Tribology and Materials
Vol. 4, No. 3, 2025, pp. 116-133

ISSN 2812-9717
https://doi.org/10.46793/tribomat.2025.007

Greenwood-Tripp model: A bibliometric overview

Maja ILIĆ [1,2,*], **Konstantinos GKAGKAS** [3], **Carsten GACHOT** [2], **András VERNES** [1,4]

[1] AC2T research GmbH, Wiener Neustadt, Austria
[2] Institute of Engineering Design and Product Development, Vienna University of Technology, Vienna, Austria
[3] R & D Material Division, Toyota Motor Europe NV/SA, Zaventem, Belgium
[4] Institute of Applied Physics, Vienna University of Technology, Vienna, Austria
*Corresponding author: ilic_maja@gmx.at

Keywords
friction
bibliometric analysis
Scopus
VOSviewer
pyBibX
ScientoPy
Bibliometrix

History
Received: 14-02-2025
Revised: 03-04-2025
Accepted: 17-04-2025

Abstract

The Greenwood-Tripp (GT) model is considered here for setting up a database with all the papers available in Scopus that used this GT model from 1972 up to 2025. After showing how the GT model can be applied for determining the friction force in mixed and boundary lubrication regimes, this database is then analysed by using bibliometric tools implemented in Bibliometrix, ScientoPy, pyBibX and VOSviewer for identifying the trends within the application of the GT model. The resulting bibliometric overview is shown to be suitable for more in-depth research to exploit the GT model further. In this manner, for example, it is demonstrated that the formula aiming to calculate the friction force in mixed and boundary lubrication regimes, respectively, persists to hold universally. However, its main application field nowadays is centred on internal combustion engines, i.e. the ring-cylinder liner tribological system.

1. Introduction

In tribology, namely in all problems related to contact, friction and wear, the roughness of surfaces plays an important role. Thus, an accurate characterisation of roughness is essential for these investigations. Therefore, investigations in tribology would be incomplete without considering the real contact area. Developed in the late 1970s, the Greenwood-Tripp model (GT) [1] was and persists to be a significant theoretical advancement in tribology, providing a framework for understanding and predicting the contact behaviour of rough surfaces [2]. This GT model extends the earlier contributions of Greenwood and Williamson by addressing the complexities of contact mechanics between two rough surfaces rather than limiting the focus to a rough surface interacting with a smooth plane [1,3].

The GT model fundamentally characterises surface asperities as an assembly of semi-spherical peaks of different heights, which provides a statistical approach to surface roughness. This perspective enables the prediction of critical contact parameters, including the real contact area, the distribution of contact pressure and the correlation between the applied load and the separation of contacting surfaces [1]. The latter is necessary for switching between a load-controlled and separation-controlled description of the interaction between contacting rough surfaces. The separation meant here is the distance between the reference planes with respect to which the roughness of contacting surfaces is defined and hence measured.

The sustained significance of the GT model within tribology can be attributed to its capacity to deliver analytical solutions for intricate contact situations. This feature is especially advantageous in various applications, such as bearings, gears and micro-electromechanical systems [4]. Even with the introduction of more sophisticated numerical models in recent years, a relatively recent state-of-the-art review is provided elsewhere [5], the GT model remains widely considered due to its balance of accuracy and computational efficiency [6]. Hence, it still attracted the attention of many scientists. As engineering surfaces evolve and new materials are developed, researchers continue to refine and adopt the GT model. This commitment guarantees its relevance to current issues in surface engineering and contact mechanics [7]. The continuous evolution of the GT model underscores its vital significance in bringing theoretical contact modelling together with practical tribological applications.

The main objective of this study is to employ bibliometric analysis to evaluate the content of academic articles published between 1972 and 2025 related to the GT model by using recently developed software packages. It will be shown that bibliometric analysis of a large amount of paper is a proper investigation modality to get a lot of useful information within the shortest time possible. On the other hand, the conducted bibliometric analysis can be straightforwardly used to set up a full view of the state-of-the-art concerning the GT model and identify beyond development trends and the gaps in the knowledge related to this topic too.

Bibliometrics refers to the quantitative examination of academic literature, primarily utilising citation data to evaluate the influence of research articles, journals, authors and institutions [8]. This field offers a structured approach for assessing research output, influence and collaboration across different fields [9]. The field emerged with the introduction of citation indexing by Garfield in 1979 [10], which allowed researchers to track the flow of knowledge within and across various scientific fields. Today, bibliometric indicators such as the total citations, *h*-index [11] and journal's impact factor [12] play a crucial role in assessing academic performance. These metrics influence decisions related to funding, faculty appointments and institutional rankings [13]. Moreover, bibliometrics assists in identifying new research trends and assessing interdisciplinary collaborations, making it a vital tool for policymakers, institutions and scholars [14].

Bibliometric analysis is a methodical approach. The first step involves collecting data from specialised bibliographic databases such as Web of Science, Scopus or Google Scholar [15,16]. Following this, the data is preprocessed, which includes the removal of duplicates, disambiguation of author names and normalisation of institutional affiliations [17]. The primary analytical methods used in this analysis are citation analysis, co-citation analysis [18] and bibliographic coupling, which explore the connections between scientific publications [19]. Additionally, network analysis is applied to visualise co-authorship trends and research collaborations. Advanced bibliometric tools, such as VOSviewer [20] and CiteSpace [21], support data visualisation and clustering, facilitating the identification of knowledge structures and thematic developments in various research areas. As bibliometric methodologies progress, they offer an enhanced understanding of research impact and the dynamics of scientific advancement.

The bibliometric analysis performed in the present study is based on the principles of how to write a review established by Webster and Watson [22] and in accordance with the guidelines provided by Donthu et al. [23]. Therefore, our contribution includes database selection, bibliometric data analysis and visualisation.

2. Mixed and boundary lubrication regimes

2.1 Three-term kinetic friction law

The three-term kinetic friction law (3-TKFL) [24] expresses the load-dependent friction force $F(L)$ in terms of three constitutive system parameters: the Derjaguin-offset F_0, effective shear strength τ and coefficient of friction μ, as a function of the load-dependent real contact area $A_c(L)$ and the load L itself:

$$F(L) = F_0 + \tau A_c(L) + \mu L. \quad (1)$$

Formally, 3-TKFL combines Derjaguin's generalisation [25] of the Amontons-Coulomb kinetic friction law [26,27] $F_0 + \mu L$ with the Bowden-Tabor law [28] $\tau A_c(L)$ – both known to hold independently on the macroscopic length scale. In the former case, the friction is said to be load-controlled, which is typical for lubricated tribological systems, whereas when the Bowden-Tabor term dominates, the friction is considered to be adhesion-controlled, e.g. in dry contact situations.

The validity of 3-TKFL in the form shown in Equation (1), i.e. when all three terms are simultaneously occurring, was first shown numerically for nanoscopic tribological systems by post-processing molecular dynamics (MD) simulations with a properly adapted smooth particle method (SPM) [29]. It turned out that SPM applied to MD data straightforwardly permits to estimate the $A_c(L)$ relative precisely [30] in comparison with the more accurate Voronoi tessellation providing the same load-dependent real contact area [24] – a typical quantity for continuum media and widely used in contact mechanics. However, SPM is computationally by far less demanding than the Voronoi tessellation. More exactly, it was proven that the three constitutive system parameters F_0, τ and μ within 3-TKFL, as shown in Equation (1), fully describe the numerically seen friction vs. load behaviour in mixed and boundary lubrication regimes and also explain entirely the transition between these lubrication regimes [24,29].

In addition, a possible physical interpretation of SPM-estimated $A_c(L)$ was given by *ab initio* calculating the electronic contribution to the load-dependent real contact area [31]. Furthermore, it was found that the Derjaguin-offset F_0 attributed to the adhesion determining the friction force at zero load when the real contact area is also vanishing, (i) is directly proportional to the load-dependent entropy quantifying the structural disorder in the lubricant [24], and (ii) it is exponentially related to the dimensionless normalised sliding resistance area [32].

Remarkable beyond that 3-TKFL gathers two macroscopic kinetic friction laws remaining valid on the nanoscopic length scale, it is also according to Equation (1) that the coefficient of friction μ is neither identical with the specific friction force $F(L)/L$ nor with the first derivative of the friction force with respect to the load $F'(L) = \mathrm{d}F(L)/L$. Therefore, generally, the three constitutive system parameters F_0, τ and μ entering 3-TKFL must be calculated via linear regression, i.e. using a least-square fitting – as described elsewhere [24]. Finally, whenever the load-dependent real contact area goes linearly with the load, e.g. $A_c(L) = A_c(0) + a_cL$, which is to be expected for rough surfaces of Gaussian height distribution, the 3-TKFL merges formally into the Derjaguin-form $F(L) = F_0^* + \mu^*L$, where the apparent Derjaguin-offset $F_0^* = F_0 + \tau A_c(0)$ and the apparent coefficient of friction $\mu^* = \tau a_c + \mu$ are definitely not constitutive systems parameters – as it has been shown by MD-grinding an atomically rough iron surface [33].

2.2 Greenwood-Williamson contact model

A central quantity which is hard to measure within the 3-TKFL is the load-dependent real contact area $A_c(L)$. Therefore, its numerical estimation is very important for determining the three constitutive system parameters describing the friction. One of the most applied contact theories providing realistic estimations of $A_c(L)$ for machined surfaces, when the height distribution of the elastic asperities is found to be Gaussian (normal),

$$G(z|0,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{z^2}{2\sigma^2}\right), \quad (2)$$

is the Greenwood-Williamson (GW) contact model [34] with all of its advantages and disadvantages, which can be seen in the state-of-the-art review elsewhere [5].

In Equation (2), σ is the standard deviation of asperity heights z relative to its mean set to zero. Accordingly, any main contact quantity, such as the number of asperities in contact N_c, the electric contact conductance Σ_c, real contact area A_c and applied normal load L, for the dimensionless separation ζ_0 between the contacting bodies (Table 1), is given by is given by [1,34]:

$$\frac{Q^{(q)}(\zeta_0)}{Q^{(q)}_{\mathrm{ref}}} = \frac{1}{\sqrt{2\pi}}\int_{\zeta_0}^{+\infty}(\zeta-\zeta_0)^q\exp\left(-\frac{\zeta^2}{2}\right)\mathrm{d}\zeta = \mathcal{g}^{(q)}(\zeta_0) \quad (3)$$

Table 1. Main contact quantities as provided by Equation (3), where A_0 is the nominal (apparent) contact area, N_0 is the total number of asperities, R is their mean radius, ρ is the specific resistivity and E^* is the reduced modulus

q	$Q^{(q)}(\zeta_0)$	$Q^{(q)}_{\mathrm{ref}}$	$\frac{Q^{(q)}(\zeta_0)}{Q^{(q)}_{\mathrm{ref}}}$	$\mathcal{g}^{(q)}(0)$
0	$N_c(\zeta_0)$	N_0	$\mathcal{g}^{(0)}(\zeta_0)$	$\frac{1}{2}$
$\frac{1}{2}$	$\Sigma_c(\zeta_0)$	$2\frac{N_0\sqrt{R\sigma}}{\rho}$	$\mathcal{g}^{(1/2)}(\zeta_0)$	$\frac{1}{2^{3/4}\sqrt{\pi}}\Gamma\left(\frac{3}{4}\right)\cong 0.411089$
1	$A_c(\zeta_0)$	$\pi N_0 R\sigma$	$\mathcal{g}^{(1)}(\zeta_0)$	$\frac{1}{\sqrt{2\pi}}\cong 0.398942$
$\frac{3}{2}$	$L(\zeta_0)\big\vert_{\mathrm{GW}}$	$\frac{4}{3}E^*N_0\sqrt{R}\sigma^{3/2}$	$\mathcal{g}^{(3/2)}(\zeta_0)$	$\frac{1}{2^{1/4}\sqrt{\pi}}\Gamma\left(\frac{5}{4}\right)\cong 0.430020$
$\frac{5}{2}$	$L(\zeta_0)\big\vert_{\mathrm{GT}}$	$\frac{16\pi\sqrt{2}}{15}\frac{E^*N_0^2R^{3/2}\sigma^{5/2}}{A_0}$	$\mathcal{g}^{(5/2)}(\zeta_0)$	$\frac{2^{1/4}}{\sqrt{\pi}}\Gamma\left(\frac{7}{4}\right)\cong 0.616634$

Since sliding is mostly load-controlled, it is mandatory to express the main contact quantities as a function of load rather than dependent on the dimensionless separation between the interacting bodies ζ_0. For this, the advantage is the fact that it can be shown with a probability of more than 99.99 % that

$$\ln\left[\frac{Q^{(q)}(\zeta_0)}{Q_{\mathrm{ref}}^{(q)}}\right]=\sum_{n=0}^{2}a_n^{(q)}\zeta_0^n=a_0^{(q)}+a_1^{(q)}\zeta_0+a_2^{(q)}\zeta_0^2,\quad \forall\zeta_0\in[0.0,4.0], \tag{4}$$

where the real-valued coefficients $a_n^{(q)}\in\mathbb{R}$ (q = 0.0, 0.5, 1.0, 1.5 and 2.5) are as listed in Table 2.

Table 2. Coefficients of quadratic form in Equation (4)

q	$a_2^{(q)}$	$a_1^{(q)}$	$a_0^{(q)}$
0	−0.4361	−0.6545	−0.7331
1/2	−0.4177	−0.8914	−0.9331
1	−0.4037	−1.0962	−0.9646
3/2	−0.3926	−1.2781	−0.8899
5/2	−0.3758	−1.5940	−0.5283

2.3 Greenwood-Tripp contact model

If the Derjaguin-offset F_0 does not exist or is found to be negligible, the 3-TKFL in Equation (1) reads

$$F(L)=\tau A_{\mathrm{c}}(L)+\mu L. \tag{5}$$

This latter form is equally applicable to determine the friction force $F(L)$ within the GW or GT model for both the mixed and boundary lubrication regimes when $A_{\mathrm{c}}(L)\neq 0$ and is linearly dependent on the load. The GT model, however, is more accurate than the GW model, and hence Equation (5) is typically used written as

$$FMEP=\tau\pi\frac{S_q S_{\mathrm{ds}}}{S_{\mathrm{sc}}}\mathcal{I}^{(1)}(\zeta_0)+\mu\frac{L(\zeta_0)|_{\mathrm{GT}}}{A_0}, \tag{6}$$

when calculating in mechanical engineering, the friction mean effective pressure $FMEP$, is defined as the ratio between the friction force $F(L)$ and the nominal (apparent) contact area A_0.

Note that apart from the load-dependent real contact area, which is estimated in both contact models applying the same expression, also the load within the GT model is a function of some surface roughness parameters, such as the root mean square roughness parameter $S_q=\sigma$, areal density of summits $S_{\mathrm{ds}}=N_0/A_0$ and the mean curvature of the summits $S_{\mathrm{sc}}=R^{-1}$, see Equation (3) and Table 1. Furthermore, all roughness parameters entering Equation (6) must be determined for the combined rough surface of the contacting bodies, e.g. by applying the sum rules of the spectral moments, which are separately obtained for the two individual rough surfaces. Note also that the dimensionless separation ζ_0 between the interacting bodies is straightforwardly obtained by solving Equation (4) for all normal loads of interest, and then this ζ_0 is used for computing $\mathcal{I}^{(1)}(\zeta_0)$ either applying a quadrature rule while integrating into Equation (3) or simply inserting it into Equation (4).

3. Setup of database

Through this bibliometric analysis, we intend to give researchers of all engineering and natural science backgrounds an overview of how the GT model [1] expanded our understanding of friction and its reduction over the last fifty-five years. In order to fulfil this challenging goal of our bibliometric study, a large amount of significant academic publications related to the GT model were gathered from the Scopus database – one of the world's largest abstract and citation databases of peer-reviewed research literature and the most frequently used one [35]. The data from this database was obtained on December 11, 2024. In the Scopus search interface, from the search field dropdown menu, "Article Title, Abstract, Keywords" was selected and the article title "The contact of two nominally flat rough surfaces" was entered in the search box to retrieve results. On the results page, the "Cited by" option showed all the publications that have cited the mentioned article.

In the first step, from the resulting dataset consisting of 1579 publications, all 33 duplicates, i.e. 2.1% of publications, were removed, remaining in a total of 1546 papers to analyse, out of which 1216 were articles, 12 books, 19 book chapters, 261 conference papers, 2 editorial, 34 reviews and one retracted. Figure 1 nicely illustrates the almost exponential growth of publications related to the GT

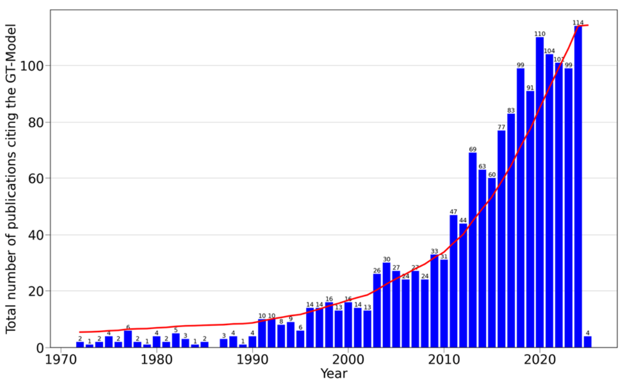

Figure 1. The growth of publications on GT model

model over the years, which shows a significant increase of interest in this model starting with 2010.

4. Bibliometric analysis

In recent years, bibliometric (scientometric) analysis has become a significant tool in all research areas for providing fresh impulses about trends and lack of knowledge. This study's bibliometric overview is obtained using ScientoPy [36] and pyBibX [37] for the combination of metadata resulting from Scopus via semantic searches in its database. Both of them are Python libraries and offer a variety of functionalities, such as exploratory data analysis (EDA), word cloud and an assortment of visualisation and analysis methods, making them ideal for researchers seeking a robust tool encompassing extensive features [37]. Some bibliometric features were also obtained with the Bibliometrix package from R [38-40].

The EDA report generated with pyBibX is given in Table 3 and summarises some main data in our database, for example, that there are 1546 documents citing the original paper by Greenwood and Tripp, with 2965 keywords set by the 2478 authors publishing their contribution between 1972 and 2025.

4.1 Analysis of authors

It is also useful to know the most active and, hence, representative authors in a given research field and to cite them with their most relevant contributions or reference-related works. Figure 2 provides such information with respect to the GT model with a particular feature, namely that it distinguishes between papers before and after 2010, marking the starting year of the GT model's current renaissance.

Table 3. Brief report of exploratory data analysis performed with pyBibX

Main information	Result
Time span	1972 – 2025
Total number of documents	1546
Total number of authors	2478
Total number of institutions	1648
Total number of references	56,373
Average documents per author	2.25
Total number of authors keywords	2956
Total number of citations	36,329
Average citations per author	14.66

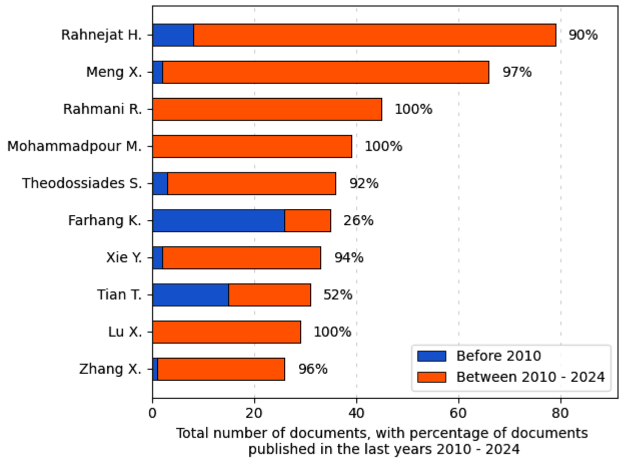

Figure 2. Top 10 authors within the last 14 years dealing with GT model

More in-depth details about the top 10 authors listed in Figure 2 are given in Table 4 by using ScientoPy-based three topics growth indicators, which are introduced to identify trends and their relative/absolute development [36].

Table 4. Total number of publications, average growth rate (AGR), average documents per year (ADY), percentage of documents in the last years (PDLY) and *h*-index of the top 10 authors within the last 14 years dealing with GT model

Rank	Author	Total	AGR	ADY	PDLY	*h*-index
1	Rahnejat H.	79	−0.1	4.7	89.0	32
2	Meng X.	66	0.5	4.3	97.0	22
3	Rahmani R.	45	0.1	3.0	100.0	22
4	Mohammadpour M.	39	0.0	2.6	100.0	17
5	Theodossiades S.	36	−0.1	2.2	91.7	18
6	Farhang K.	35	−1.0	0.6	25.7	7
7	Xie Y.	33	−0.1	2.1	93.9	19
8	Tian T.	31	0.0	1.1	51.6	17
9	Lu X.	29	0.3	1.9	100.0	10
10	Zhang X.	26	0.3	1.7	96.2	11

The average growth rate (AGR) is the average difference between the number of documents published in one year and the number of documents published in the previous year. It indicates the growth (positive number) or decline (negative number) on average inside a time frame. It is calculated using the expression

$$\mathrm{AGR}=\frac{\sum_{i=\mathrm{Y_s}}^{\mathrm{Y_e}}\mathrm{P}_i-\mathrm{P}_{i-1}}{(\mathrm{Y_e}-\mathrm{Y_s})+1}, \tag{7}$$

where Y_e is the end year, Y_s is the start year and P_i is the number of publications in year *i*.

For the Y_e, ScientoPy uses the default global end year configured in the global option or/in ScientoPy command parameters. The Y_s is calculated from Y_e, according to

$$\mathrm{Y_s}=\mathrm{Y_e}-(\mathrm{W_{in}}+1). \tag{8}$$

The width of window W_{in} is set to 14 years. Thus, if the end year is 2024, the AGR is the average growth rate between 2010 and 2024.

The average documents per year (ADY) is an absolute indicator that represents the average number of documents published inside within a time frame for a given topic. ADY is calculated using the formula

$$\mathrm{AGY}=\frac{\sum_{i=\mathrm{Y_s}}^{\mathrm{Y_e}}\mathrm{P}_i}{(\mathrm{Y_e}-\mathrm{Y_s})+1}. \tag{9}$$

The percentage of documents in the last years (PDLY) is a relative indicator that represents the percentage of the ADY relative to the total number of documentations for a given topic, and it is given by

$$\mathrm{PDLY}=\frac{\sum_{i=\mathrm{Y_s}}^{\mathrm{Y_e}}\mathrm{P}_i}{(\mathrm{Y_e}-\mathrm{Y_s}+1)\,\mathrm{TND}}100, \tag{10}$$

where TND denotes the total number of documents.

Table 4 includes, apart from the total number of publications, the average growth rate (AGR), the average documents per year (ADY) and the percentage of documents in the last years (PDLY), as well as the author's *h*-index [41].

4.2 Analysis of authors' keywords

Continuing with EDA, another way to get further insights about GT-related publications is to conduct a text analysis and create word clouds and *n*-grams. By generating word clouds and *n*-grams (*n* is a positive integer greater than 1) from the abstracts of GT-related publications, it becomes possible to identify common themes, topics and terminology used by various authors. In addition, the keywords chosen by the authors to describe the content of their publications are also considered in this analysis. Accordingly, as highlighted within the word cloud depicted in Figure 3, by using both the authors' keywords and the abstract of the publication, it becomes clear that the primary focus of the GT model and its applications is centred around friction, surfaces, contacts, in engines and pistons and when they are lubricated.

4.3 Analysis of journals

Analysing journals is a fundamental aspect of bibliometric research, as it facilitates the

Table 5. Total number of publications, average growth rate (AGR), average documents per year (ADY), percentage of documents in the last years (PDLY) and *h*-index of the top 10 sources within the last 14 years dealing with GT model

Rank	Source title	Total	AGR	ADY	PDLY	*h*-index
1	Tribology International	140	0.8	8.4	90.0	40
2	Journal of Engineering Tribology	96	0.4	5.6	87.5	26
3	Journal of Tribology	91	0.0	3.5	58.2	29
4	SAE Technical Papers	59	0.0	2.3	59.3	13
5	Lubricants	45	0.6	3.0	100.0	13
6	Tribology Transactions	39	0.1	1.5	59.0	20
7	Wear	37	0.0	1.0	40.5	24
8	Industrial Lubrication and Tribology	31	0.1	2.0	96.8	9
9	International Journal of Mechanical Sciences	19	0.5	1.2	94.7	11
10	Journal of Multi-body Dynamics	19	0.0	0.0	78.9	11

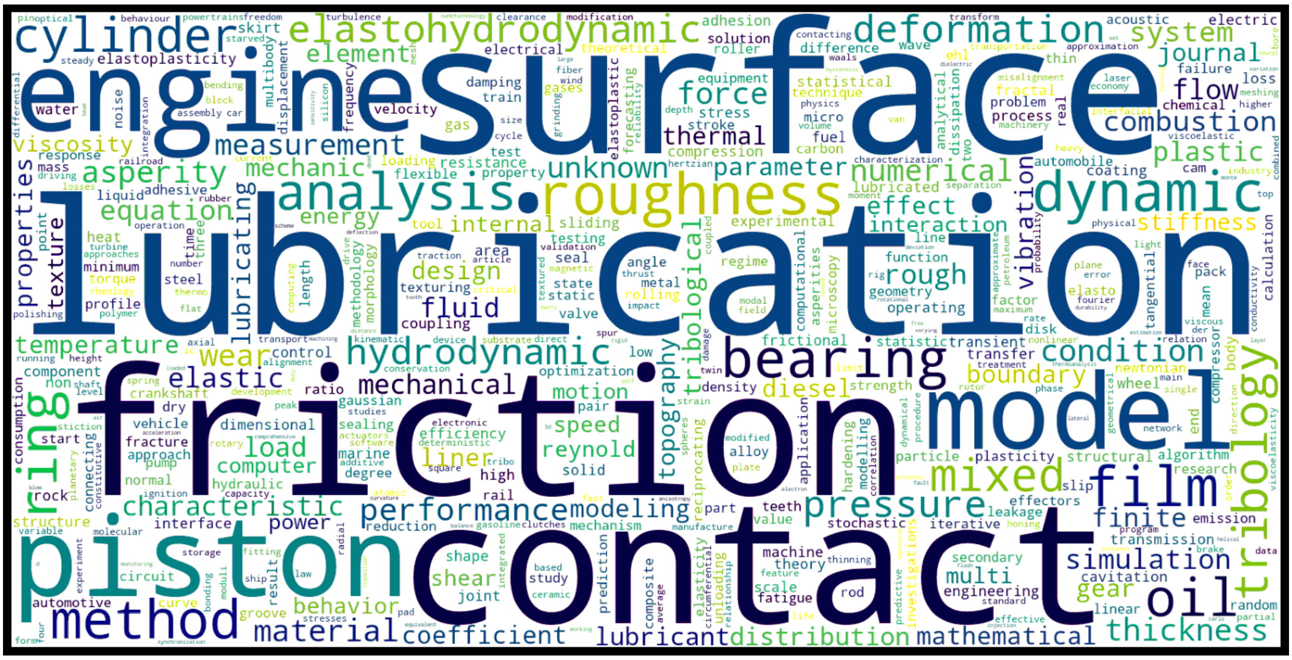

Figure 3. The word cloud visualisation illustrates essential concepts within tribology and mechanical engineering; key terms like "lubrication", "friction", "surface" and "contact" are prominently featured in this view, underscoring their vital role in the discipline; additional important terms, such as "wear", "engine", "bearing" and "material" highlight the extensive range of tribological applications and research domains; the varying font sizes indicate each term's relative significance, i.e. larger letters denote greater importance

understanding of publication trends, the impact of academic work and the flow of knowledge. The term "source" usually refers to a journal, a conference proceeding or a book. Journals are the principal mediums for sharing scholars' research, and their analysis provides critical insights into which publications dominate a field, the progress in research areas and the academic community's valuation of specific scholar contributions [13,23,42].

Table 5 shows that between 2010 and 2024, Tribology International was the leading publisher of articles associated with the GT model. The positive AGR suggests an increase in the number of articles focused on the GT model. Significantly, Tribology International holds the highest *h*-index, which reveals that at least 40 of its GT-related publications were cited regularly from 2010 to 2024. Meanwhile, certain journals have an AGR equal to zero, indicating that their publication levels have remained unchanged over the past 14 years.

5. Visualisation of gathered knowledge

Visualization software, which might come with a graphical user interface such as VOSviewer [43] or other graphical tools, is also used during bibliometric analyses.

5.1 Map of keyword co-occurrences

The major purpose of keyword co-occurrence analysis is to provide a form of content analysis that identifies connections between keywords from a selected sample of publications. This mapping technique assists researchers in recognising important themes, trends and research clusters by investigating the frequency and co-occurrence patterns of keywords found in a dataset.

In a network representation, each node signifies an entity, such as an article, author, country, institution, keyword or journal. In Figure 4, for example, a node represents a keyword. The characteristics of such a network are as follows. The size of the node is proportional to the number of the keyword's occurrence, the connections between the nodes specify the co-occurrence of the keywords, whereas the thickness of the connections is proportional to the total amount in which a particular co-occurrence appears, i.e. a large node stands for a keyword of high occurrence and a thick connection indicates a large number of co-occurrences between the connected keywords. Additionally, different colours within the network mark thematically different clusters, allowing for an in-depth analysis of the topics given by the nodes and their interrelationships [23].

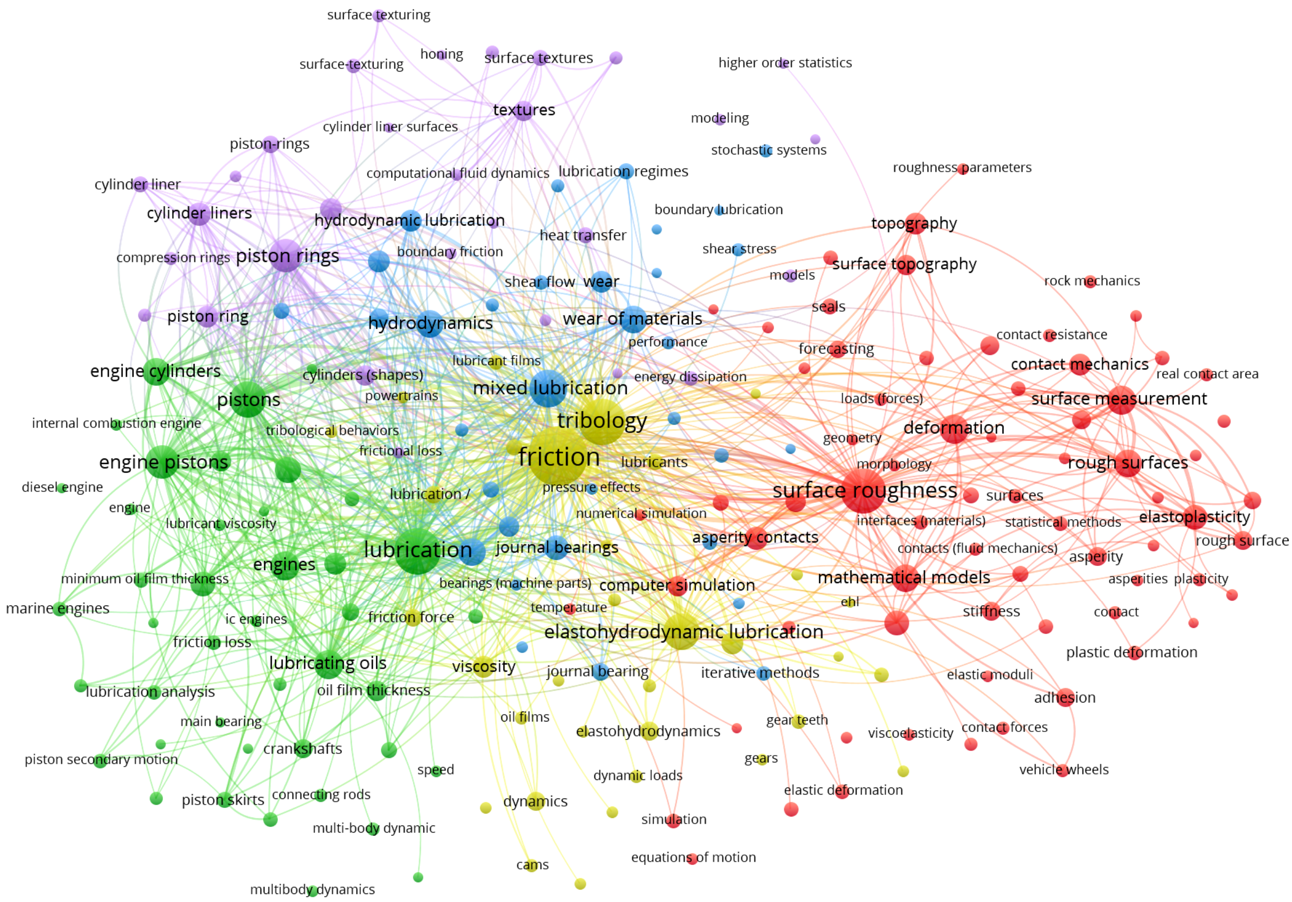

Figure 4. Network of keyword co-occurrence linked to tribology, lubrication, surface roughness and mechanical engineering research as generated by VOSviewer; the nodes (coloured circles) indicate specific research terms, and their size measures the frequency of occurrence; the edges (the connection between nodes) signify co-occurrences, meaning that these terms are frequently appearing together in the literature; the clusters (different colours) group related topics, revealing some underlying themes in the field of interest

Setting a threshold for keyword co-occurrence analysis in VOSviewer is crucial for filtering out less relevant keywords, ensuring that the visualisation highlights the most significant terms. This threshold defines the frequency required for a keyword to be included in the final map based on its occurrence in the bibliographic dataset.

By limiting the minimum number of occurrences for identifying a keyword to 15, 209 keywords are obtained out of 8351, as seen in Figure 4, which are accordingly grouped into only five clusters. Lubrication and engine systems cluster (green cluster) focuses on pistons, engine lubrication, lubricating oils, viscosity and friction loss and includes internal combustion engines, crankshafts and bearings, i.e. tribological behaviour of mechanical systems. Surface roughness and contact mechanics cluster (red cluster) covers contact mechanics, rough surfaces, deformation, elastoplasticity and adhesion. It also investigates asperity contacts, plastic deformation and surface measurement techniques. Hydrodynamics and wear cluster (blue cluster) includes hydrodynamic lubrication, boundary lubrication and wear of materials. It is related to computational fluid dynamics, heat transfer and shear stress effects. Tribology and numerical simulation cluster (yellow cluster) explores elastohydrodynamic lubrication, journal bearings, numerical simulation and dynamic loads. It is relevant to gear mechanics, elasticity and iterative computational methods. Surface texturing and material optimisation cluster (purple cluster) studies cylinder liner texture, honing and higher-order statistics in tribology. It examines texture surfaces and their impact on friction and lubrication performance.

Occurrences in Table 6, as a metric, indicate the frequency of a keyword's appearance within the bibliographic dataset, which may include publications, abstracts or complete text documents. A higher count suggests that the topic is frequently studied. According to Table 6, keywords with high occurrences (e.g. friction, lubrication, tribology, surface roughness, mixed lubrication and piston) represent core topics within the research field of tribology and as frequently occurring terms, they suggest popular or well-established research domains.

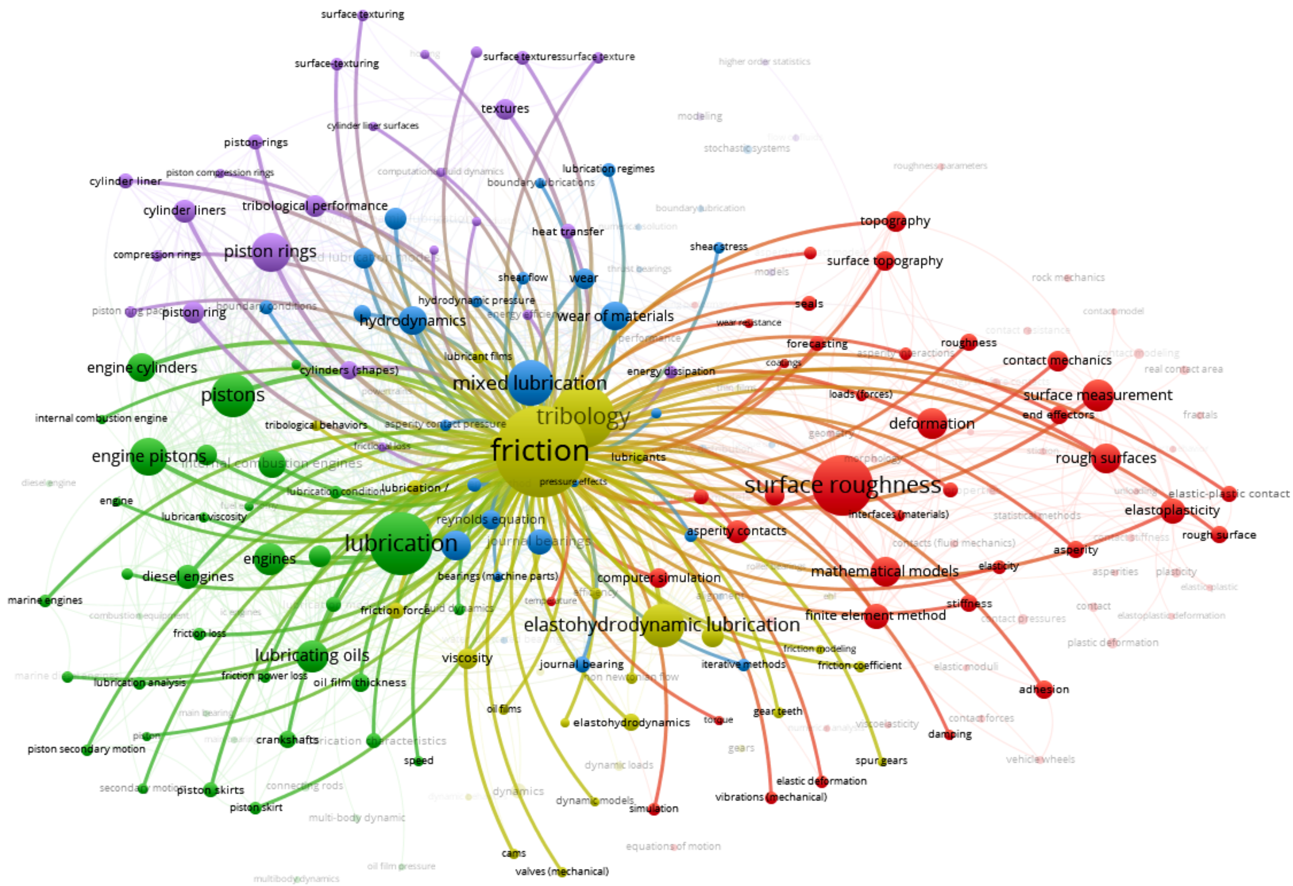

Figure 5. The interaction between the identified five clusters illustrates a highly interdisciplinary research field where mechanical engineering, materials science and computational modelling are coming together

The VOSviewer network visualisation illustrates the complex interconnections among clusters, as seen in Figure 5, reflecting the significant relationships among primary research themes in tribology. Each cluster, identified by a unique colour, represents a collection of closely associated keywords, whereas the links between these clusters denote the degree of interdisciplinary impact and co-occurrence present in the bibliographic dataset.

The relationship between the yellow and green clusters highlights the essential connection between friction and lubrication within the field of tribology. Friction, as a fundamental concept, is intricately associated with lubrication, which emphasises the necessity of developing strategies to mitigate wear and energy loss in tribological systems. This relationship is particularly pronounced in investigations focused on optimising lubricants and applying tribological coatings, both of which are crucial for reducing frictional losses. Terms such as "elastohydrodynamic lubrication" and "lubricant viscosity" serve as vital links, merging core tribological principles with practical applications, especially in the context of engine design and enhancing efficiency.

The relationship between the yellow and red clusters underscores the essential influence of surface interactions on frictional behaviour. Surface roughness plays a pivotal role in tribological performance, as indicated by terms like "asperity contacts" and "deformation", which imply that changes in surface morphology can significantly affect wear mechanisms. Research in this area aims to elucidate how surface topography and material deformation influence friction, particularly in high-load scenarios such as aerospace, automotive and industrial machinery. Furthermore, the inclusion of terms such as "mathematical models" and "finite element methods" reflects a substantial dependence on computational simulations to forecast and control friction and wear, thereby increasing the efficiency and durability of machine elements.

The relationship between the yellow and blue clusters underscores the vital connection between lubrication regimes and material wear. Hydrodynamic principles are integral to tribology, as evidenced by terms such as "shear stress" and "boundary lubrication", which pertain to investigations of lubricant film behaviour under different load and speed scenarios. The mention of "wear of materials" highlights the exploration of material degradation processes, especially in fluid-lubricated settings like marine engines and wind turbines. This relationship accentuates the necessity of comprehending how hydrodynamic and boundary lubrication conditions affect wear rates, ultimately informing the advancement of more effective lubrication techniques and wear resistant materials in high-performance mechanical systems.

Table 6. Top five most frequently occurring keywords in the resulting five clusters for a threshold of 15

Term	Occurre-nces	Cluster colour
Friction	615	yellow
Lubrication	353	red
Tribology	351	yellow
Surface roughness	334	red
Mixed lubrication	223	blue
Piston	206	green
Elastohydrodynamic lubrication	204	yellow
Piston rings	175	purple
Engine pistons	163	green
Lubricating oils	130	green
Surface measurement	126	red
Engines	125	green
Deformation	119	red
Rough surfaces	117	red
Film thickness	114	blue
Hydrodynamics	111	blue
Wear of materials	100	blue
Journal bearings	90	blue
Cylinder liners	76	purple
Friction coefficients	72	yellow
Piston ring	71	purple
Tribological performance	70	purple
Viscosity	64	yellow
Textures	62	purple

The relationship between the yellow cluster, representing tribology and the purple cluster, which encompasses piston rings and engine components, underscores the critical importance of friction and lubrication in the performance of internal combustion engines. Essential elements, like piston rings and cylinder liners, are significantly influenced by tribological forces, where excessive friction can result in increased wear and diminished efficiency. Research in this area aims to enhance engine longevity through the development of coating technologies, surface treatments and innovative lubrication methods designed to reduce energy losses. By optimising the tribological performance at the piston-cylinder interfaces, these investigations play a vital role in improving fuel efficiency, lowering emissions and prolonging the operational life of contemporary engines. The strong interconnections suggest that research in tribology is evolving through integrated approaches, combining surface engineering, lubrication science and numerical modelling to optimise performance and reduce wear and friction in mechanical systems.

5.2 Map of keyword overlay

In VOSviewer, a keyword overlay map is an essential tool for uncovering research trends, tracking the advancement of topics and identifying key or developing areas. By analysing the placement and colour differentiation of keywords, researchers and policymakers can effectively manoeuvre through the landscape of scientific knowledge, Figure 6. This analysis offers important perspectives on the progression of research themes by employing colour coding to represent the average year of publication or the citation impact associated with specific keywords. Topics that have been extensively researched in the past are typically denoted in blue, while newly emerging fields are indicated in yellow, highlighting their recent significance.

Monitoring research development entails examining the transition of keyword clusters from blue (representing older studies) to yellow (indicating newer studies) over time, reflecting a shift in scholars' attention. Conversely, certain keywords may persist in blue, suggesting a decrease in research interest. Furthermore, in citation-based overlays, the use of colour aids in pinpointing high-impact research domains, with yellow keywords signifying highly cited subjects that exert considerable academic influence, while blue keywords may represent less prominent or nascent areas that have not yet achieved broad acknowledgement. This visualisation is crucial for identifying both established and innovative research trends.

The keyword overlay visualisation in tribology research illustrates new trends and enduring interdisciplinary links while core concepts (friction, lubrication and wear) remain central to the field. Nodes marked in yellow, including surface texturing and stochastic systems, indicate an increasing emphasis on innovative techniques designed to enhance tribological performance. These emerging fields signify a transition towards precision engineering, utilising computational modelling and investigating sustainable lubrication strategies. Concurrently, terms such as elastohydrodynamic lubrication, plastic deformation and adhesion underscore the profound interdisciplinary foundations of tribology, connecting materials science, physics and mechanical design to tackle intricate challenges that encompass experimental research, theoretical frameworks and industrial applications.

5.3 Network of co-authorships

Co-authorship analysis focuses on the collaborative relationships between researchers and their affiliated institutions and is determined by the volume of the number of jointly authored publications. This analytical approach is frequently employed to discern and evaluate the dynamics of scientific collaboration across various areas [44]. In the considered 1546 GT-related publications, 2478 authors were identified and a minimum threshold of three publication per author and a minimum number of five citations was set for depicting then the resulting 465 authors fulfilling these criteria.

A co-authorship table presents a coherent framework for examining academic collaboration, cataloguing key authors along with their publication output, citation impact and total link strength, which evaluates the strength of their collaborative ties. Comprehending these metrics is crucial for identifying prominent researchers, high-impact publications and effective research networks. To enhance the comprehension of the co-authorship analysis, Table 7 displays the leading 15 authors ranked by the citations within the current bibliographic dataset.

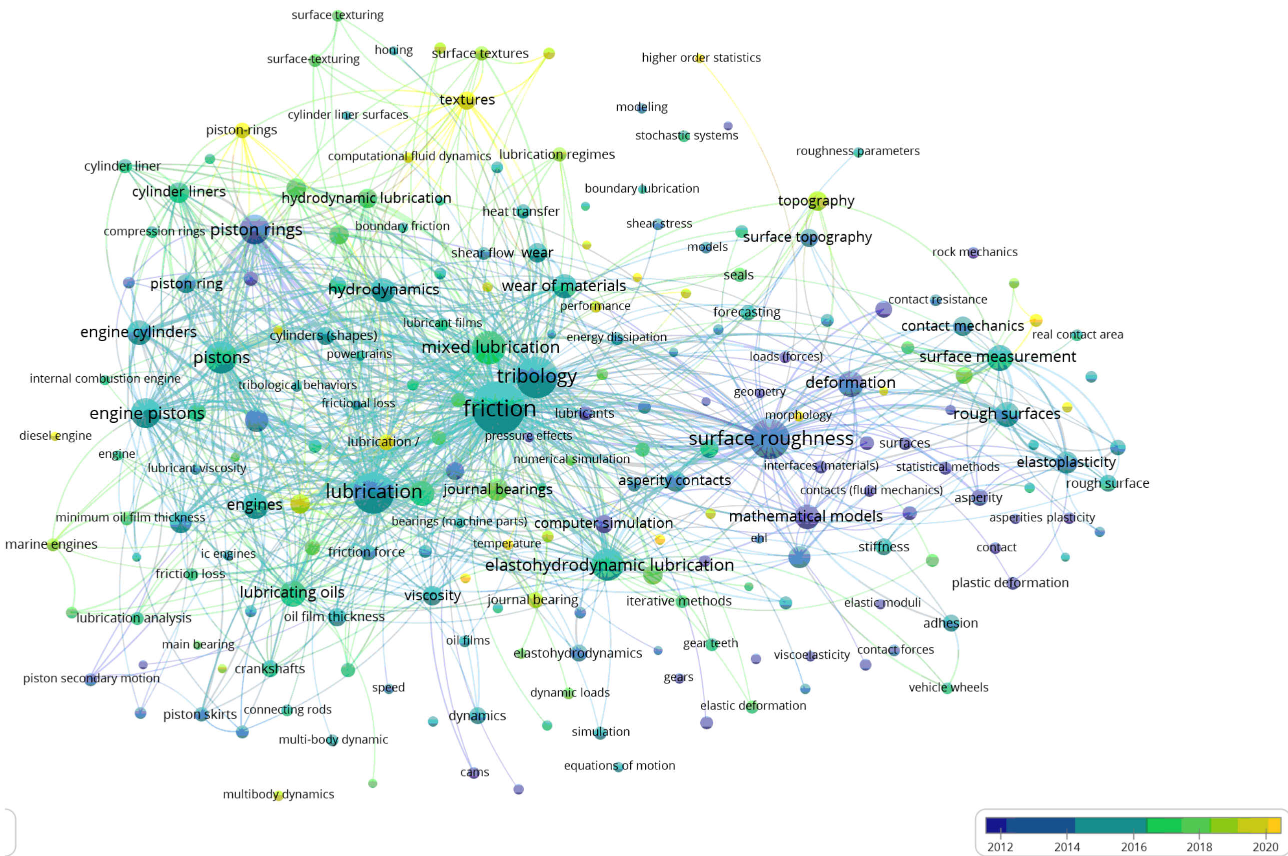

Figure 6. The overlay visualisation of keyword co-occurrences in VOSviewer depicting the temporal dynamics of various research topics; the colour scheme reflects the average publication year associated with each keyword, where blue signifies older topics (e.g. surface roughness and piston rings), green stands for topics with sustained interest over time (e.g. mixed lubrication), while yellow denotes emerging trends (e.g. surface texturing and computational methods); the dimensions of each node represent the frequency occurrence of the keywords, whereas their spatial arrangement and connections depict the relationships of co-occurrence

Table 7. Top 15 authors within the selected publications related to the GT model

Author	Docu-ments	Cita-tions	Total link strength
Rahnejat Homer	83	2490	243
Etsion Izhak	14	2451	15
Bogy David B.	4	1726	6
Chang Wei R.	3	1722	6
Rahmani Ramin	45	1431	150
Zhu Dong	9	1185	6
Meng Xin	67	1173	184
Jackson Robert L.	10	1168	6
Jing Li	3	1095	4
Thomas Tom R.	9	1069	5
Green Itzhak	3	992	3
Tian Tian	37	923	51
Theodossiades Stephanos	37	887	94
Bhushan Bharat	5	854	0
Zhao Yang	5	788	7

Figure 7, created using the Bibliometrix R package, is an advanced visualisation tool that provides profound insights into researchers' publication trends and impact over time. This dynamic representation allows for a comprehensive understanding of scholarly output and influence, surpassing basic metrics. The figure's innovative bubble chart format offers a multi-dimensional perspective on each author's career development. The horizontal axis delineates the timeline, illustrating the progression of an author's work throughout the years. Each bubble denotes a year of publication, with its size reflecting the number of articles published, thus providing an immediate visual indication of periods characterised by high productivity. What makes this visualisation particularly effective is its use of colour intensity to represent citation impact. The different shades of blue effectively highlight both the quantity and quality of scholarly contributions. Darker bubbles represent publications that have received more citations, allowing viewers to quickly recognise an author's most significant works.

This strategy for visualising data allows for multiple unique analytical perspectives. Periods marked by larger bubbles indicate a surge in research productivity, reflecting an uptick in publication frequency, which may be linked to significant projects, grants or collaborative efforts (career momentum). By scrutinising the size and colour of the bubbles, one can evaluate the delay between publication and citation impact, aiding in understanding when an author's work achieves notable recognition (impact lag). When this analysis is extended to multiple authors, the visualisation reveals changes in research focus, illustrating how topics, methodologies or trends evolve within a discipline (field evolution). The simultaneous presence of large, dark-collared bubbles for several authors suggests the success of collaborative projects that have attracted considerable citation

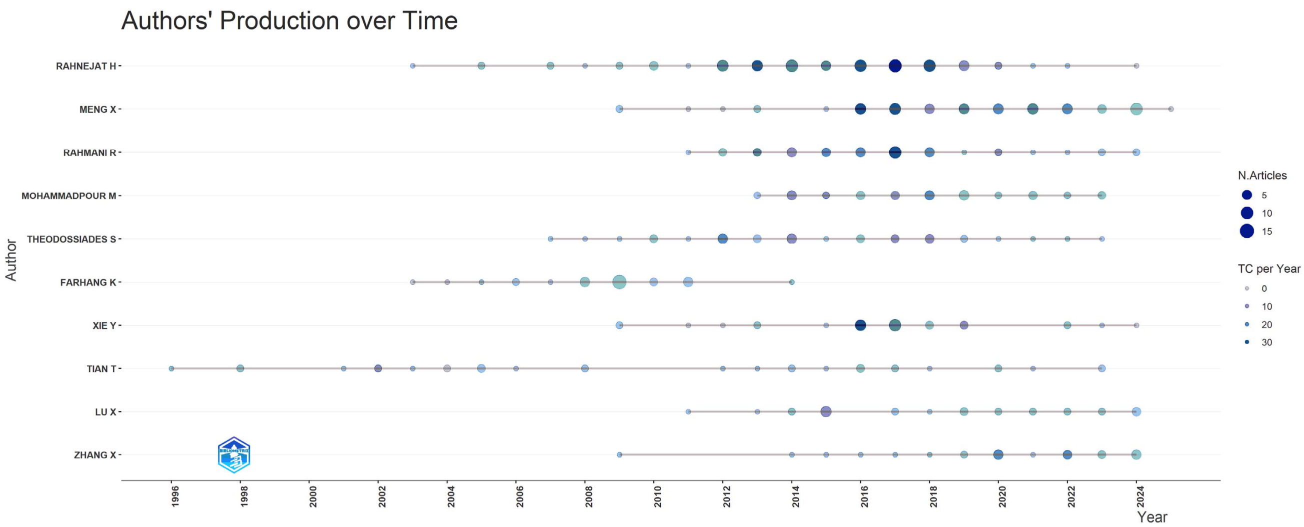

Figure 7. Visualisation of the author's production over time using the Bibliometrix R package; the size of the bubbles goes linearly with the number of publications per year, while colour intensity indicates the citation's impact; larger bubbles suggest periods of high research productivity, whereas darker colours reflect highly cited works; the distribution of bubbles over time helps identify career momentum, impact lag and shifts in research focus; simultaneous large, dark bubbles across multiple authors indicate successful collaborations, while the overall trend provides insights into early-career growth, peak productivity and late-career stages in academic research

attention (collaboration patterns). The temporal distribution of these bubbles can reflect various stages of an academic career: early-career researchers may demonstrate irregular yet increasing output, mid-career scholars typically reach their peak productivity, while late-career academics may show consistent or diminishing publication rates (career stage analysis).

5.4 Network of co-citations

The co-citation analysis involves the evolution of the publications by one or another author cited by other publications within the selected dataset, as well as the analysis of the relationships among these publications [44]. This approach aims to enhance comprehension of the fundamental themes emerging within the research domain related to the GT model. In other words, the relatedness is determined based on the number of publications cited together. Applying a minimum citation threshold of 20, 1130 authors satisfy this criterion out of 37,801. To get a picture of co-citation defined in this way, Figure 8 shows a network of co-citations centred around authors whose research was focused on the GT model, indicating five significant clusters.

The yellow cluster, named "Automotive and engine tribology", signifies a vital domain within tribology research, particularly concerning automotive and engine applications. Esteemed researchers such as T. Tian [45,46], J. B. Heywood [47], E. G. Giakoumis [48] and S. Aoyama [49] have made significant contributions to the development of internal combustion engines and lubrication systems. The varied composition of this cluster indicates a wide array of research subjects, including engine oil formulation, methods for reducing friction and strategies for controlling emissions. Its robust links to the green and red clusters highlight the relationship between lubrication science and surface mechanics, emphasising the necessity of optimising tribological characteristics to improve engine efficiency and longevity.

The green cluster, named "Elastohydrodynamic lubrication and contact mechanics", features leading researchers, such as W. Wang [50], B. Zhao [51] and Z. Zhang [52] and is pivotal to lubrication theory and contact mechanics, with a particular emphasis on elastohydrodynamic lubrication and the modelling of film thickness. The extensive network of collaborations suggests a vibrant research community where core models are regularly enhanced to advance industrial lubrication solutions. This cluster plays a crucial role in bridging theoretical developments with practical applications connected to surface roughness (red) and hydrodynamic wear mechanics (blue), thereby highlighting the essential role of lubrication in reducing friction and wear across a range of engineering systems.

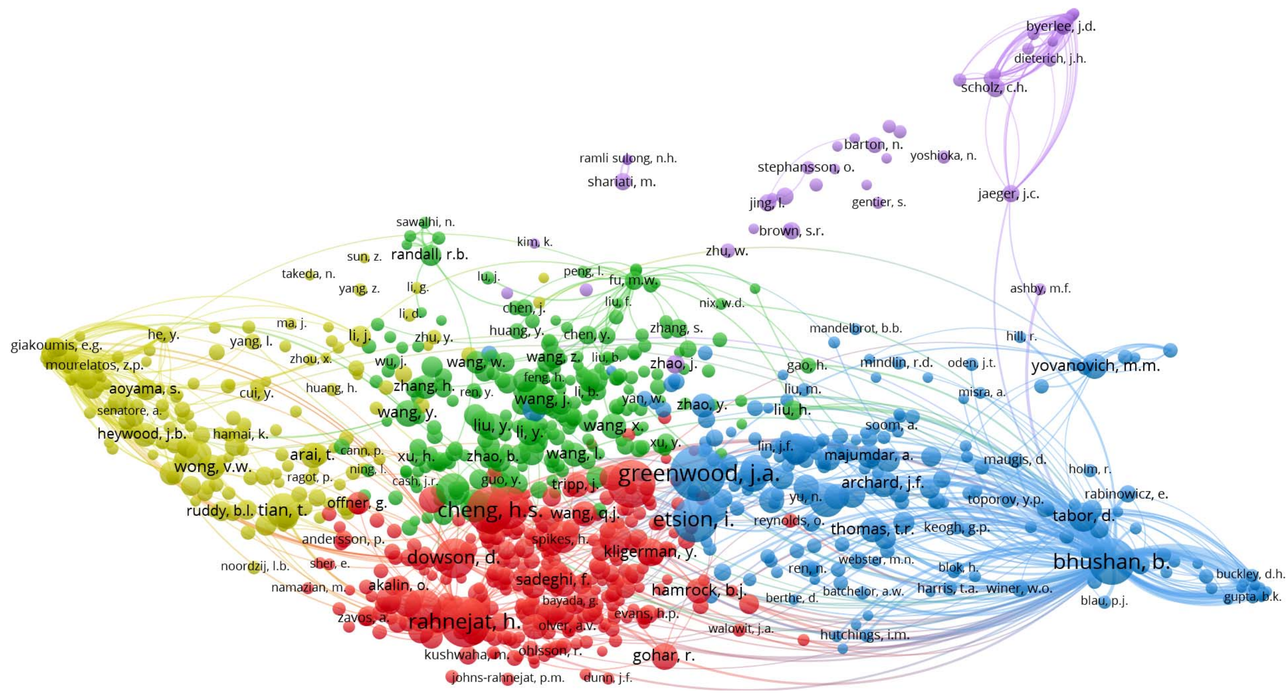

Figure 8. The co-citation network yields the intellectual framework of tribology; the nodes stand for prominent authors, with their size reflecting the number of citations they have received, and they are linked according to the co-citation frequency; different colours indicate various research clusters, highlighting the connections between sub-disciplines in tribology and associated areas of study

The red cluster, named "Surface roughness, wear and deformation", with representative authors such as H. Rahnejat [53], H. S. Cheng [54] and D. Dowson [55], concentrates on the vital contributions of surface roughness, asperities and material deformation to friction and wear dynamics. Its close connection with the green cluster illustrates the significant reliance of lubrication performance on surface topography, thereby underscoring the need for enhanced coatings and surface treatments to optimise tribological efficiency. The interdisciplinary nature of this research is reflected in its strong associations with mechanical engineering, tribomaterial studies and industrial applications, emphasising its critical role in the development of wear-resistant materials and the improvement of mechanical system longevity.

The blue cluster, named "Nanotribology", is mainly influenced by B. Bhushan [56], D. Tabor [57], J. A. Greenwood [58], I. Etsion [59] and M. M. Yovanovich [60], with a focus on the study of wear, tribomaterials and hydrodynamics, especially at the nanoscale. Together, these researchers have established an understanding of nanoscale friction, adhesion and lubrication, significantly impacting contemporary applications within precision engineering, biomedical coatings and advanced tribomaterials. The robust links to the green cluster, namely, lubrication theory and the red cluster, i.e. surface mechanics, illustrate the critical influence of fluid interactions on wear, thereby highlighting the necessity for innovative material coatings and lubrication techniques to improve performance and longevity in high-friction settings.

The purple cluster, named "Geological and seismological tribology", is represented by researchers including J. D. Byerlee [61], C. H. Scholz and J. C. Jaeger [62] and is committed to the exploration of geological and seismological tribology. This research area specifically delves into the frictional behaviour of fault systems, the mechanics of underlying earthquakes and the modelling of fault slip. Its relatively isolated position within the research network suggests that geotribology is a highly specialised part of tribology, with a limited direct overlap with conventional tribology dealing with lubrication and wear. Nonetheless, the few connections to mechanical tribology point to potential applications, particularly in rock drilling, high-pressure friction investigations and studying materials under extreme stress conditions. This emphasises how knowledge derived from fault mechanics can be applied to engineering challenges, including deep-earth mining, geothermal energy extraction and material performance analysis in high-stress environments.

5.5 Network of bibliometric coupling

Bibliometric coupling examines the relationships among publications to evaluate the relevance of documents within a dataset based on their network positioning. The relatedness of publications is determined by the number of references they share. This analysis allows a deeper understanding of the relationships among publications, thereby providing insights into their significance within the selected dataset in terms of their networking roles [44]. Setting five cited publications per author for the minimum amount of sharing resulted in 229 authors that met this criterion, as shown in Figure 9.

The red cluster stands for the largest and most interconnected group within the network, signifying that the authors within this cluster are frequently referring to similar sources. It includes notable researchers, such as X. Meng, X. Ma, Y. Liu, X. Zhang and B. Zhao, who play a pivotal role. Their tendency to cite overlapping references indicates a significant degree of collaboration or a shared emphasis on particular research themes. This cluster likely embodies a leading subfield, possibly concentrating on experimental and computational investigations in disciplines such as engineering, physics or materials science. The robust interconnections among these authors may reflect a well-established research domain where fundamental theories and methodologies are routinely considered and further developed.

The green cluster constitutes a notable and distinct domain of research, with key contributors including K. Farhang, T. Tian, Q. Zhang and W. Wang. This cluster exhibits a moderate degree of connectivity to the red cluster, indicating a relationship between the two, albeit with separate research focuses. The moderate linkage suggests that while there is some shared literature between the clusters, the specific research themes may diverge significantly. Research within the green cluster focuses on theoretical modelling or practical applications in materials science and mechanical engineering. The authors associated with this cluster investigated topics such as friction, wear, lubrication and material characteristics or utilised mathematical models to enhance the understanding of tribological systems.

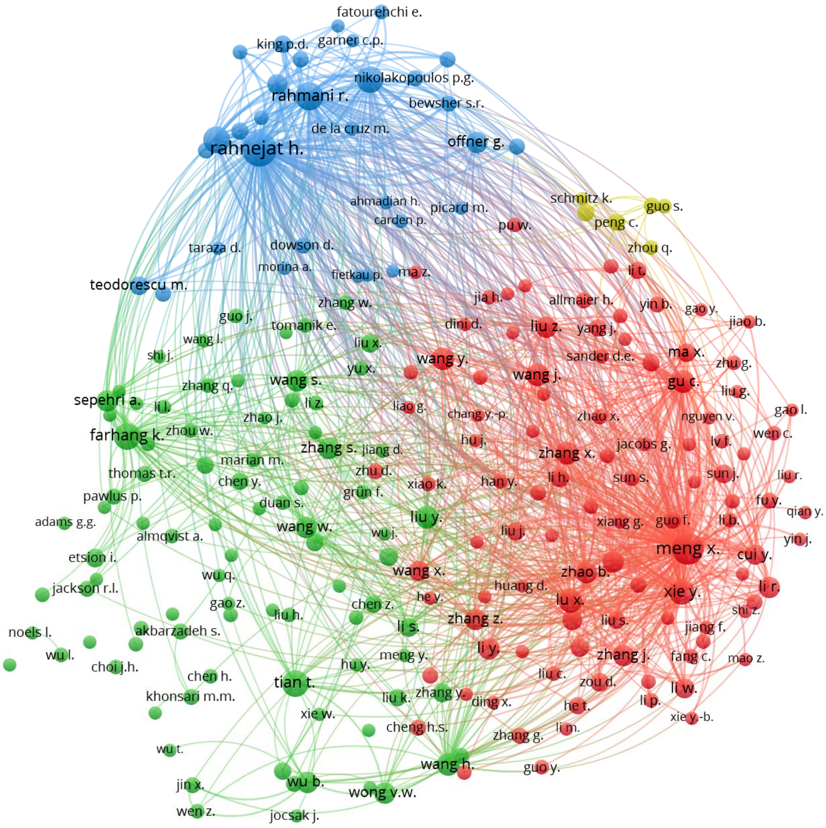

Figure 9. Visualisation of the bibliographic coupling network, elucidating the relationships among authors; the size of each node reflects the number of publications, while the connections between nodes indicate the intensity of co-citation among authors; different colours denote various research areas or communities within the discipline

The blue cluster is characterised by a smaller yet densely populated group of researchers, such as H. Rahnejat, R. Rahmani, G. Offner, D. Dowson and M. Teodorescu. This cluster is somewhat distinct from the red and green ones, indicating a more focused area of research. The degree of isolation noticed suggests that although there may be some overlap with other research topics, the primary concentration of this cluster is on a specific niche within the broader research domain.

The blue cluster is likely engaged in research related to computational mechanics, numerical simulations or advanced lubrication models. These areas typically involve the application of computational methods to model complex systems or analyse fluid dynamics in mechanical engineering with implications on material science and engineering design.

The yellow minicluster consists of a small yet essential group of researchers, including S. Guo, C. Peng, K. Schmitz and Q. Zhou. This group serves as an interdisciplinary connector between the larger and more distinct red and blue clusters. Their research overlaps with both clusters, indicating a potential integration of knowledge across multiple disciplines. This cluster's focus involves the combination of experimental and theoretical techniques by employing computational models to validate experimental outcomes or utilising empirical data to refine theoretical models. Additionally, their work features cross-disciplinary applications, where insights from one field, such as computational mechanics, are applied to another. This bridging feature underscores the critical role of these researchers in promoting knowledge over various research domains. Authors Y. Wang and S. Guo appear near the intersection of multiple clusters, suggesting that they are working across disciplines, possibly integrating computational methods with experimental research. Authors with fewer connections (small nodes) are likely working on specialised topics or topics newer to the field. These researchers may introduce novel ideas that could later become central ones.

6. Summary and conclusion

In this contribution, the huge potential within the bibliometric analysis has been exploited to understand the relatively late and overwhelming success of the GT model when dealing with mixed and boundary lubrication regimes. For this, more than 1500 documents, published in the last 55 years and available online, related by Scopus to the GT model have been studied.

The visualisation tools considered in this bibliometric analysis yielded various network maps, e.g. those of the keywords defined by the authors. Inspecting these network maps closely, especially those containing the co-occurrences and overlay of the keywords, it has evidenced that the nowadays noticed renaissance of the GT model is primarily thanks to its application towards estimating the frictional losses in internal combustion engines, and there as happens within tribological system build-up by the ring and cylinder liner.

Acknowledgement

This work was carried out as part of the COMET Centre InTribology (FFG no. 906860), a project of the "Excellence Centre for Tribology" (AC2T research GmbH). InTribology is funded within the COMET – Competence Centres for Excellent Technologies Programme by the federal ministries BMK and BMAW as well as the federal states of Niederösterreich and Vorarlberg based on financial support from the project partners involved. COMET is managed by The Austrian Research Promotion Agency (FFG).

References

[1] J.A. Greenwood, J.H. Tripp, The contact of two nominally flat rough surfaces, Proceedings of the Institution of Mechanical Engineers, Vol. 185, No. 1, 1970, pp. 625-633, DOI: 10.1243/PIME_PROC_1970_185_069_02

[2] R.I. Taylor, Rough surface contact modelling – A review, Lubricants, Vol. 10. No. 5, 2022, Paper 98, DOI: 10.3390/lubricants10050098

[3] H. Jia, J. Li, J. Wang, K. Xiao, Y. Han, A lubricated wear model for determining wear surface geometry on journal-bearing surfaces, Surface Topography: Metrology and Properties, Vol. 8, No. 3, 2020, Paper 035002, DOI: 10.1088/2051-672X/ab9fd2

[4] R.E. Jones, A Greenwood-Williamson model of small-scale friction, Journal of Applied Mechanics, Vol. 74, No. 1, 2007, pp. 31-40, DOI: 10.1115/1.2172269

[5] M.H. Müser, W.B. Dapp, R. Bugnicourt, P. Sainsot, N. Lesaffre, T.A. Lubrecht, B.N.J. Persson, K. Harris, A. Bennett, K. Schulze, S. Rohde, P. Ifju, W.G. Sawyer, T. Angelini, H.A. Esfahani, M. Kadkhodaei, S. Akbarzadeh, J.-J. Wu, G. Vorlaufer, A. Vernes, S. Solhjoo, A.I. Vakis, R.L. Jackson, Y. Xu, J. Streator, A. Rostami, D. Dini, S. Medina, G. Carbone, F. Bottiglione, L. Afferrante, J. Monti, L. Pastewka, M.O. Robbins, J.A. Greenwood, Meeting the contact-mechanics challenge, Tribology Letters, Vol. 65, No. 4, 2017, Paper 118, DOI: 10.1007/s11249-017-0900-2

[6] M. Ciavarella, V. Delfine, G. Demelio, A "re-vitalized" Greenwood and Williamson model of elastic contact between fractal surfaces, Journal of the Mechanics and Physics of Solids, Vol. 54, No. 12, 2006, pp. 2569-2591, DOI: 10.1016/j.jmps.2006.05.006

[7] F. König, C. Sous, G. Jacobs, Numerical prediction of the frictional losses in sliding bearings during start-stop operation, Friction, Vol. 9, No. 3, 2021, pp. 583-597, DOI: 10.1007/s40544-020-0417-9

[8] A. Vencl, N.M. Vaxevanidis, M. Kandeva, A bibliometric analysis of scientific research on tribology of composites in Southeastern Europe, IOP Conference Series: Materials Science and Engineering, Vol. 724, 2020, Paper 012012, DOI: 10.1088/1757-899X/724/1/012012

[9] R. Kumar, Bibliometric analysis: Comprehensive insights into tools, techniques, applications, and solutions for research excellence, Spectrum of Engineering and Management Sciences, Vol. 3, No. 1, 2025, pp. 45-62, DOI: DOI: 10.31181/sems31202535k

[10] E. Garfield, Citation Indexing – Its Theory and Application in Science, Technology, and Humanities, John Wiley & Sons, New York, 1979.

[11] J.E. Hirsch, An index to quantify an individual's scientific research output, Proceedings of the National Academy of Sciences, Vol. 102, No. 46, 2005, pp. 16569-16572, DOI: 10.1073/pnas.0507655102

[12] E. Garfield, The history and meaning of the journal impact factor, JAMA, Vol. 295, No. 1, 2006, pp. 90-93, DOI: 10.1001/jama.295.1.90

[13] H.F. Moed, Measuring contextual citation impact of scientific journals, Journal of Informetrics, Vol. 4, No. 3, 2010, pp. 265-277, DOI: 10.1016/j.joi.2010.01.002

[14] L. Leydesdorff, The Challenge of Scientometrics, Universal Publishers, Irvine, 2001.

[15] K. Börner, C. Chen, K.W. Boyack, Visualizing knowledge domains, Annual Review of Information Science and Technology, Vol. 37, No. 1, 2003, pp. 179-255, DOI: 10.1002/aris.1440370106

[16] I. Passas, Bibliometric analysis: The main steps, Encyclopedia, Vol. 4, No. 2, 2024, pp. 1014-1025, DOI: 10.3390/encyclopedia4020065

[17] L. Egghe, R. Rousseau, Introduction to Informetrics, Elsevier Science Publishers, Amsterdam, 1990.

[18] H. Small, Co-citation in the scientific literature: A new measure of the relationship between two documents, Journal of the American Society for Information Science, Vol. 24, No. 4, 1973, pp. 265-269, DOI: 10.1002/asi.4630240406

[19] M.M. Kessler, Bibliographic coupling between scientific papers, American Documentation, Vol. 14, No. 1, 1963, pp. 10-25, DOI: 10.1002/asi.5090140103

[20] N.J. van Eck. L. Waltman, Software survey: VOSviewer, a computer program for bibliometric mapping, Scientometrics, Vol. 84, No. 2, 2010, pp. 523-538, DOI: 10.1007/s11192-009-0146-3

[21] C. Chen, CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature, Journal of the American Society for Information Science and Technology, Vol. 57, No. 3, 2006, pp. 359-377, DOI: 10.1002/asi.20317

[22] J. Webster, R.T. Watson, Analyzing the past to prepare for the future: Writing a literature review, MIS Quarterly, Vol. 26, No. 2, 2002, pp. 13-23.

[23] N. Donthu, S. Kumar, D. Mukherjee, N. Pandey, W.M. Lim, How to conduct a bibliometric analysis: An overview and guidelines, Journal of Business Research, Vol. 133, 2021, pp. 285-296, DOI: 10.1016/j.jbusres.2021.04.070

[24] A. Vernes, S. Eder, G. Vorlaufer, G. Betz, On the three-term kinetic friction law in nanotribological systems, Faraday Discussions, Vol. 156, 2012, pp. 173-196, DOI: 10.1039/C2FD00120A

[25] B. Derjaguin, Molekulartheorie der äußeren Reibung [Molecular theory of external friction], Zeitschrift für Physik, Vol. 88, No. 9-10, 1934, pp. 661-675, DOI: 10.1007/BF01333114 [in German].

[26] M. Amontons, De la resistance causée dans les machines [On the resistance caused in machines], Mémoires de l'Académie Royale des Sciences, 1699, pp. 206-227 [in French].

[27] C.A. Coulomb, Théorie des machines simples [Theory of simple machines], Mémoires de Mathématique et de Physique, Vol. 10, 1785, pp. 161-332 [in French].

[28] F.P. Bowden, D. Tabor, The Friction and Lubrication of Solids, Oxford University Press, Oxford, 2001, DOI: 10.1093/oso/9780198507772.001.0001

[29] S. Eder, A. Vernes, G. Vorlaufer, G. Betz, Molecular dynamics simulations of mixed lubrication with smooth particle post-processing, Journal of Physics: Condensed Matter, Vol. 23, No. 17, 2011, Paper 175004, DOI: 10.1088/0953-8984/23/17/175004

[30] S. Eder, A. Vernes, G. Betz, Methods and numerical aspects of nanoscopic contact area estimation in atomistic tribological simulations, Computer Physics Communications, Vol. 185, No. 1, 2014, pp. 217-228, DOI: 10.1016/j.cpc.2013.09.021

[31] M. Wolloch, G. Feldbauer, P. Mohn, J. Redinger, A. Vernes, Ab initio calculation of the real contact area on the atomic scale, Physical Review B, Vol. 91, No. 19, 2015, Paper 195436, DOI: 10.1103/PhysRevB.91.195436

[32] S.J. Eder, A. Vernes, G. Betz, On the Derjaguin offset in boundary-lubricated nanotribological systems, Langmuir, Vol. 29, No. 45, 2013, pp. 13760-13772, DOI: 10.1021/la4026443

[33] S.J. Eder, G. Feldbauer, D. Bianchi, U. Cihak-Bayr, G. Betz, A. Vernes, Applicability of macroscopic wear and friction laws on the atomic length scale, Physical Review Letters, Vol. 115, No. 2, 2015, Paper 025502, DOI: 10.1103/PhysRevLett.115.025502

[34] J.A. Greenwood, J.B.P. Williamson, Contact of nominally flat surfaces, Proceedings of the Royal Society of London A, Vol. 295, No. 1442, 1966, pp. 300-3019, DOI: 10.1098/rspa.1966.0242

[35] Scopus, available at: https://www.scopus.com, accessed: 11.12.2024.

[36] J. Ruiz-Rosero, G. Ramirez-Gonzalez, J. Viveros-Delgado, Software survey: ScientoPy, a scientometric tool for topics trend analysis in scientific publications, Scientometrics, Vol. 121, No. 2, 2019, pp. 1165-1188, DOI: 10.1007/s11192-019-03213-w

[37] V. Pereira, M.P. Basilio, C.H.T. Santos, PyBibX – A Python library for bibliometric and scientometric analysis powered with artificial intelligence tools, Data Technologies and Applications, Vol. 59, No. 2, 2023, pp. 302-337, DOI: 10.1108/DTA-08-2023-0461

[38] M. Aria, C. Cuccurullo, *Bibliometrix*: An R-tool for comprehensive science mapping analysis, Journal of Informetrics, Vol. 11, No. 4, 2017, pp. 959-975, DOI: 10.1016/j.joi.2017.08.007

[39] S. Büyükkıdık, A bibliometric analysis: A tutorial for the bibliometrix package in R using IRT literature, Journal of Measurement and Evaluation in Education and Psychology, Vol. 13, No. 3, 2022, pp. 164-193, DOI: 10.21031/epod.1069307

[40] Bibliometrix, available at: http://www.bibliometrix.org, accessed: 13.01.2025.

[41] N.J. van Eck, L. Waltman, Generalizing the *h*- and *g*-indices, Journal of Informetrics, Vol. 2, No. 4, 2008, pp. 263-271, DOI: 10.1016/j.joi.2008.09.004

[42] N.M. Vaxevanidis, A. Vencl, P. Psyllaki, Research on tribology in Southeastern Europe: A bibliometric study, FME Transactions, Vol. 43, No. 3, 2015, pp. 259-268, DOI: 10.5937/fmet1503259V

[43] VOSviewer, available at: https://www.vosviewer.com, accessed: 20.01.2025.

[44] C. Bota-Avram, Bibliometric analysis of sustainable business performance: Where are we going? A science map of the field, Economic Research-Ekonomska istraživanja, Vol. 36, No. 1, 2023, pp. 2137-2176, DOI: 10.1080/1331677X.2022.2096094

[45] T. Tian, Dynamic behaviours of piston rings and their practical impact. Part 1: Ring flutter and ring collapse and their effects on gas flow and oil transport, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 216, No. 4, 2002, pp. 209-228, DOI: 10.1243/135065002760199961

[46] T. Tian, Dynamic behaviours of piston rings and their practical impact. Part 2: Oil transport, friction and wear of ring/liner interface and the effects of piston and ring dynamics, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 216, No. 4, 2002, pp. 229-248, DOI: 10.1243/135065002760199970

[47] T. Tian, L.B. Noordzij, V.W. Wong, J.B. Heywood, Modeling piston-ring dynamics, blowby, and ring-twist effects, Journal of Engineering for Gas Turbines and Power, Vol. 120, No. 4, 1998, pp. 843-854, DOI: 10.1115/1.2818477

[48] E.G. Giakoumis, Cylinder wall insulation effects on the first- and second-law balances of a turbocharged diesel engine operating under transient load conditions, Energy Conversion and Management, Vol. 48, No. 11, 2007, pp. 2925-2933, DOI: 10.1016/j.enconman.2007.07.013

[49] Y. Hu, H.S. Cheng, T. Arai, Y. Kobayashi, S. Aoyama, Numerical simulation of piston ring in mixed lubrication – A nonaxisymmetrical analysis, Journal of Tribology, Vol. 116, No. 3, 1994, pp. 470-478, DOI: 10.1115/1.2928867

[50] W. Wang, P.L. Wong, Z. Zhang, Partial EHL analysis of rib-roller end contact in tapered roller bearings, Tribology International, Vol. 29, No. 4, 1996, pp. 313-321, DOI: 10.1016/0301-679X(95)00059-D

[51] B. Zhao, B. Zhang, K. Zhang, Modelling three-dimensional soft elastohydrodynamic lubrication contact of heterogeneous materials, Tribology International, Vol. 129, 2019, pp. 377-389, DOI: 10.1016/j.triboint.2018.08.042

[52] Z. Zhang, J. Liu, Y. Xie, Design approach for optimization of a piston ring profile considering mixed lubrication, Friction, Vol. 4, No. 4, 2016, pp. 335-346, DOI: 10.1007/s40544-016-0130-x

[53] N. Morris, R. Rahmani, H. Rahnejat, P.D. King, B. Fitzsimons, Tribology of piston compression ring conjunction under transient thermal mixed regime of lubrication, Tribology International, Vol. 59, 2013, pp. 248-258, DOI: 10.1016/j.triboint.2012.09.002

[54] D. Zhu, H.S. Cheng, T. Arai, K. Hamai, A numerical analysis for piston skirts in mixed lubrication – Part I: Basic modeling, Journal of Tribology, Vol. 114, No. 3, 1992, pp. 553-562, DOI: 10.1115/1.2920917

[55] M. Priest, D. Dowson, C.M. Taylor, Theoretical modelling of cavitation in piston ring lubrication, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol. 214, No. 3, 2000, pp. 435-447, DOI: 10.1243/0954406001523092

[56] B. Bhushan, Contact mechanics of rough surfaces in tribology: Multiple asperity contact, Tribology Letters, Vol. 4, No. 1, 1998, pp. 1-35, DOI: 10.1023/A:1019186601445

[57] F.P. Bowden, D. Tabor, The area of contact between stationary and moving surfaces, Proceedings of the Royal Society of London A, Vol. 169, No. 938, 1939, pp. 391-413, DOI: 10.1098/rspa.1939.0005

[58] J.A. Greenwood, J.J. Wu, Surface roughness and contact: An apology, Meccanica, Vol. 36, No. 6, 2001, pp. 617-630, DOI: 10.1023/A:1016340601964

[59] Y. Morag, I. Etsion, Resolving the contradiction of asperities plastic to elastic mode transition in current contact models of fractal rough surfaces, Wear, Vol. 262, No. 5-6, 2007, pp. 624-629, DOI: 10.1016/j.wear.2006.07.007

[60] Y.S. Muzychka, M.M. Yovanovich, Thermal Spreading and Contact Resistance: Fundamentals and Applications, John Wiley & Sons, 2023, DOI: 10.1002/9781394187560

[61] W.F. Brace, J.D. Byerlee, Stick-slip as a mechanism for earthquakes, Science, Vol. 153, No. 3739, 1966, pp. 990-992, DOI: 10.1126/science.153.3739.990

[62] J.C. Jaeger, The frictional properties of joints in rock, Geofisica pura e applicata, Vol. 43, 1959, pp. 148-158, DOI: 10.1007/BF01993552