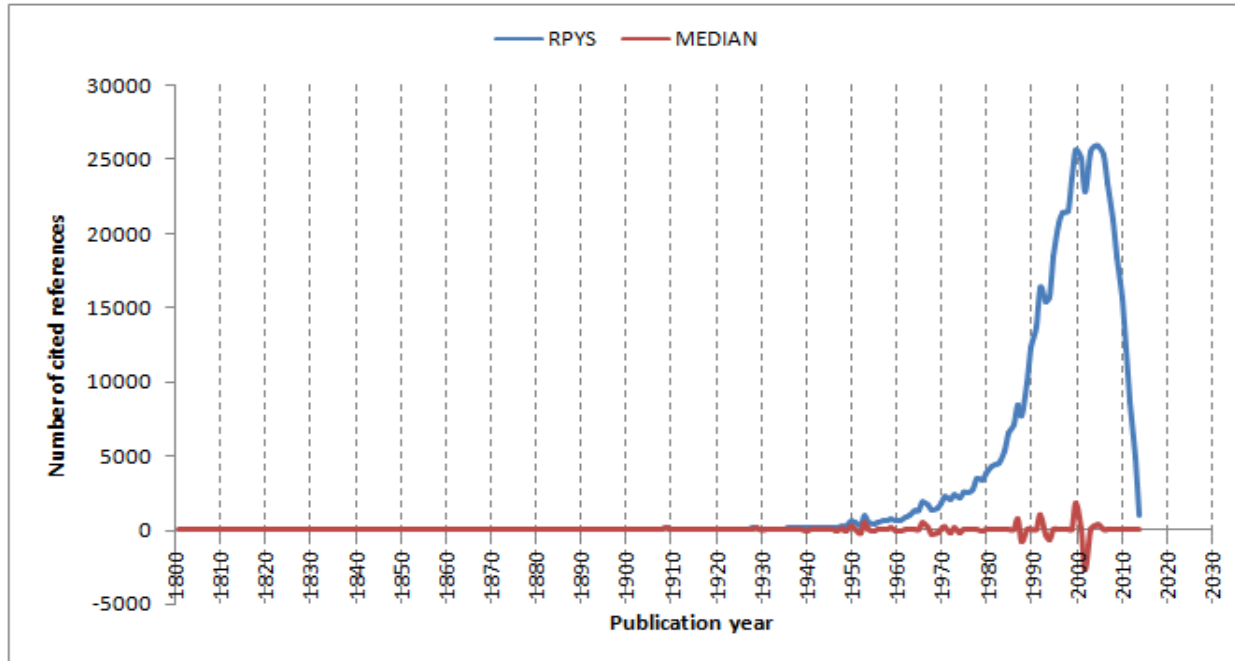

Figure 1 – Referenced publication years (1801 – 2014) of tribology research publications
(published between 1953 and 2014)

1801	8.4	1837	12.6	1873	40.1	1909	64.0	1945	64.4	1981	84.58
1802	7.9	1838	12.1	1874	18.2	1910	47.6	1946	68.2	1982	85.05
1803	16.8	1839	1.	1875	35.5	1911	42.0	1947	65.4	1983	85.52
1804	24.	1840	22.	1876	17.7	1912	38.7	1948	69.1	1984	86.45
1805	50.4	1841	11.6	1877	25.	1913	49.0	1949	68.6	1985	86.92
1806	16.3	1842	37.8	1878	25.2	1914	49.5	1950	71.9	1986	87.39
1807	7.4	1843	22.4	1879	37.3	1915	38.3	1951	71.	1987	88.32
1808	15.8	1844	21.9	1880	24.7	1916	46.2	1952	69.6	1988	87.85
1809	15.4	1845	11.2	1881	58.8	1917	36.9	1953	76.1	1989	89.25
1810	7.0	1846	21.	1882	61.2	1918	48.	1954	70.5	1990	90.19
1811	6.5	1847	10.7	1883	52.8	1919	48.1	1955	70.	1991	90.66
1812	6.0	1848	0.9	1884	39.7	1920	54.2	1956	71.0	1992	92.53
1813	5.6	1849	21.0	1885	5	1921	55.6	1957	72.4	1993	91.12
1814	5.1	1850	28.0	1886	55.1	1922	53.7	1958	73.3	1994	92.06
1815	14.9	1851	0.4	1887	17.2	1923	56.0	1959	74.	1995	92.99
1816	14.4	1852	20.5	1888	41.1	1924	53.2	1960	72.	1996	93.93
1817	4.6	1853	36.4	1889	8.8	1925	57.9	1961	73.8	1997	94.86
1818	4.2	1854	27.5	1890	29.9	1926	54.6	1962	74.7	1998	95.93
1819	3.7	1855	32.2	1891	45.	1927	58.4	1963	75.2	1999	96.73
1820	14.0	1856		1892	39.2	1928	61.6	1964	76.6	2000	
1821	34.1	1857	20.	1893	51.8	1929	67.2	1965	77.1	2001	97.2
1822	29.4	1858	31.7	1894	45.3	1930	57.0	1966	79.4	2002	95.8
1823	3.2	1859	10.2	1895	42.9	1931	56.5	1967	78.5	2003	
1824	2.8	1860	27.1	1896	52.3	1932	59.8	1968	77.5	2004	
1825	33.6	1861	31.3	1897	35.0	1933	59.3	1969	78.0	2005	
1826	13.5	1862	26.6	1898	42.5	1934	60.2	1970	78.9	2006	97.07
1827	2.3	1863	41.5	1899	34.5	1935	60.7	1971	80.8	2007	96.26
1828	1.8	1864	9.8	1900	44.8	1936	67.7	1972	79.9	2008	94.39
1829	23.8	1865	26.1	1901	47.	1937	66.3	1973	81.3	2009	93.46
1830	13.0	1866	30.8	1902	57.4	1938	64.9	1974	80.3	2010	91.59
1831	28.9	1867	35.9	1903	40.6	1939	66.8	1975	82.2	2011	89.72
1832	23.3	1868	19.6	1904	46.7	1940	63.0	1976	81.7	2012	88.79
1833	33.1	1869	19.1	1905	44.3	1941	62.6	1977	82.7	2013	85.98
1834	32.7	1870	30.3	1906	43.4	1942	65.8	1978	83.6	2014	75.7
1835	28.5	1871	18.6	1907	51.	1943	62.1	1979	83.1		
1836	43.9	1872	9.3	1908	50.9	1944	63.5	1980	84.1		

Figure 2 – Quantiles of the yearly number of cited references. The higher the quantile for a specific referenced publication year, the darker the corresponding cell.

The RPYs are grouped into two periods of investigation, i.e. 1801-1900 and 1901-1965, based on the following remarks: (i) the 19th century was an era of rapidly accelerating scientific discovery and invention with significant developments in the fields of mathematics, physics, chemistry, biology, electricity, and metallurgy. The developments laid the groundwork for the technological advances of the 20th century. With the RPYs, we expect to find basic literature in the historical science which is also important for tribology. (ii) Since the term "tribology" was

introduced in 1966 by Jost (1966), we study the period between 1901 and 1965 to identify early important publications for the field at the beginning and at the middle of the 20th century.

Referenced Publication Years from 1801 to 1900

There are five larger peaks exhibited between 1801 and 1900 (in a span of 100 years). As the deviations from the median (red line) in Figure 3 shows, these peaks appear in 1805, 1882, 1886, 1893, and 1896. Obviously, some important historical papers for the development of tribology research were published at end of the 19th century.
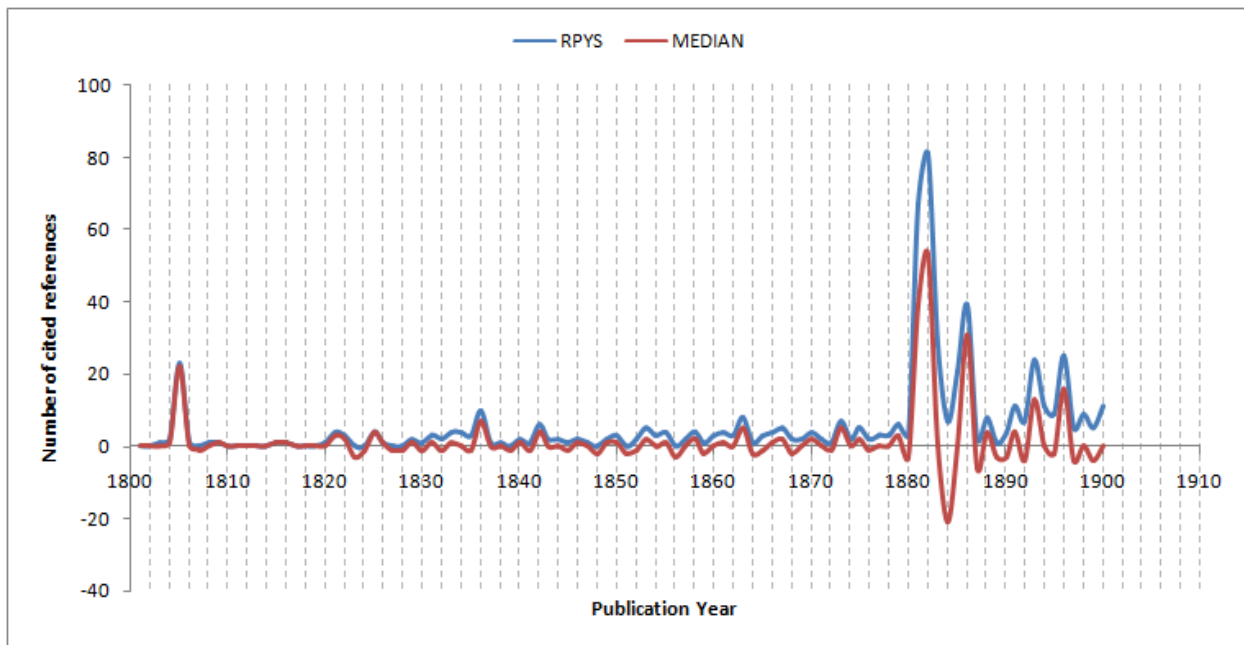

Figure 3 – Referenced publication years between 1801 and 1900

If one analyzes the publications underlying RPYS peaks in the 19th and the first half of the 20th century, they often go back to single highly-cited publications (Leydesdorff et al. 2014). This is also the case in the current study, as shown by the results in Table 2.

Table 2 - Most frequently cited publications between 1801 and 1900		
RPY	**TCR**	**Frequently Cited Publications**
1805	23	All refer to Young T (1805). PhilosTrSocLond, v95: p65
1882	82	78 refer to Hertz H (1882). Angenw Math, 92: 156.
1886	39	34 refer to Reynolds O (1886). PhilosTrSocLond, 177: 157
1893	24	14 refer to Barus C (1893). Am J Sci, 45:87
1896	25	21 refer to Hertz H (1896). Miscellaneous Papers, 146
RPY = Referenced Publication Year, TCR = Total Number of Cited References		

The first peak in 1805 refers to the paper "An Essay on the Cohesion of Fluids" by **Young (1805)**. Contact angle and wetting are the starting points for heterogeneous thin film development. The concept of "surface tension" was also introduced in Young (1805). Young's equation describes the force balance between the interfacial tensions formed at the solid–liquid–vapor contact line. This equation is being used to calculate the surface tension and contact angle even now after centuries (Quere and Reyssat 2008; Simpson et al. 2015).

The second peak in 1882 refers to the paper "Über die Berührung fester elastischer Körper" (On the Contact of Elastic Solids) by **Hertz (1882)** published initially in German. Contact mechanics originated from Hertz's work, played an important role in tribology and other engineering applications. It provides necessary information for the safe and energy efficient design of technical systems and for the study of tribology and hardness of indentation. Hertz (1882) formulated the law of interaction which is a landmark in the field of linear elasticity. The Hertzian contact theory is being used to determine the relationship between contact pressure distribution and contact radius (Song and Gu 2012). Hertzian contact stress forms the foundation for the equations for load bearing capabilities and fatigue life in bearings, gears, and other bodies where surfaces are in contact.

The third peak in 1886 refers to the paper "On the Theory of Lubrication and Its Application to Mr. Beauchamp Tower's Experiments, Including an Experimental Determination

of the Viscosity of Olive Oil" by **Reynolds (1886).** The author reveals classic examples on film lubrication. Reynolds' equation on film lubrication and pressure describes fluid flow accurately. This leads to various applications in dampers of aircraft, gas turbines, gear boxes, journal bearings, air bearings, and human joints in the usage of smooth surface geometrics of elastohydrodynamic lubrication.

The fourth peak in 1893 is especially based on the article "Isothermals, Isopiestics and Isometrics relative to Viscosity" by **Barus (1893)**. In this article, Barus provides a relationship between the viscosity and pressure of liquids. This is known as the Barus equation. Conventional viscometry normally uses the Barus equation for correlations. The viscosity-pressure dependence described by the well-known Barus law is extensively used by the engineers. Later, van Leeuwen (2009) proved the Barus equation to be non-applicable at high film pressures of 1 GPa or more.

The fifth peak in 1896 traces back to the article "On the contact of elastic solids" by **Hertz (1896).** It is the English translation of **Hertz (1882)**.

Referenced Publication Years from 1901 to 1965

There are six larger peaks exhibited between 1901 and 1965 (in a span of 65 years). As the deviations from the median in Figure 4 show, these peaks appear in 1909, 1929, 1948, 1950, 1953, and 1959. The peaks suggest that important papers for the development of tribology research have been published in the 20th century before the term "tribology" was introduced in 1966. The papers which have been most frequently cited in the six peak years (see Figure 4) are listed in Table 3.
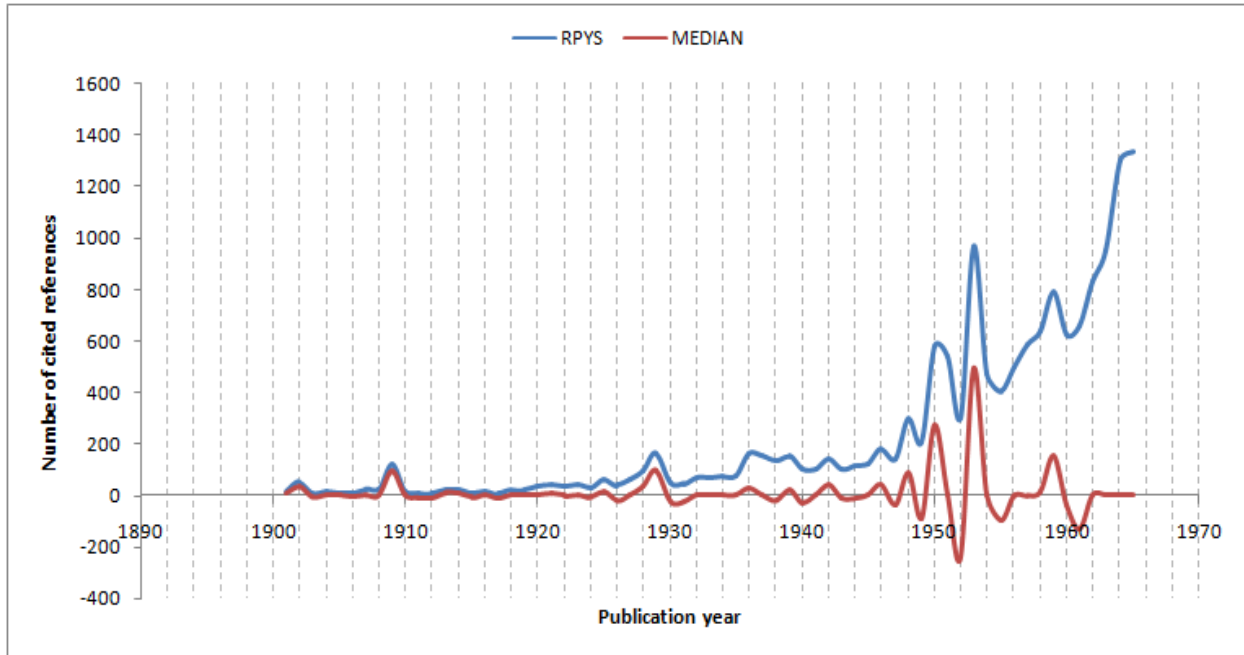
Figure 4 – Referenced publication years between 1901 and 1965

RPY	TCR	Frequently Cited Publications
Table 3 – Most frequently cited publications between 1901 and 1965		
1909	121	102 refer to Stoney G G (1909). P Roy ScoLond A, 82: 172.
1929	163	107 refer to Tomlinson G A (1929). Philos Mag, 7: 905.
1948	299	72 refer to Savage R H (1948). J App Phys, 19: 1.
1950	579	233 refer to Bowden F P (1950). Friction Lubrication, 1/2.
1953	968	484 refer to Archard J F (1953). J app Phys, 24: 981.
1959	792	128 refer to Archard J F (1959). Wear, 2: 438.
RPY = Referenced Publication Year, TCR = Total Number of Cited References		

The first peak in 1909 refers to the article "The Tension of Metallic Films deposited by Electrolysis" by **Stoney (1909)**. Stresses in thin films are determined mainly using Stoney's equation which explains the relationship between the surface stress change and cantilever's tip deflection.

The second peak in 1929 is especially based on the article "A Molecular Theory of Friction" by **Tomlinson (1929)**. A pioneering attempt to explain friction on the atomic level was made in this article. Accordingly, friction is due to the interaction of molecules very close to

each other which leads to the prediction of lattice properties and friction between various materials.

The third peak in 1948 goes back to the article "Graphite Lubrication" by **Savage (1948)**. Due to strong cohesion of planes, graphite becomes fine dust which leads to its failure of lubrication in vacuum as founded by Savage (1948).

The fourth peak in 1950 refers to the book "The Friction and Lubrication of Solids" by **Bowden and Tabor (1950)** which is an important landmark in the development of tribology research. David Tabor is the first recipient of the Tribology Gold Medal. The book covers the behavior of non-metals, especially elastomers, elastohydrodynamic lubrication, and the wear of sliding surfaces, which gradually replaced the earlier concept of the friction mechanism. The adhesion theory advocated by Bowden and Tabor is accepted as the fundamental theory of friction in the field of tribology.

The fifth peak in 1953 traces back to the article "Contact and Rubbing of Flat Surfaces" by **Archard (1953)**. Number and size of contact areas increase with the load on the model upon which mechanical wear and electrical contact also depend. Hence, high hardness of tool material maximizes the tool life as stated in Archard Wear Law used in sliding wear.

The sixth peak in 1959 is especially based on the article "The Temperature of Rubbing Surfaces" by **Archard (1959)** where a condensed version of flash theory is proposed. Later the theory became an idealized model in the rubbing contact.

DISCUSSION

RPYS implies to analyze the early RPYs cited within the body of publications of a specific research field. Major contributions (single frequently referenced publications) appear as

prominent peaks in the time series regarding the frequency of cited references as a function of RPYs. As a rule, these contributions are the origins or historical roots of a research field (Barth et al. 2014). Recently the RPYS was used by Barth et al. (2014) in physics, by Leydesdorff et al. (2014) in information science, by Marx and Bornmann (2014) in biology, and by Comins and Hussey (2015) in global positioning systems.

In this study, the RPYS software (Marx et al. 2014; Bornmann et al. in press) is used to analyze the important historical publications in tribology research. The results on tribology show that RPYS has the potential to identify the important publications in the early history of tribology research: most of the publications which have been identified in this study as highly referenced (cited) publications are landmark publications in the field of tribology.

Even though, the term tribology was coined during 1966 by Jost (1966), the basic of tribology dates centuries back. Tribology started with the thin film development and contact mechanism initially. A subsequent development was Reynolds' equation which had led to various applications using fluid flow. The developed Barus equation is used only for fluid flow and viscosity at low pressure. The further development in tribology was initiated with friction theory and lubrication. During the mid of the 20th century, tool lives were improved using wear law and contact friction. Further, wear mechanism maps played an important role.

REFERENCES

Archard, J. F. (1953). Contact and rubbing of flat surfaces. *Journal Applied Physics*, 24, 981-988.

Archard, J. F. (1959). The temperature of rubbing surfaces. *Wear,* 2, 438-455.

Barus, C. (1893). Isothermals, isopiestics and isometrics relative to viscosity. *American Journal of Science,* 45, 87-96.

Barth. A., Marx, W., Bornmann, L., & Mutz, R. (2014). On the origins and the historical roots of the Higgs boson research from a bibliometric perspective. *European Physical Journal Plus*, 129(6), 1-13.

Bornmann L, Thor, A., Marx, W., & Leydesdorff, L. (in press). Identifying seminal works most important for research fields: Software for the Reference Publication Year Spectroscopy (RPYS). *Collnet Journal of Scientometrics and Information Management*.

Bowden, F. P., & Tabor, D. (1950). *The Friction and Lubrication of Solids*, Part 1, Oxford: Clarendon Press.

Comins, J. A., & Hussey, T. W. (2015). Detecting seminal research contributions to the development and use of the global positioning system by reference publication year spectroscopy. *Scientometrics*, 104(2), 575-580. doi: 10.1007/s11192-015-1598-2

Elango, B., Bornmann, L., & Shankar, S. (in press). Study of citation networks in tribology research. *Collnet Journal of Scientometrics and Information Management*.

Elango, B., Rajendran, P., & Bornmann, L. (2015). A scientometric analysis of international collaboration and literature growth at the macro level. *Malaysian Journal of Library and Information Science*, 20(2), 41-50.

Hazen, A. (1914). Storage to be provided in impounding reservoirs for municipal water supply. *Transactions of American Society of Civil Engineers,* 77, 1539-1640.

Hertz, H. (1882). Über die Berührung fester elastischer Körper. *J. Reine Angew, Math*. 92, 156-171.

Hertz, H. (1896). On the contact of elastic solids. In *Miscellaneous Papers by H. Hertz (1882)*. London, U.K.: Macmillan.

Jost, H. P. (1966). *Lubrication (Tribology) Education and Research*. A Report on the Present Position and Industry's Needs (Her MajestiesStationary Office, London).

Kuhn, T. S. (1962). *The structure of scientific revolutions* (2nd ed.). Chicago, IL, USA: University of Chicago Press.

Leydesdorff, L., Bornmann, L., Marx, L., & Milojević, S. (2014). Referenced Publication Years Spectroscopy applied to iMetrics: Scientometrics, Journal of Informetrics, and a relevant subset of (JASIST). *Journal of Informetrics*, 8(1), 162-174. doi:10.1016/j.joi.2013.11.006

Leydesdorff, L. (2008). Caveats for the use of citation indicators in research and journal evaluations. *Journal of the American Society for Information Science and Technology*, 59(2), 278-287. doi: 10.1002/asi.20743

Marx, W., & Bornmann, L. (2014). Tracing the origin of a scientific legend by reference publication year spectroscopy (RPYS): the legend of the Darwin finches. *Scientometrics*, 99(3), 839-844. doi: 10.1007/s11192-013-1200-8

Marx, W., Bornmann, L., Barth, A., & Leydesdorff, L. (2014). Detecting the historical roots of research fields by reference publication year spectroscopy (RPYS). *Journal of the American Society of Information Science and Technology*, 65(4), 751-764. doi: 10.1002/asi.23089

Popper, K. R. (1961). *The logic of scientific discovery* (2nd ed.). New York, NY, USA: Basic Books.

Quere, D. & Reyssat, M. (2008). Non-adhesive lotus and other hydrophobic materials. *Philosophical Transactions of the Royal Society A,* 366, 1539-1556.

Reynolds, O. (1886). On the Theory of Lubrication and Its Application to Mr. Beauchamp Tower's Experiments, Including an Experimental Determination of the Viscosity of Olive Oil. *Philosophical Transactions of the Royal Society*, 177, 157-234.

Savage, R. H. (1948). Graphite lubrication. *Journal of Applied Physics,* 19(1), 1-10.

Song, J., & Gu, R. G. (2012). A finite element-based methodology for inverse problem of determiningcontact forces using measured displacements. *Inverse Problems in Science and Engineering*, 20(6), 769-783.

Stoney, G. G. (1909). The tension of metallic films deposited by electrolysis. *Proceedings of the Royal Society A*, 82(553), 172-175.

Simpson, J. T., Hunter, S. R., & Aytug, T. (2015). Superhydrophobic materials and coatings: a review. *Reports on Progress in Physics*, 78, 086501. doi:10.1088/0034-4885/78/8/086501

Tomlinson, G. A. (1929). A molecular theory of friction. *Philosophical Magazine Series,* 7, 905-931.

van Leeuwen, H. (2009). The determination of the pressure–viscosity coefficient of a lubricant through an accurate film thickness formula and accurate film thickness measurements. *Proceedings of the Institution of Mechanical Engineers Part J*, 223(8), 1143-1163. doi: 10.1243/13506501JET504

Young, T. (1805). An Essay on the Cohesion of Fluids. *Philosophical Transactions of Royal Society*, 95, 65-87. doi: 10.1098/rstl.1805.0005