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Exploring the Future Development of Research, Technology and Business of Machine Tool Domain in new-generation information technology environment based on Machine Learning

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Abstract: The combination of new-generation information technology and manufacturing technology has resulted in major and profound impact on future development paradigm of manufacturing. It is challenging for existing methods to conduct a multidimensional trend exploration related to machine tool domain, which is the basis of virtually everything in manufacturing. In this paper, we proposed an integrating approach framework combined topic models, bibliometric, trend analysis and patent analysis to mine insightful information about future development from multi-source data related to machine tool, such as papers, grants, patents and news. Specifically, papers and grants provided two different perspectives to explore the current focuses and future trends in machine tool research. Furthermore, the future technology development of machine tool was investigated through patents analysis. Finally, news related to machine tool industry in recent years was analyzed to analyze future machine tool business mode. The integration of the above various analytical methods and the multi-dimensional mining of literatures enabled the analysis of the future development of machine tool domain systematically from multi-perspectives which include research, technology development and industry. The conclusions obtained in this paper is beneficial to different communities of machine tool in terms of determining the research directions for researchers, identifying industry opportunities for corporations and developing reasonable industry policy for policy makers.

Keywords: future development analysis; machine tool; machine learning; multi-source data; topic model

1. Introduction

The explosive growth of the new-generation information technology and the deep integration with manufacturing technology have formed the main driving forces of the new round industrial revolution, which is triggering major and profound changes in the manufacturing technical systems, development paths and industry modes [1-3]. The machine tool is the ubiquitous instruments in manufacturing industry and virtually everything in industries is manufactured on the basis of the Machine tool [4]. As machine tool plays a unique role in industry, machine tool technology is bound to become the essential part to the change of manufacturing in the condition of new-generation information technology and thus support the sustainable development of manufacturing further [5]. As a support and symbol of manufacturing paradigm change, exploring the development trend of machine tool is of great significance to identify and grasp the opportunity to develop manufacturing industry for a variety of communities.

The development of specific technology domain depends on the synergy of intrinsic characteristics of technology and external factors. Through the analysis, we conclude that machine tool discipline possesses the following two complex characteristics.

1) Complex inherent heterogeneous nature of machine tool technology. The reason lies in machine tool technology belongs to an interdisciplinary categorization whose technical category covers various fields such as mechanics, hydraulics, control, materials, microelectronics and information technology. Complex interactions and effects exist in various related technical fields, presenting complex intrinsic heterogeneity [6].

2) The dimension complexity of development caused by the deep integration of the new-generation information technology and machine tool technology. The cross-integration of the new-generation information technology and machine tool domain runs through all aspects of research, management, service and other technical activities. It is noting that conducting a simple analysis of a certain dimension of technical activities is difficult to clarify the future evolution in machine tool field comprehensively [7].

The two complexities summarized above make it a challenging task to analyze the development trend of the machine tool field.

Many research have been employed to explore the development trend of machine tool discipline. Raju et al. carried out an qualitative literature study to describe research focus and current trends on Micro Electro-Discharge Machining, including its requirements, performance and applications [8]. In addition, there exists other similar literature reviews carried out to explore the current states and trends of specific subcategory of machine tools [9, 10]. The characteristic of these studies are based on the accumulated expert's experience to qualitative review the papers related to a specific sub-technology of machine tools and analyze its development trend. With the change of information environment in machine tool domain recently, some other researches aimed at exploring future development trend of machine tool technology overall which also depended on qualitative analysis [5]. Based on expert domain experience, these works provided valuable insights to some extent for guiding the future development of technology. However, it is difficult to explore a large number of related papers by reading them because of the enormous time and energy required and the difficulties in comprehending topics in heterogeneous areas [11]. The above qualitative analysis method is incapable of keeping up with the rapid increase number of papers comprehensively in the whole machine tool discipline. In addition, it is challenging for conventional qualitative review method to tackle the complex inherent heterogeneous of machine tool technology. Moreover, the above qualitative works are based solely on the literature review of the papers of specific machine tool technology or the analysis based on expert experience, but failed to conduct multi-dimensional collaborative exploration from various aspects of as research, technology development and business mode. As a result, the conclusion of the review analysis is easy to generate knowledge solidification and make predictions along the existing technical paradigm, which may lead to the neglect of emerging trends under the new technology development paradigm [12, 13].

Scientific literatures have been considered as a valuable and rich source of knowledge or a key proxy about technology development, reflecting the current technological focuses in their respective disciplines and the trend of technology development in both theory and practice [14, 15]. Bibliometric or patent analysis method have been widely employed by many researchers to analyze scientific literatures quantitatively, which was regarded as a more systematic, objective, and effective method compared to qualitative literature review approach to explore the evolution trend of specific discipline [16-19]. For example Ernst analyzed the patent data in the machine tool industry to explore the future development trend of CNC technology [20]. Attempts to quantitative analysis of the development of domain by methods such as bibliometric can help to solve the limitations of objectivity and comprehensiveness of qualitative review method to some extent [21, 22]. However, these works ignored the multi-dimensional analysis of multi-source literatures related to specific domain [23]. To solve the limitation in above traditional quantitative analysis works, more and more researchers have focused on the integration of multi-source data to conduct the task of technology trend exploration [24, 25]. The combination of multi-source technology data contributes to incorporate more information to carry out a more comprehensive analysis of technology evolution. However, these studies lack the semantic analysis of the content of scientific literatures and make it difficult to dig into the content of the literatures to explore the evolution trend of technology [15]. In light of the fact that literatures can enable us to obtain the solutions to specific problems and learn the creation of new ideas, a large amount of information reflecting the technological development trend exist in the content of scientific literatures. Implementing detailed mining of literatures content can help us obtain deeper insight into technology development [11]. To effectively process and analyze the content of scientific literatures, machine learning method based on topic models have been proposed and widely used in technical foresight tasks in recent years [26-32]. The topic models in above works can be employed to mine a large number of literature contents to obtain latent intellectual structures of technological focuses related with a specific technology domain, which can model the complex inherent heterogeneous technology structures. The limitation of existing technology forecasting works based on topic models is to choose only papers for analysis and lack multi-dimensional data association and integration to explore future evolution of technology.

To investigate the development of machine tool discipline, we proposed an integrated approach framework in this paper. The proposed framework combined machine learning, trend analysis, patent analysis and bibliometric to analyze multi-source literatures related to machine tool systematically, including papers, funds, patents and news. What's more, the integrated framework proposed in this paper could analyze the future evolution of machine tool domain from the multi-view perspectives of research, technology development and business mode. Concretely, machine learning method based on topic models were applied to obtain existing intellectual structures of research focuses within machine tool domain. Trend analysis method models dynamic evolution over time for the extracted research focuses to predict future research trends. Science grants is an important dimension reflecting research activity and bibliometric is used to analyze the NSF grants of machine tool as a complement to machine tool papers analysis. Based on the analysis of the above research perspective, the proposed approach used patent analysis methods, including patent development trajectories and institutional cooperation networks to analyze patents to explore the technology development of machine tool. Finally, topic model extracted the latent intellectual structures from the latest news contents related to machine tool business to model the business modes focuses of machine tool industry. As a result, the framework proposed by us can carry out multi-dimensional and semantic analysis of multi-source data and explore the development of machine tool from multi-layered perspective.

The rest of this paper is organized as follows: Section 2 reviews the related researches. Section 3 presents the main framework proposed and the data applied for subsequent analysis. Section 4 discusses the experiments and discussions, and finally Section 5 concludes this paper.

2. Related Work

Although much attention has been paid to explore future development trend of specific technology, existing methods are limited in terms of taking the whole ecosystem of technology domain into consideration when analyzing the evolution of domain. In this section, we review recent progress on the task of technology trend analysis and give a brief summary.

2.1 Trend analysis of machine tool

Recently, machine tool domain has been given new connotations and entered a new stage of development [7]. Many researchers adopted qualitative review method of literatures to explore the evolution trend of machine tool [8-10]. Tang provided a state of the art review on algorithms for collision detection and avoidance in five-axis NC machining and explored the challenges that needed to be addressed further [33]. Lauro et al. presented a brief review of monitoring techniques and signal processing methods applied in machining processes to identify technological focus in that field [34]. Cao et al. carried out an in-depth review of the state-of-the-art progress of intelligent spindles and

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prospected future trends of technology [35]. In addition, similar works include qualitative review of papers literatures of specific technology such as spindle thermal error compensation, reliability analysis and reconfigurable machine tools to identify technological focuses and explore future trends of specific technology [36-38]. The characteristics of these studies are based on the expert's experience to conduct an in-depth qualitative review for papers related to a sub-technology of machine tools and analyze the current progress and future trend of the technology. However, given the limited research scope and energy of single expert it is difficult to analyze a large number of related documents by reading them. As a result, the above literature review method is incapable of keeping up with the rapid increase number of papers comprehensively in the whole machine tool discipline and makes it hard to analyze and track the future development of machine tool systematically. In addition, the application of qualitative review method based on papers above is difficult to generalize to a comprehensive analysis of the future development of the entire machine tool domain.

Some other researches aimed to study future development trend of the entire machine tool field [4, 7, 39]. For example, Liu et al. proposed a new generation of machine tool, i.e. Cyber-Physical Machine Tool as a future development trend of machine tools technology [5]. However, these works depended only on the experience of experts to explore the future development of machine tool. The conclusions are easy to generate knowledge solidification and make predictions along the existing technical paradigm, resulting in their objectivity, consistency and validity is limited [12, 13]. In particular, the impact of the new-generation information technology on machine tool field runs through the entire technology cycle and it is essential to carry out multi-dimensional analysis of research, technology development and business to clarify the current and future development of machine tool. The existing works lack a multi-layer analysis of machine tool technical activities.

2.2 Bibliometric and patent analysis for technology forecasting

Compared with qualitative review method, based on available abundant scientific literatures the use of quantitative analysis method can provide objective information to explore technology future development [19, 40]. Many researchers have adopted bibliometrics or patent analysis method to investigate future evolution of technology [17, 40]. Marzi et al. presented a bibliometrics analysis to discuss product and process innovation in the manufacturing and provided insights about future research avenues in the manufacturing field [16]. Ernst analyzed the patent data in the machine tool industry to explore the future development trend of CNC technology [20]. The quantitative analysis method helps to relieve the limitations of the objectivity and validity of the qualitative review method to a certain extent [21, 22]. However, existing works only analyze a single data dimension (papers or patents) and ignore to conduct collaborative analysis of multi-source data, such as papers, patents, funds, and news, to explore the future development of technology from a more comprehensive perspective. Multi-dimensional data maps all aspects of technical activities, including richer information on domain development. Recently, more and more works focused on the integration of multi-source literature data to conduct technology trend analysis [25]. Wang et al. carried out a review and emerging technology forecast in nanogenerator using integrating methods to analyze papers and patents literature [24]. Xu et al. conducted a method to explore the innovation capacities of a multi-layered innovation ecosystem, merging publication data, patent data and business data [41]. Multi-source data integration enables analyzing the development trend of technology domain more objectively. However, no work attempts to analyze the multi-source literature data in the machine tool to explore the its future development. Moreover, It is noting that the existing quantitative analysis works of multi-source data used for technology forecasting consider limited information and lack of in-depth semantic analysis of the content of scientific literatures [15].

2.3 Machine learning method in emerging technologies analysis

The content of the scientific literature contains abundant information and knowledge reflecting the technology concerns and future development trends. Further exploration and understanding of the literature contents will help us gain insights into the future evolution of technology [30]. To deeply analyze the contents of scientific literatures, machine learning method based on topic models

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has been widely used in technology trend analysis tasks in recent years [26-29, 32].Yang et al. explored the research trending topics of smart factories using topic modeling method to determine the future research directions [11]. Abuhay et al. modeled the underlying topical structures of the International Conference on Computational Science and provided insights regarding the past and future technology trends in computational science [31]. In these works, topic models mined a large number of literature contents to obtain latent intellectual structures of technological focuses related with a specific technology domain which could be used subsequent technology forecasting task. To the best of our knowledge, no research has been done applying topic models to perform a large-scale and systematic research of scientific literatures related to Machine Tool. In addition, there exists obvious limitation in these existing works. Specifically, the above works take only a single data dimension into consideration for analysis and lack the association and integration of multi-dimensional data, making it difficult to collaboratively explore the technology domain future evolution from the multi-perspective of research, technology development and business.

Compared with qualitative literature review method, quantitative methods can improve objectivity and validity of analysis results. Moreover, the integration of multi-source literatures can more comprehensively analyze the development trends of the technical domain. Furthermore, the topic model can conduct semantic analysis for the contents of the literatures to model complex inherent heterogeneous of the technology. Based on the above analysis and in light of the complex characteristics of the machine tool domain, in this paper we proposed an integration framework combining machine learning method and other data mining approaches to analyze multi-source literature data related to machine tool domain and explore the future trend of this domain from multi-perspective including research, technology development and business dynamics.

3. Method and Data

In this section, we will discuss the proposed framework and literature data for analysis in this paper. Specifically, in section 3.1 we will first discuss the research framework to explore the future development of machine tool domain from multiple-dimension perspectives. Then in Section 3.2, we will discuss the multi-source literature data acquisition in machine tool. Finally, In Section 3.3 we will detail discuss topic model which is core component in the proposed framework.

3.1 Method Framework

Given the fact that it is critical to identify and grasp the opportunity to develop machine tool, the future development of the machine tool field is an important question to be solved. In light of the emerging information technologies penetrate into all aspects of machine tool domain, the above problem can be broken down into the following three sub-problems. First, what new changes will occur in machine tool research in the future under the influence of the new-generation information technology? Second, what impact will emerging information technology have on technology development of machine tool? And third, what emerging business modes emerge in machine tool industry. In order to solve above problems, this paper developed an approach framework as shown in figure 1. The proposed framework is based on the integration of four methods, including topic model, trend analysis, patent analysis and bibliometric.

This framework explored the future development of research, technology and business in machine tool discipline by analyzing multi-source data related to machine tool. Specifically, we mainly select literature of papers to analyze the research evolution of machine tool as papers is a source of knowledge that maps specific discipline research activities and contains abundant information that reflects current development and future trend of that discipline [15]. The papers reflect the output of the research activity, while the grants reflect the input of the research. Compared with papers, the literature of grants contains some additional information on the people, inputs and processes of science activity [42]. We choose the literature of grants related with machine tool to conduct an auxiliary analysis for the research evolution. The literature of patents is a mapping of technology development in a specific domain. For this reason, the patents have been considered as a source of fruitful knowledge to identify technology development in practical applications [43]. We

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choose patents to investigate the new changes of technology development of machine tool. Given the fact that the Google searches news publications written to reflect the business and market, we apply the Google news related with machine tool industry to analyze the new changes of business modes of this industry [44]. Data collection methods and pre-processing steps will be discussed in section 3.2.

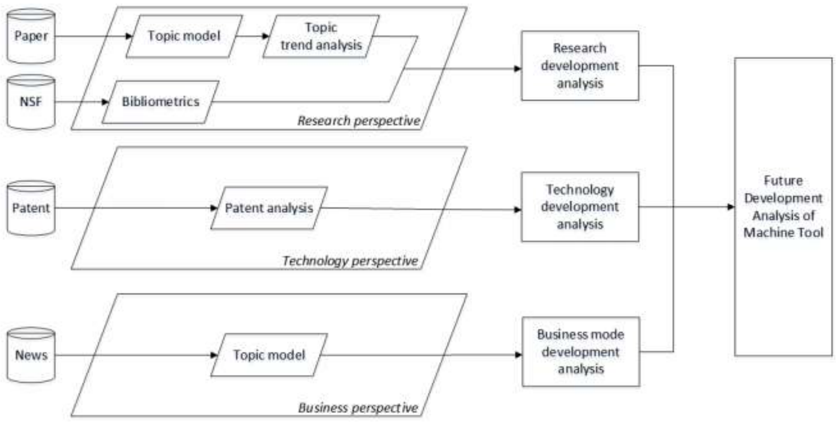

Figure 1. Future Development analytical framework of machine tool

The integrated framework proposed above is used to analyze the multi-source literatures data of machine tool. In order to analyze the research development of machine tool, topic model is used for mining latent intellectual structures of research concerns from literature of papers. Then based on topic strength development through time of modeled research focuses, we conduct trend analysis by the way of Mann-Kendall test method and predict development trend of research focuses [45]. As a useful supplement to the literature of papers, a simple bibliometric analysis of grants is carried out as an auxiliary perspective to explore the research development of machine tool. Furthermore, patent analysis methods (including Patent growth trajectory and institutional cooperation network) are applied to analyze the technology development of machine tool. Patent growth trajectory can reflect the state of technological development very well [46]. Finally, in order to clarify the problem of the change of the machine tool business mode, topic model is used to mine the latent intellectual topics of business focuses from the collected news. The advantage of the approach framework proposed is that it can integrate semantics, time dynamics and the fusion of multi-dimensional data to carry out multi-perspective evolution analysis of machine tool domain in complex environment. The main machine learning method involved in our framework will be discussed in Section 3.3 below.

3.2 Data collection

In this study, we selected papers, funds, patents, and news related to machine tool domain to analyze its development. This section will discuss in detail the acquisition method and pre-processing steps of data used for analysis.

Papers data used in this paper were searched from Science Citation Index Expanded(SCI-EXPANDED) and Social Sciences Citation Index(SSCI) databases on the Web of Science, which are the most authoritative scientific and technical literature indexing tool [47]. The search time range of SCI-EXPANDED database was set from 1997-2018 as SCI-EXPANDED did not contain data before the year of 1997. For the same reason, the search time range of SSCI database was set from 2000-2018. In addition, in order to ensure the quality of the retrieved data and facilitate subsequent analysis, at the time of retrieval we restricted results by English language and set document type as Article. Based on above settings, we searched papers literatures that contained terms such as "Machin* tool*", “machin* center*”, “milling center*” and "NC machin*" et al. as the raw data. The raw papers collected included the title, abstract, author, publication year, source and other field information. Because the abstract is a compact representation of a paper, we chose the exported abstract field to represent a paper for subsequent analysis. The raw text content of abstract field contains a lot of noise

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information that hinders subsequent data mining analysis. We performed the pre-processing steps listed in Table 1 below to remove the noise information. Among which, NLTK stop words list is a commonly used stop word list in natural language processing, including a, the, of, for, etc., which do not contain valuable information to comprehend the future development of technology. The CNC machine tool domain stop words list refers to the stop word list specific to the machine tool, including words such as abstract, paper, experiment, method, etc., which also do not contain useful information for exploring the development of domain. After pre-processing steps, we collected 7832 papers to constitute the final paper dataset of machine tools for analysis experiments.

Table 1. pre-processing steps

Step	Description
1	Remove repeat document
2	Remove stop words from NLTK stop words list
3	Remove stop words from CNC machine tool field stop words list
4	Remove low and high frequency words
5	Remove abstract whose length less than 20

For grants related with research, we extracted from the National Science Foundation (NSF) award database. NSF is a federal funding agency and searching the NSF award database allows for retrieval the whole awards issued by the NSF [42]. In this paper, we used the keywords "Machin* tool*", “machin* center*”, “milling center*” and "NC machin*" et al. to retrieve fund data related with machine tool and time range is set from 1984 to 2019. Then 675 awards were retrieved from the NSF award database. As for patent data analyzed in this paper, we built a unique patent database on machine tool from Derwent World Patents Index database with time range from 1997 to 2018. We searched the patents belonging to the two IPC classification numbers B23 and G05B001918. The specific retrieve keywords are given in the section 4.2. The reason for selecting these two IPC classification numbers is that the B23 classification number indexes patents within machine tool, and G05B001918 indexes the patents related to the numerical control system. Finally, we obtained 10090 patents for subsequent experiment analysis and we also chose the patent abstract information as a proxy for the patent text. As for the news related to machine tool business, we selected the keywords "business model", "market trend", "future trend" OR "new mode" et al. within the range of machine tool represented by the keywords of "Machin* tool*", “machin* center*”, “milling center*” and "NC machin*" to retrieve relevant news data from Google search with time range from 2015 to 2019. Then we used the crawler tool to crawl the search results from Google Chrome. The acquired news dataset was used for subsequent data analysis tasks after the pre-processing steps shown in Table 1. After removing the noise data, the final 1120 news were obtained. The various multi-source data information related to machine tool field is summarized in Table 2.

Table 2. Information summary of multi-source data related with machine tool

Dataset	Source	Number
Papers	Web of Science	7832
Grants	NSF award database	675
Patents	Derwent World Patents Index database	10090
News	Google News	1120

3.3 Topic Model

Given a document corpus, the purpose of topic model is to allow users to explore the hidden intellectual structures behind the corpus in the form of topics. Latent Dirichlet Allocation (LDA) has been widely used for inferring latent topics from document collections based on the basic assumptions that each topic is represented as a multinomial distribution over a vocabulary and each document is represented as a multinomial distribution over these topics [26]. In this paper we use LDA to extract research and industry focuses from document corpus related to machine tool. In this

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section we discuss the principles of LDA in detail. The notations and their corresponding meanings used in this paper are summarized in table 3.

The graph model of LDA is shown in figure 2. Given a document collection containing M documents, the dictionary generated by this collection consists of V different words. We assume the number of latent topics contained in this collection is K.

Table 3. Notations used in topic modeling.

Notations	Meaning
M	number of documents in the corpus
$\vec{d}$	documents in the corpus
V	number of words in the vocabulary
K	number of predefined latent topics
N_m	number of tokens in document m
m, k, n, t	index for document, topic, token in a document, years
$\vec{\theta}_m$	multinomial distribution over topics for document m
θ_m^k	proportion of topic k in document m
$\vec{z}_m$	topic labels of document m
$\vec{\varphi}_k$	multinomial distribution over words for topic k
$n_m^{(k)}$	number of tokens assigned to topic k in document m
$\neg i$	word w_i is excluded from the counting
$n_k^{(w_i)}$	number of times of word w_i assigned to topic k
I	number of iterations
n_m	number of topics in document m
n_k	number of words in topic k
α、β	parameter of Dirichlet distribution for $\vec{\theta}_m$ and $\vec{\varphi}_k$
t_m	publication year of document m
θ_k^t	proportion of topic k at year t

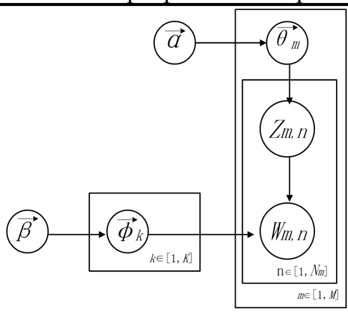

Figure 2. Graphical model of LDA

LDA is a probabilistic generative model. When generating the *mth* ($m \in [1, M]$) document in corpus, LDA samples a topic multinomial distribution $\vec{\theta}_m$ for the ducument m from a Dirichlet prior distribution with hyper-parameter $\vec{\alpha}$: $\mathrm{p}(\vec{\theta}_m|\vec{\alpha}) = Dir(\vec{\theta}_m|\vec{\alpha})$ where $\vec{\alpha}$ and $\vec{\theta}_m$ are both K dimensional vectors and the elements of $\vec{\theta}_m$ are satisfied with: $\sum_k \vec{\theta}_{m,k} = 1$, k=1,...,K. Then LDA assigns a latent topic $z_{m,n}$ for each word $w_{m,n}$ in document m ($m \in [1, M]$) based on the topic multinomial distribution $\vec{\theta}_m$ of the *mth* document. n characterizes the position of the word in document and satisfies collection $n \in [1, N_m]$ where N_m states the number of words in ducument m. Assuming all words is independent from each other in a document in LDA, for document m, the joint probability of topic assignments for all words is shown in formula 1 where $\vec{z}_m$ characterizes topic assignments for all words in *mth* document.

$$\mathrm{p}(\vec{z}_m|\vec{\theta}_m) = \prod_{n=1}^{N_m} \mathrm{p}(z_{m,n}|\vec{\theta}_m) \tag{1}$$

As discussed above the *kth* topic is assumed to be a multinomial distribution over V words in the dictionary. According to LDA, each multinomial distribution of topic $\vec{\varphi}_k$ follows a Dirichlet prior distribution with hyperparameters $\vec{\beta}$: $\mathrm{p}(\emptyset|\vec{\beta}) = Dir(\vec{\varphi}_k|\vec{\beta})$ where both $\vec{\varphi}_k$ and $\vec{\beta}$ are V

dimensional vectors, $\emptyset$ denotes a matrix with $K \times V$ dimension containing all topics' multinomial distributions. $\vec{\varphi}_{k,w}$ denotes the probability of generating word w given topic k and it satisfies $\sum_w \vec{\varphi}_{k,w} = 1$, where w=1,...,V. Then each word in document m can be generated by sampling from the corresponding multinomial distribution of latent assignment topic: $p(w_{m,n}|z = z_{m,n}) = \vec{\varphi}_{z_{m,n}}$.

Given a document collection, $w_{m,n}$ is observable variable, α and β are prior hyper-parameters. $z_{m,n}$、$\vec{\theta}_m$ and $\vec{\varphi}_{z_{m,n}}$ are hidden variables which can be estimated by the observed words in corpus. The joint distribution of all variables is as follows:

$$p(\vec{w}_m, \vec{z}_m, \vec{\theta}_m, \emptyset|\vec{\alpha}, \vec{\beta}) = \prod_{n=1}^{N_m} p(w_{m,n}|\vec{\varphi}_{z_{m,n}}) \cdot p(z_{m,n}|\vec{\theta}_m) \cdot p(\vec{\theta}_m|\vec{\alpha}) \cdot p(\emptyset|\vec{\beta}) \tag{2}$$

The hidden variables in the generative process can be approximated by applying the Gibbs Sampling method. The parameters inference method of Gibbs Sampling has been widely used in various parameters estimating problems of topic models. We can derive the conditional distribution to sample a topic z for each word of corpus in every iteration as follows:

$$p(z_i = k|\vec{z}_{\neg i}, \vec{w}) \propto \frac{n_{m,\neg i}^{(k)} + \alpha}{\sum_{k=1}^{K}(n_{m,\neg i}^{(k)} + \alpha)} \cdot \frac{n_{k,\neg i}^{(w_i)} + \beta}{\sum_{i=1}^{V}\left(n_{k,\neg i}^{(w_i)} + \beta\right)} \tag{3}$$

Figure 3 presents the abstract of a randomly selected machine tool paper and the results of the topic modeling. The selected paper discusses about cloud service mode in machine tool manufacturing. Compared with other topics, topic 174 has a much higher proportion in modeling results. It can be seen from the word distribution under topic 174 that the topic is mainly about cloud services, which demonstrates the effectiveness of topic modeling.

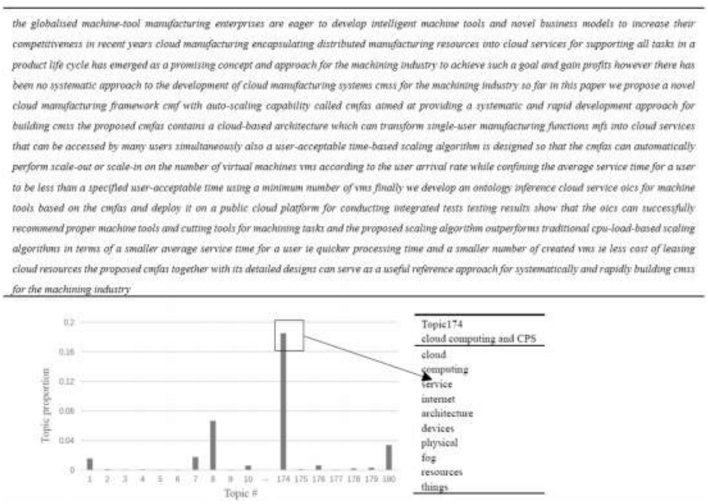

Figure 3. topic modeling result of paper abstract

4. Results and Discussions

This section presents the results of the experimental analysis and discussion. Concretely, Section 4.1 presents data mining results for papers and grants to analyze current focuses and future trends of machine tool domain under research perspective. Then, section 4.2 discusses the analysis of patents to explore the technology development of machine tool. Finally, in section 4.3 we examine the changes in the business mode of machine tool industry through the analysis of news.

4.1 Analysis to research trend of machine tool

4.1.1 Topic modeling of machine tool papers

In this section, we conducted topic modeling for papers of the machine tool domain to mine intellectual structures of research concerns. As discussed earlier, the LDA model is widely used in

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topic extraction tasks. Previous studies have shown that consider only statistical indicator to determine the hyper-parameters of the LDA may produce incoherent quality topics which constitutes the primary obstacle to acceptance of topic models in practice [48, 49]. The main reason lies in the objective function of the LDA model may not correlate well with human judgments [50]. In order to model the technical concerns in the actual machine tool research activities more accurately, we used manual inspection method to adjust the model to optimize the modeling effect and determine the hyper-parameters of LDA. Upon manual inspection, we found that 180 topics resulted in a granularity that better captures the scientific intellectuals within machine tool domain, i.e., K was set 180. As for other hyper-parameters α、β and I, we recommend setting α=0.1, β=0.01 and I=1000. Under this set of hyper-parameters setting, the LDA model works best. After completing the topic modeling of the machine tool papers, we employed manual interpretation method to check the mined research topics and removed noisy topics. The noise topic refers to a topic that does not reflect a clear technology meaning as a whole. For example, a modeled topic consists of words such as ”size”, “average”, “sample”, “factor”, “small” and “large” etc. To facilitate subsequent analysis, we removed these noise topics and finally obtained 158 topics. For reasons of display space, the overall topic modeling results of the machine tool papers are shown in table A1 in the appendix. Some of the representative results we selected are shown in Table 4 below. Every piece of intellectual structures modeled is characterized by 15 high frequency terms. Furthermore, based on prior knowledge of machine tool, we labeled each topic and mapped it to the actual machine tool research concerns, as seen in the "Meaning column" in Table A1.

Table 4. Examples of the topic modeling results of machine tool papers

Meaning	Topic	High-frequent terms
online monitoring	Topic13	sensors, monitoring, sensing, system, online, fusion, measurements, wireless, information, signals, in-process, installed, sensory, monitor, integration
tool path planning	Topic64	tool, cutter, surface, path, machining, orientation, five-axis, method, contact, paths, orientations, point, location, positioning, generate

We further give a brief analysis and explanation for the topic modeling results of machine tool papers. For example, Topic 92 is composed of terms like “vibration”, “frequency”, “amplitude”, “mode”, “resonance” and “suppression” etc., which refers to the research point of “vibration suppression”. Topic 133 consists of “component”, “structural”, “design”, “mechanical”, “performance” and “topology” etc., which reflects “structure design” of machine tool. Based on prior domain knowledge, we can know that both of above topics are sub-areas of machine tool design research. Furthermore, topic 25 (characterized by "measuring", "inspection", "coordinate", "system", "error", and "profile" etc.) refers to "profile control", which belongs to research of numerical control system category. In addition, there are many topics in the modeling results reflecting technologies related to process system in machine tool. For example, topic 64 characterizes "tool path planning" concern. Based on our domain knowledge, the latent intellectual structures obtained by topic modeling are highly correlated with the actual research activities of the machine tool. In addition, many research concerns obtained by LDA model exceed the research scope of traditional machine tools domain. Topic139 contains words like “learning”, “deep”, “algorithms”, “representations”, “convolutional” and “temporal” and refers to “deep learning” technology in artificial intelligence (AI). Deep learning is the research frontier and hot spot of current AI. The topic mining results reflect that deep learning has been applied to research exploration in the field of machine tools and has become a research focus in this field. Similar research focuses are abundant in the results of modeling like topic153 etc., indicating that external information technologies has been widely integrated with research in the machine tool domain.

4.1.2 Analysis of research development in machine tool domain

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In order to further explore the impact of the new-generation information technology on machine tool research activities, we divide the research concerns modeled in the 4.1.1 section according to the category of the machine tool domain to which it belongs, as shown in Table 5. We can classify the machine tool technology category into "Machine Tool Body and Design", "Machine Tool Components", "Numerical Control System", "Process System" and "Machine tool industry" et al., which conform to the conventions of the traditional machine tool field. In addition, the "Machine tool industry" category consists of some research concerns about the management of machine tools industry, as our paper dataset contains some SSCI papers which cover the management aspects of machine tools. In all categories, the "Process System" category and "Numerical Control System" category contains the largest number of research concerns, accounting for 34.8% and 19.0% of the total research concerns respectively. In light of our prior domain knowledge, these two categories are the focuses of research in machine tool domain.

Table 5. Categorization of machine tool research concerns

Category	Topic
Machine Tool Body and Design	Topic 3, Topic 7, Topic 9, Topic 12, Topic 26, Topic 29, Topic 37, Topic 41, Topic 44, Topic 51, Topic 56, Topic 71, Topic 76, Topic 77,Topic 80, Topic 92, Topic 102, Topic 110, Topic 133, Topic 137, Topic 143
Machine Tool Components	Topic 2, Topic 6, Topic 32, Topic 42, Topic 46, Topic 61,Topic 73, Topic 84, Topic 87, Topic 95, Topic 99, Topic 105, Topic 106, Topic 111, Topic 119, Topic 134, Topic 154
Numerical Control System	Topic 10, Topic 13,Topic 16, Topic 20, Topic 22, Topic 25, Topic 27, Topic 36, Topic 63, Topic 67, Topic 68, Topic 74, Topic 78, Topic 83, Topic 86, Topic 88, Topic 90, Topic 93, Topic 100, Topic 107, Topic 112, Topic 114, Topic 121, Topic 125, Topic 128, Topic 129, Topic 132, Topic 136, Topic 144, Topic 151
Process System	Topic 4, Topic 5, Topic 11,Topic 15, Topic 18, Topic 19,Topic 21, Topic 23, Topic 24, Topic 28, Topic 31, Topic 33, Topic 38, Topic 39, Topic 43, Topic 45, Topic 47, Topic 49, Topic 50, Topic 52, Topic 53, Topic 54, Topic 55, Topic 59, Topic 60, Topic 64, Topic 66, Topic 69, Topic 70, Topic 72, Topic 75, Topic 81, Topic 85, Topic 89, Topic 94,Topic 96, Topic 98, Topic 108, Topic109, Topic 113, Topic 116, Topic 117, Topic 130, Topic 138, Topic 140, Topic 141, Topic 145, Topic 146, Topic 147, Topic 148,Topic 149, Topic 150, Topic 152, Topic 156, Topic 157
Machine Tool Industry	Topic 8, Topic 14, Topic 30, Topic 48, Topic 91, Topic 124, Topic 126, Topic 155
Smart Machine Tool	Topic 40, Topic 57, Topic 101, Topic 123, Topic 153
Intelligent Machine Tool	Topic 1, Topic 17, Topic 34, Topic 35, Topic 58, Topic 62, Topic 65, Topic 79, Topic 82, Topic 97, Topic 103, Topic 104, Topic 115, Topic 118, Topic 120, Topic 122, Topic 127, Topic 131, Topic 135, Topic 139, Topic 142, Topic 158

However, by analyzing the results of the topic modeling, we can find a considerable amount of research concerns do not belong to the traditional machine tool domain. For this reason, we cannot simply divide them into the original machine tool categories. It is noting that these concerns reflect new developments in machine tool research under the influence of emerging information technologies. Based on the characteristics of these research focuses, we divided them into two new categories labeled "Smart Machine Tool" and "Intelligent Machine Tool" respectively in Table 5. Concretely, the "Smart Machine Tool" category contains research focuses such as "Internet of things (IoT)", "protocol and security of IoT", "big data", "distributed platform" and "cloud computing and Cyber-physical system". The above research concerns are closely related to emerging information technologies, reflecting that the interconnection of machine tool equipment and the collection of machine tool big data is getting more and more attention from scholars within domain. For "Intelligent Machine Tool", this category contains research concerns like "deep learning", "machine learning", "neural network", "expert system" and "heuristic algorithm" et al. These concerns are all about intelligent analysis methods, among which deep learning is leading the rapid development of artificial intelligence domain with its powerful feature representation learning ability. In addition, this category also includes research on machine tool intelligent application technology supported by intelligent analysis methods, such as "prognostics and health management of machine tool" and "machine tool condition monitoring". The categorization of "Intelligent Machine Tool" shows that intelligent methods such as deep learning and its application in the machine tool domain have become the focuses of researchers and many research works have been carried out around the direction of machine tool intelligence. Through the above investigation, we can conclude that the integration of the new-generation information technology and machine tools has brought significant changes to the research system in the machine tool domain, which has led to new exploration directions outside the traditional research scope of machine tool. Researchers are beginning to focus on the integration of machine tools with artificial intelligence, industrial Internet of things, big data analytics, cloud computing and cyber-physical systems to enable machine tool to operate in a more flexible, efficient, energy-efficient and sustainable manner.

Based on the above analysis, we selected the representative research concerns in the two categories of "Smart Machine Tool" and "Intelligent Machine Tool" to draw the evolution river map during the research process of machine tool, aiming at more intuitively displaying the impact of the new-generation information technology on the research activities of machine tools which is shown in Figure 4 below. The width of the evolution curve for each particular research concern selected in each year is proportional to the topic strength of the research concern at that year. The calculation formula of topic strength for a specific technology is as follows:

$$\theta_k^t = \frac{\sum_{m=1}^{M}\left(\theta_m^k \times \mathrm{I}(t_m = t)\right)}{\sum_{m=1}^{M}\mathrm{I}(t_m = t)} \tag{4}$$

where M is the number of papers in the corpus and t_m is the publication year of paper m. $I(\cdot)$ denotes indicator function, that the function takes a value of 1 when the expression in parentheses is true, otherwise it takes a value of 0.

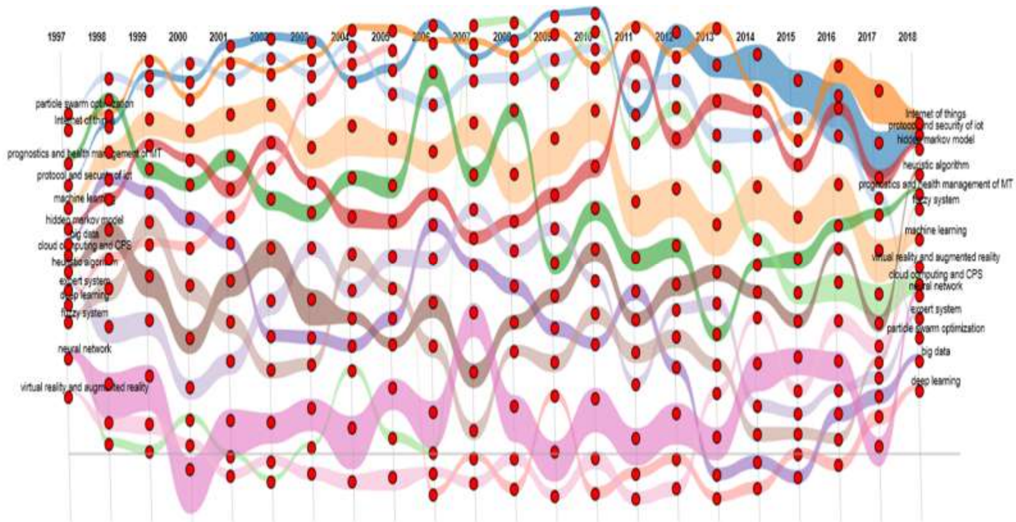

Figure 4. evolution river map of the selected research concerns

From the river map of technology evolution, we can see that the research concerns like "Internet of things", "protocol and security of IoT", "cloud computing and Cyber-physical system", "machine learning" and "deep learning" etc. have gradually become more and more important in the research community of machine tools. This further clarify the characteristic of gradual integration between machine tool research and emerging information technologies.

4.1.3 Topic trend analysis

The above discussion analyzes the emerging research concerns that occur in research community of machine tool and the evolution of the selected representative emerging concerns in the research

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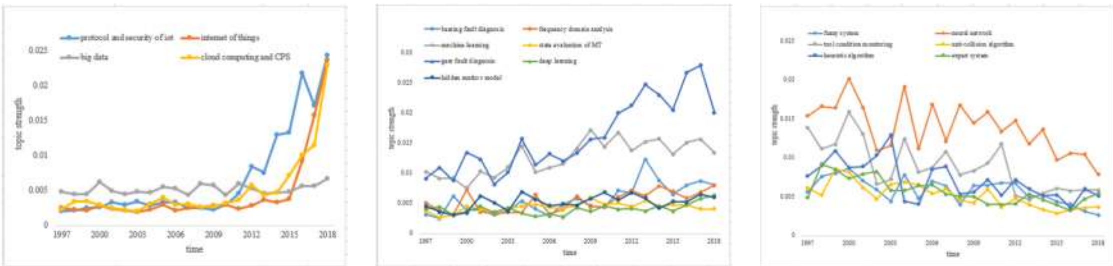
process of machine tool. In this section, we further explore the future development trend of these emerging research concerns generated in machine tool domain. In experiment, we focused on the research topics contained in the two categories of “Smart Machine Tool” and “Intelligent Machine Tool” in Table 5, because these two categories best reflect the impact of the new-generation information technology on the research ecology of machine tool. According to formula 4, we calculated the topic strength of 27 elements under two categorization year by year and further obtained the evolutionary sequence of 27 elements over time respectively. Then we used the Mann-Kendall trend analysis method to detect the rising or falling trend of the selected research focuses [45]. Through trend analysis, “protocol and security of IoT”, “internet of things”, “big data” and “cloud computing and CPS” in the “Smart Machine Tool” category showed a significant rising trend, as shown in the following Figure 5(a). This suggests the fact that these technologies will become increasingly important in future machine tool research. Furthermore, for the "Intelligent Machine Tool" category, "deep learning", "machine learning", "hidden markov model" and other seven topics presented a rising trend as shown in Figure 5(b). In addition, the six research topics including "fuzzy system", "neural network", "expert system" and so on showed a significant falling trend as shown in Figure 5(c) below.



(a) (b) (c)

Figure 5. Research topic trends of machine tool

We conducted a brief analysis of the research topics characterized with an increasing or decreasing trend. The rise or decline of a specific research focus implies deep principles of discipline development. In view of the fact that the new-generation information technology has changed the information environment of the manufacturing industry and will greatly improve the operational performance and efficiency of physical objects, researchers in the machine tool domain will also focus on how to obtain inside and outside big data of the CNC machine tool and how to apply artificial intelligence to mine big data to realize self-learning of knowledge. Then, based on the interconnection of machine tools, the problem of accumulation and inheritance of knowledge will be further solved. The self-learning, accumulation and inheritance of knowledge in the machine tool is a core issue in the domain, which further promotes the attempts of machine tool researchers to solve it through emerging information technology. Big data research focus is mainly about data collection, transmission, storage and fusion of multi-source heterogeneous data. Multi-source heterogeneity is also a typical feature of machine tool big data, which can explain that big data will become more and more important in the research of machine tools. Cloud computing studies how to analyze big data efficiently to meet the speed requirements of data analysis in the industry. The machining process of machine tool continues to accumulate a large amount of internal and external data, which requires real-time analysis of the data and rapid feedback of the analysis results. This real-time data analysis demand will make cloud computing attract more and more attention in future machine tool research. Internet of things studies how to achieve equipment interconnection. As discussed above, the interconnection of equipment will improve the ability to manage machine tool resources and the sharing of domain knowledge. Given the special characteristic of industrial production, safety is of paramount importance. The protocol and security of internet of things (IoT) focuses on explore how to ensure the security of the Internet of Things. The above discussion can explain the rising trend of IoT and security related concerns in research of machine tool. As for machine learning, it aims to extract value from accumulated big data. Especially deep learning, in view of its powerful feature

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representation learning ability, has achieved the state-of-the-art performance on many predictive tasks related with machine tool. Based above reasons, machine learning, in particular deep learning, will receive more and more focus by machine tool researchers. The exploration of these advanced algorithm models makes it possible to develop from the descriptive analysis to the diagnostic, predictive and strategic analysis, which further promotes the research of intelligent applications like fault prediction and prognostic and health management in machine tool and help improving people's analytical decision-making ability for complex tasks under uncertain environment. Under the synergy of big data, internet of things, cloud computing and artificial intelligence, the enhancement of the perception, analysis and control ability of the machine tool processing state makes it possible to map the actual machining state of the machine tool to the virtual space. As can be seen from Figure 5(a), more and more research focuses on cyber-physical system (CPS) modeling of machine tools. The reason lies in that the fusion of the cyber and physical space of will further greatly improve the traditional simulations and actual machining methods in the domain of machine tools.

For the research concerns that decline in Figure 5(c), fuzzy system, expert system and heuristic algorithm belongs to the research category of traditional analysis methods. These methods solve some of the problems in the machine tool domain but inevitably have many limitations, which makes them gain decreased attention. For instance, it is difficult for expert system to acquire and represent domain knowledge of expert, which resulted in its generalization ability in practical tasks is not strong. It is worth noting that the trend of neural networks as a classical machine learning method is also declining in machine tool research. The reason lies in that, different from deep learning, neural network refers to the shallow network and requires manual feature engineering as input. However, deep learning enables end-to-end modeling to learn features automatically. In addition, the deep learning model owes a larger capacity than the neural network, which means that the model can complete complex learning tasks. In view of the advantages of deep learning and the application of big data and cloud computing, deep learning has replaced the research of shallow neural networks to some extent in the machine tool domain.

4.1.4 Research analysis of machine tools based on fund data

As research input, grants is an important data dimension reflecting research activities. We retrieved the grants related to machine tool from the NSF award database to analyze the research in the machine tool domain further. The retrieval method for grants is described in Section 3.2 and we obtained 675 grants related to the machine tool domain through retrieval. The number over time of machine tool grants granted by NSF is shown below.

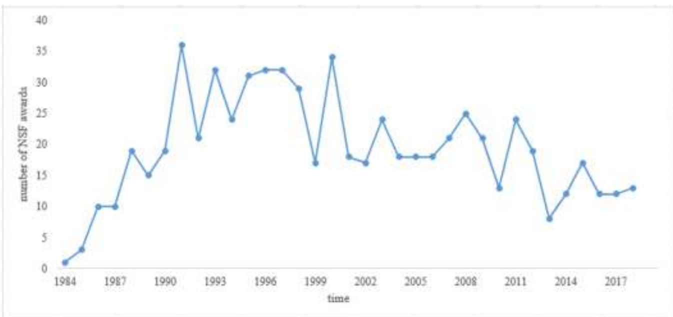

Figure 6. The number over time of machine tool grants granted by NSF

It can be observed from Figure 6 that the number of granted grants by NSF related to machine tool has declined in recent years. The possible reason lies in that the US manufacturing industry has gradually focused on cutting-edge research, and funding awards for conventional manufacturing technologies have been reduced. And the United States is the first country in the world to carry out research on machine tool technology, and many of its machine tool research technologies have gradually matured. Since the year of 2015, the number of machine tool grants is 54, accounting for

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7.96% of the total number of machine tool grants granted by NSF. We further analyzed the 54 grants since 2015 and found that two research concerns were the focuses of NSF funding in recent years. One of the research topic is the “Cyber-physical system” which has been the fund award focus for the past five years as shown in Table 6 below, accounting for 9.3% of the total number of machine tool grants after 2015. Given the fact that individual research funding activity of NSF does not cover the whole research scope of the machine tool domain, we are unable to verify all of the above conclusions derived from the machine tool papers at the global level. However, from the analysis perspective of machine tool funds, we can still prove that cyber-physical system is the focus and trend of research in the machine tool domain, which is consistent with the conclusion mined by machine tool papers. It is also worth noting that another NSF's focus in recent years is sustainability, as shown in the table below. The reason is that the critical role of machine tools in the manufacturing industry and the increasing constraints of global environmental and resource direct the future development direction of the machine tool industry to be low energy, high efficiency, green and sustainable. According to Topic 14 which is modeled from papers of machine tools in Section 4.1.1, sustainability is also the focus topic of machine tool research. Topic 14 contains high-frequent terms such as “industry”, “safety”, “construction”, “cost”, “economic”, “environmental”, “sustainability”, “enhance”, “sustainable” and “costs” et al, representing research topic of sustainability for machine tool.

Table 6. The grants of machine tool about cyber-physical system and sustainability

Funding direction		Award Number	Title	Start Date
Cyber-Physical System	1	1547105	EAGER/Cybermanufacturing: Just-In-Time Compilation of Product Manufacturing Data to Machine Instructions via an Industrial Machine Operating System	09/01/2015
	2	1547075	EAGER: Cybermanufacturing: Design and analysis of a cyberphysical systems approach for custom manufacturing kiosks	09/01/2015
	3	1546993	EAGER: Cybermanufacturing: Defending Side Channel Attacks in Cyber-Physical Additive Layer Manufacturing Systems	10/01/2015
	4	1646013	CPS: Synergy: CNC Process Plan Simulation, Automation and Optimization	08/01/2016
	5	1837146	CPS: Small: Mechanical Vibration Based Prognostic Monitoring of Machinery Health with Sub-millisecond Accuracy Using Backscatter Signals	01/01/2019
Sustainability	1	1512217	UNS: Advancing Environmental Sustainability through Innovative Design and Operation of Digital Manufacturing Equipment	05/01/2015
	2	1563475	Atomized Dielectric-Based Electric Discharge Machining for Sustainable Manufacturing	04/01/2016
	3	1635347	Eradication of Microbial Contamination in Metal Working Fluids	09/01/2016
	4	1760616	Eradication of Biofilms in Metal Working Fluids	09/01/2018

4.2 Development trend analysis of machine tool technology dimension

Patents have been considered as an important proxy to reflect technological development in industry. In this section, we analyzed the patents to explore the development characteristics of machine tool technology dimension under the environment of new-generation information technology. From the analysis of section 4.1, the impact of emerging information technology on the machine tool domain is mainly reflected in the integration and application of technologies such as big data, cloud computing, internet of things, cyber-physic system and artificial intelligence. Based

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on this observation, we mainly focused on the development of the above technologies in the domain of machine tools, as an extension of technology development dimension for the analysis of in Section 4.1. We searched the patent data of the relevant technologies in machine tool through the keywords that constituted the various technologies in the Table 7 below. In this section, we used patent development trajectories and institutional cooperation networks to analyze patent data to explore the technology development of machine tool.

Table 7. The keywords that constituted the emerging technologies in machine tool

Technology	Keywords
Big data	big data, data collection, data transmission, transfer protocol, Ethernet, industrial wireless network, MQTT, NC-Link, MT-Connect, wireless transmission, distributed platform, Hadoop
Cloud computing	cloud computing, edge device, edge module, fog calculation, fog end equipment, cloud platform, cloud service, cloud storage, cloud, industrial cloud, distributed computations, parallel computing, cloud manufacturing
Internet of things	Internet of Things, Industrial Internet of Things, Industrial internet, IoT, IIoT
Cyber-physical systems	Cyber-Physical system, CPS, Digital twins
Intelligent methods and applications	artificial intelligence, machine learning, logistic regression, support vector machines, naïve bayes, decision tree, random forest, transfer learning, deep learning, Virtual Reality, Augmented Reality, Convolutional neural network, Recurrent neural network, Restricted Boltzmann machine, supervised learning, unsupervised learning, neural networks, customized production, remote monitoring, shared manufacturing, state prediction, state forecasting

4.2.1 Trajectories of technologies development

we explored the development status of specific technologies in the machine tool domain through the method of patent growth trajectory. We counted the number of patents retrieved for each of the emerging technologies in Table 7 by year, as shown in Figure 7 below. It can be observed from Figure 7 that the number of patents of the emerging technologies listed above in machine tool domain has been increasing through time, indicating that these technologies play an increasingly important role in the practical application of machine tools. Specifically, for big data technology, the phenomenon that the number of affiliated patents in machine tool domain has been increasing by year since 2000 reflects the accumulation of technologies related with machine tool data acquisition, transmission and storage and the gradually improvement for data basis. With the accumulation of more and more data, the efficient analysis of data has become more and more critical. As can be observed from the figure, the application of cloud computing technology in the machine tool domain has made great progress since 2012. In addition, the internet of things technology has been applied in the field of machine tools since 2017 and there has been a significant increase in the number of patents in 2018, indicating that internet of machine tool is in the early stage of promotion and application. With the landing of big data, cloud computing and internet of things in machine tool and the gradual improvement of the machine tool information foundation, intelligent technologies such as machine learning and machine learning-based applications have increased significantly from the year after 2015, indicating that these intelligent technologies are gradually contributing value in the practical application of machine tools. However, for cyber-physical system (CPS) technology, the number of its patents in the machine tool is very small. In fact, we only retrieved a related patent, indicating that

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the whole of CPS is still in the research stage and has not been widely used in the machine tool field. CPS is currently an emerging direction for machine tool research, and more and more patents will appear in the future.

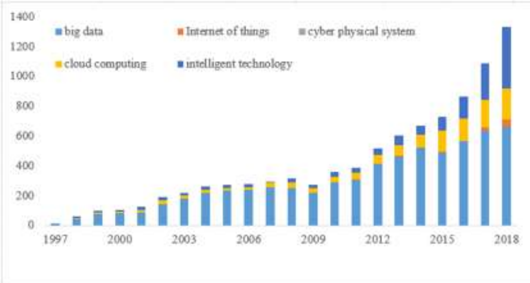

Figure 7. Patent growth trajectory for emerging technologies in the machine tool domain

Further, we selected a leading organization of machine tool, i.e. FANUC, to count the number of patents in the machine tool field of the emerging technologies of mentioned above. As can be observed from the Figure 8, the number of patents of big data, cloud computing and intelligent related technologies in FANUC is basically consistent with the number of the overall machine tools domain. It is worth noting that the number of applications for patents related to intelligent technologies has increased significantly in 2017 and 2018, reflecting FANUC's high attention to machine tool intelligence in recent years. However, it is surprise that FANUC has not laid out IoT technology in the machine tool domain. We conducted in-depth research on this issue and found that FANUC launched the FANUC Intelligent Edge Link and Drive (FIELD) system in 2016 to connect machine tools, robots, peripherals and sensors in automated systems and provide advanced data analysis functions. One reason for not being able to retrieve the FANUC's IoT-related patents in the machine tool field may be that the company's business has robotics and other fields besides the machine tool, and its patent applications of IoT may be distributed in other domains. Another reason is that FANUC and Cisco, Rockwell Automation etc. jointly developed the FIELD system, which may reduced its patent application for internet of things in the field of machine tools.

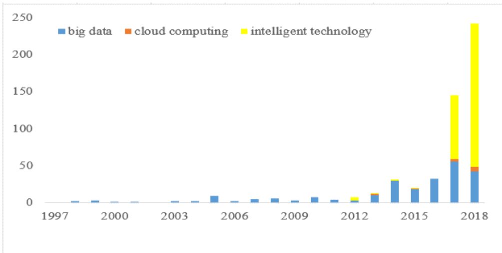

Figure 8. Patent growth trajectory for emerging technologies in FANUC

Through the above analysis, the conclusions are summarized as follows: 1) Big data and cloud computing have been applied in the machine tool domain and the number of their patents is still increasing in recent years, indicating that these two technologies have begun to land and generate practical value in machine tool; 2) The IoT technology has undergone significant changes in the domain of machine tool in the past two years, indicating that the technology is still in the early stage of promotion and will be the focus of technology development in the machine tool field in the future; 3) The number of patent applications related to intelligent technologies within the field of machine tools has increased significantly in recent years, indicating that machine tool intelligence is receiving more and more attention in the industry. With the development of artificial intelligence technology and the further improvement of the basis of machine tool information, more and more research and development exploration will appear in this direction. 4) Cyber-physics system technology has not

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yet had abundant patent applications, and the technology is still immature in the domain of machine tools.

4.2.2 Analysis of Institutional cooperation networks

We analyzed the institutional cooperation network of patents related to the selected emerging technologies within machine tool. In the study, the time span of patents (1997-2018) was divided into two phases, and 2010 was set as the demarcation point. The reason lies in that the evolution of emerging technologies in the machine tool domain is accelerating after the year of 2010, which can be observed from Figure 9 and Figure 10. The institutional cooperation network of the patents from 1997 to 2010 is shown in Figure 9 below. In addition, the institutional cooperation network of the patents from 2011 to 2018 is shown in Figure 10. In the two figures, the red node represents the type of company in the domain of information technology, the blue represents the type of company in the traditional machine tool field, and the green represents the type of university institution.

Comparing the institutional cooperation network of patents within domain of machine tool at two periods of time, we can observe the following phenomena. Firstly, compared with the period from 1997 to 2010, more and more companies outside the machine tool domain have applied for patents in the domain of machine tools in recent years. These companies include both giant companies in various fields such as SONY, HITACHI, MATSUSHITA, SAMSUNG, SCHNEIDER, TOSHIBA, Google, GENERAL ELECTRIC CO and also emerging artificial intelligence startups like Preferred Network. This Indicates that a significant change brought by the new-generation information technology to the machine tool domain is that the cross-border competition in this domain will become the norm in the future. The reason lies in the emerging technologies such as big data, cloud computing, internet of things and artificial intelligence are common enabling technologies and can be widely applied to manufacturing value innovation, production innovation, service innovation and other manufacturing value chains of discrete manufacturing or process manufacturing, which can empower businesses in different industries to unleash greater technical and economic value and lower the cost of technology development. The enabling characteristic of these technologies makes technology cross-border applications possible. This phenomenon is very important, indicating that competition within machine tool domain in the future will become increasingly fierce. In addition, almost all leading organizations in the machine tool domain have developed patents in these emerging directions in recent years, including not only DMG, FANUC, SIEMENS, OKUMA, but also component companies like MITSUBISHI, YOKOGAWA, OMRON and YASKAWA. This observation shows that under the influence of the new information technologies, the phenomenon of attention change for traditional machine tool enterprises from hardware to software will become more and more common. Meanwhile, based on above observations, cooperation between enterprises in the traditional machine tool industry and enterprises outside the machine tool domain may become more and more common. For example, a typical instance in Figure 10 is the collaboration between the Japanese startup Preferred Network and FANUC. Preferred Network's powerful AI modeling capabilities and FANUC's rich business scenarios, extensive data and abundant domain knowledge form a good complementarity. These cooperation will help different types of companies to take advantage of their respective advantages to quickly bring technology to the market and occupy the market. Further, we can observe from Figure 9 and Figure 10 that more and more university institutions apply for patents about emerging information technology in the machine tool domain, indicating that the university plays a critical role in promoting the integration of the machine tool technology with the emerging information technologies.

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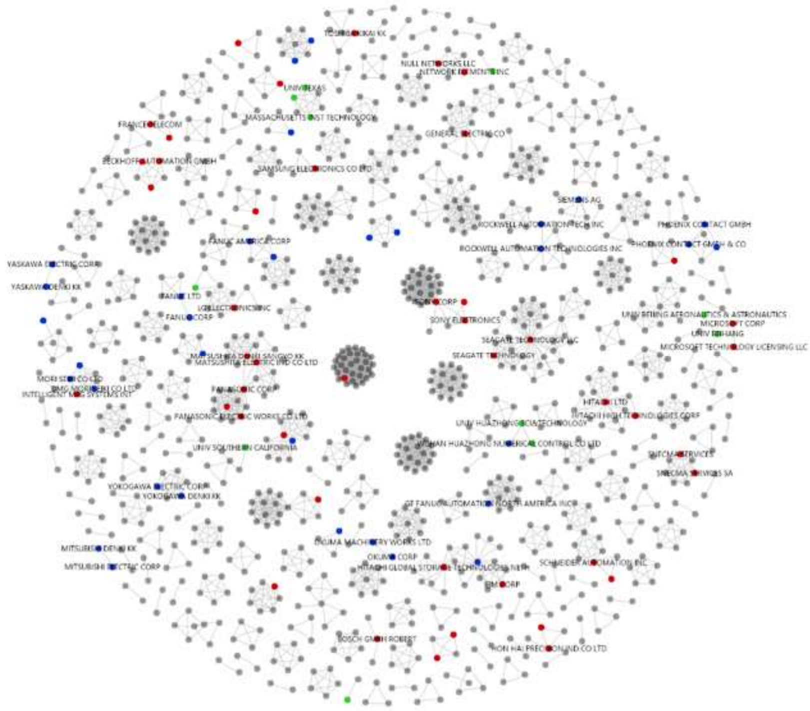

Figure 9. Institutional cooperation network of selected emerging technologies within machine tool (1997-2010)

Figure 10. Institutional cooperation network of selected emerging technologies within machine tool (2011-2018)

4.3 Business model analysis of machine tool industry

In this section, we further explore the changes in the business mode of the machine tool industry under the influence of the new-generation information technology. In order to analyze the changes

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of the industrial mode of the machine tool industry, we crawled the Google news released after 2015 related to the machine tool business mode for topic modeling analysis. Similar to the topical modeling method of machine tool papers in Section 4.1.1, we used manual inspection to adjust the topic model hyper-parameters to optimize the modeling results. Upon manual inspection, we set the hyper-parameters K, α, β, I to K=80, $\alpha = 0.1$, $\beta = 0.01$ and I=1000. After completing the topic modeling for news, we applied the manual interpretation method to check the business modes that focused in recent years of machine tool industry. The extracted business modes are shown in Table 8 below.

Table 8. The modeled business concerns of machine tool industry

Topic	High-frequent terms
Topic 1	Intelligence, technologies, learning, reality, information, technology, artificial, augmented, businesses, part, plc, future, data, virtual, deep
Topic 2	Data, information, process, system, production, control, sensors, monitoring, real-time, connected, productivity, cloud, sensor, analytics
Topic 3	Machine, monitoring, manufacturing, system, data, oee, company, production, equipment, shopfloor, data-driven, status, network, downtime, cloud-based
Topic 4	Equipment, service, customer, downtime, technology, quality, productivity, machine, monitoring, predictive, reliability, efficiency, increase, remote, preventive
Topic 5	Facility, facilities, energy, central, industry, processing, economic, services, production, expansion, distribution, e-commerce, cluster, clean, green
Topic 6	Control, machine, cnc, fanuc, app, program, technology, programming, interface, apps, features, programs, connected, manufacturing, iIoT
Topic 7	Device, devices, healthcare, supply, technology, chain, market, health, industry, tool, technologies, program, competitive, iIoT, application
Topic 8	Data, platform, analytics, digital, cloud, applications, platforms, plant, real-time, ecosystem, predix, twin, transformation, application, cloud-based
Topic 9	IoT, industrial, iIoT, things, security, cloud, devices, connected, edge, computing, standards, applications, connectivity, factory, services
Topic 10	Network, data, wireless, security, machine, system, device, networks, devices, company, server, programs, technology, computers, miller

By analyzing the modeling results of the news in Table 8, we can draw the following conclusions. The content of Topic 9 and Topic 10 refers to information about the IoT cloud platform in the machine tool domain. The machine tool industry Internet platform based on IoT technology enables machine tool enterprises to extend machine tools from the shop floor to the cloud and then use data analysis technologies such as cloud computing and artificial intelligence to improve the user's insight into plant and production performance, enabling companies to achieve asset management and data management in a sustainable and economical way to accelerate the process of enterprise intelligence transformation. From the modeling results of these two topics, we can conclude that the business mode based on the machine tool IoT cloud platform is one of the concerns of the future development of the machine tool industry. The machine tool IoT cloud platform essentially connects people, processes, data and things through the Internet of Things technology, and reshapes the value chain of the machine tool industry through the sharing and integration optimization of various resources between intra-enterprise and inter-enterprise. Information about cloud services is reflected in Topic 8, Topic 2, Topic 3 and Topic 4. With the continuous improvement of the digital foundation of the

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machine tool domain and the emergence of intelligent technologies and applications, machine tool companies not only achieve increased productivity but also may derive new service mode in addition to machine tool products. The transformation of the machine tool industry mode characterized by intelligent services is another concern of the change of the machine tool industry mode under the influence of the new-generation information technology, which makes the machine tool enterprises develop from "production-oriented manufacturing" to "manufacturing service-oriented". Machine tool companies can realize value creation based on machine tool services in the future. For example, Topic 2, Topic 3 and Topic 4 reflect that on the basis of big data, industrial Internet of things and artificial intelligence (Topic 1), machine tool enterprises establish a cloud platform for monitoring the operation of machine tool equipment, which can monitor the operation state of machine tool equipment and gradually evolve from state monitoring to predictive maintenance. Predictive maintenance of machine tools will also greatly improve the supply chain of the traditional machine tool industry, increasing production efficiency while further reducing costs (Topic 7). In addition, Topic 6 reflects the application of industrial App in the field of machine tools, indicating that the machine tool App ecosystem may be another important paradigm of the machine tool industry mode. The Industrial App ecosystem is a common enabling technology focused on the generation and utilization of knowledge in the machine tool field and the decision-making ability enhancement of machine tool system. The construction of the machine tool App ecosystem revolutionizes the efficiency about generation, utilization, inheritance and accumulation of machine tool knowledge, and further promotes the precipitation and sharing of knowledge in the machine tool domain. The development of the IoT platform of the machine tool can realize the automatic and repetitive use of knowledge by machine tools, avoiding the limitations of time and space to further increase the value of knowledge. Through the above analysis, it can be summarized that the emerging industry mode of the machine tool industry is shown in Table 9 below. The change of the machine tool industry mode will also promote the sustainable development capability of the machine tool industry and make the future development of the machine tool industry become more and more clean and green. Sustainability will become a focus of the future development of the machine tool industry (Topic 5).

Table 9. Emerging business mode in the machine tool industry

Cloud-based Machine Tool IoT Ecosystem	Machine Tool IoT Cloud Platform	Topic 9, Topic 10
	Cloud Service Mode	Topic 8, Topic 2, Topic 3, Topic 4
	Machine Tool App Ecosystem	Topic 6

4.4 Discussion

Through the multi-perspective analysis about research, technology development and industrial mode, we explored the future development roadmap of the machine tool domain in this paper. First of all, under the influence of the new-generation information technology, the machine tool domain is gradually developing towards the intelligent direction. Based on the accumulation and analysis of machine tool big data, the new information technologies promote data-driven knowledge mining in machine tool domain. As can be seen from exploration in Section 4.1 for machine tool papers and funds, big data, cloud computing, Internet of Things, cyber-physics systems and deep learning have become the focuses and important trends of machine tool research. The combination of these emerging technologies and machine tool research is highlighted in the failure prediction and state monitoring for machine tools and components. The reason lies in that the accumulation of machine tool big data and the application of complex algorithms such as deep learning make the related research gradually develop toward predictive maintenance. With the maturity of these technologies, the performance and operating efficiency of machine tool equipment will be greatly improved, making the sustainable development of the machine tool industry possible. Secondly, based on the above research foundation, the machine tool industry has also begun to accelerate the application of above emerging technologies. Machine tool companies represented by FUNAC have also strengthened their investment in technologies such as big data, cloud computing and machine

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learning in recent years. In view of the enabling characteristics of cloud computing, Internet of Things and artificial intelligence, not only the traditional machine tool giants are focusing on layout but many non-machine tool companies are also stepping up their technical investment in these directions, leading to the further formation of cross-border integration in the machine tool field. The competition in the machine tool domain will be further intensified, which will also promote the cooperation between enterprises with different technical backgrounds. Finally, the emerging technologies generated by the integration of the machine tool domain and the new-generation information technologies laid the technical condition for the transformation of the machine tool industry mode. From the analysis of Section 4.3, the cloud-based machine tool IoT ecosystem is the core concern of the future development of the machine tool industry mode. The cloud-based machine tool IoT ecosystem is embodied in the machine tool IoT cloud platform, cloud service mode and machine tool App ecosystem. This marks the machine tool industry change from the traditional manufacturing industry towards service-oriented manufacturing. The new-generation information technology is causing major and profound changes in the development concept and industrial mode of the machine tool industry. This change will promote the machine tool industry to gain new competitive advantages and promote the development of global manufacturing industry into a new stage.

The above findings may offer important implications for systematic and nuanced policies in machine tool domain. For researchers, more attention can be paid to the combination of big data, artificial intelligence and machine tools domain. In particular, the cyber-physics system technology of machine tools has not been applied at present, and it is one of the research concerns in the field of machine tools in the future. For machine tool enterprises, they should pay attention to the improvement of the Internet of Things and cloud computing technology for enterprise business. Enterprises also should attach importance to the collection of machine tool big data, data-driven knowledge mining and the transformation towards manufacturing service-oriented enterprises. For the machine tool industry, it is necessary to organize and implement a standard system including industrial information security, interconnection and communication. Finally, in view of the basic role of the machine tool industry in manufacturing, national policies should be developed at various national levels to encourage collaborative innovation in industry, academia and research in the international arena. Relevant laws and regulations should also be enacted to ensure the security of big data and the Internet of Things platform in the machine tool field.

5. Conclusions

The complex intrinsic heterogeneity of machine tool discipline and the dimension complexity of machine tool development make the exploration of the future trend of machine tools become a challenging task. In this paper, we proposed a integrating framework to solve above challenge by analyzing multi-source literatures. The proposed framework consists of machine learning, bibliometric, patent analysis, and trend analysis methods and has semantic, time dynamic, and multi-dimensional analysis capabilities. The main contributions of the article are as follows.

Firstly, the future development of machine tool domain in complex environment is analyzed. The main findings are as follows. Firstly, through the analysis of machine tool papers and funds, we found that big data, cloud computing, Internet of Things, cyber-physical system, machine learning and deep learning have become the focuses and important research trends of machine tool research. Secondly, through the analysis of the machine tool patents, we found that these emerging technologies have been applied in practical applications of machine tool in recent years to generate value, except for cyber-physical system. Not only the traditional machine tool giants are focusing on these emerging technologies layout but many non-machine tool companies are also stepping up their technical investment in these directions, leading to the further formation of cross-border integration in the machine tool field. We also observed that universities have played an increasingly important role in the application transformation of emerging technologies in the machine tool industry. Finally, it is found that the future business mode of the machine tool has changed greatly based on the analysis of machine tool news. The cloud-based machine tool IoT ecosystem is the core characteristic of the future development mode of the machine tool industry, indicating the machine tool industry is moving from traditional manufacturing industry to service-oriented manufacturing industry.

Secondly, we performed a systematic analysis of multi-source scientific literatures related to machine tool to explore its future evolution trend from the multi-view perspectives of research, technology development and business mode. Through the multi-dimensional analysis of the future development, this paper systematically clarified the roadmap of the impact of the new-generation information technology on the machine tool domain. We find that the impact of external information technologies on the machine tool field is gradually transferred from research, technology development to industrial mode. Machine tool research and technology development constitute the cornerstone of the machine tool industry mode change.

Finally, we proposed a new research framework with semantic, temporal dynamics and multi-perspective analysis capabilities. The proposed method framework not only provide effective support for the analysis of future development trends in the machine tool field, but also has certain versatility. Especially for the evolution of traditional domains influenced by the new-generation information technology, our proposed method also applies.

The limitations of this paper are as follows. Our work aims to use the quantitative analysis methods like machine learning to study the future development of machine tools. The future integration of expert domain knowledge to combine the analysis of qualitative and quantitative is of significance for predicting the future development of machine tools. In addition, the paper focuses on the impact of the new-generation information technology on the machine tool field. Many traditional machine tool technology developments have not been analyzed. The analysis of these technologies will facilitate a more comprehensive exploration of the future development of this domain.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Topic modeling results of machine tool papers

Meaning	Topic	High-frequent terms
fuzzy system	Topic1	fuzzy, system, logic, rules, inference, adaptive, anfis, rule, neuro-fuzzy, performance, input, learning, systems, appropriate, function
industrial robot	Topic2	robot, industrial, robotic, system, control, purpose, task, trajectory, arm, flexibility, mobile, perform, robotics, flexible, human-robot
joints dynamic modeling	Topic3	joint, assembly, tool, dynamics, model, coupling, point, dynamic, modeling, modeled, interface, beam, interfaces, rigid, response
efficiency improvement	Topic4	method, calculation, effective, accurate, accurately, experiment, realize, combination, improve, effectiveness, fast, feasible, efficiency, optimizing, theory
dynamic response analysis	Topic5	dynamic, model, stiffness, system, static, response, dynamics, effects, coupling, nonlinear, coupled, damping, analysis, time-varying, influence
high speed spindle	Topic6	spindle, high-speed, spindles, high, speeds, rotating, motorized, system, radial, rotational, axial, rotation, displacement, centrifugal, effects

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versatility machine tool	Topic7	machine, tools, tool, parts, precise, mapping, calculate, rapidly, versatile, acquire, repeatable, versatility, institute, vms, structured
production management	Topic8	manufacturing, management, production, information, industry, market, case, competitive, manufacturers, rfid, enterprises, supply, chain, resource, costs
joints stiffness theory	Topic9	contact, deformation, elastic, stiffness, theory, pressure, area, force, influence, distribution, displacement, load, theoretical, normal, plastic
non-linear modeling	Topic10	model, modelling, process, performance, forecasting, data, non-linear, empirical, physical, estimate, situations, polynomial, mathematical, data-driven, gradient-based
vibration signal analysis	Topic11	mode, method, decomposition, signal, empirical, signals, emd, singular, intrinsic, entropy, analysis, feature, vibration, local, decomposed
tolerance design method	Topic12	method, tolerance, equations, equation, tolerances, parametric, design, quadratic, differential, non-linear, equivalent, solving, initial, dimensions, partial
online monitoring	Topic13	sensors, monitoring, sensing, system, online, fusion, measurements, wireless, information, signals, in-process, installed, sensory, monitor, integration
development of machine tool	Topic14	industry, safety, construction, cost, risk, improvement, case, economic, environmental, sustainability, enhance, care, sustainable, health, costs
rapid prototyping technology	Topic15	rapid, prototyping, tooling, metal, manufacturing, casting, slicing, part, deposition, cnc, prototype, processes, mould, material, slice
feed servo system	Topic16	feed, rate, drive, rates, drives, high, servo, machining, machine, high-speed, tool, cycle, speeds, accurately, torque
bearing fault diagnosis	Topic17	signal, noise, signals, method, fault, bearing, weak, adaptive, ratio, filter, resonance, effectiveness, impulses, components, periodic
part machining	Topic18	part, parts, set-up, machining, machined, dimensions, volumes, grouping, manufactured, modelled, set-ups, determines, three-axis, define, ensuring
response analysis	Topic19	response, parameters, analysis, design, models, process, mathematical, rsm, responses, values, factor, variance, surface, model, variables
intelligent control system	Topic20	intelligent, system, support, intelligence, control, autonomous, agent, decision, artificial, distributed, architecture, decision-making, autonomously, evolution, self-learning
material properties	Topic21	layer, surface, thickness, layers, machined, recast, steel, material, materials, properties, resistance, higher, hardness, high, lower
motion control	Topic22	position, velocity, moving, desired, motion, acceleration, maximum, positions, commands, follower, generate, track, computed, move, command
multiobjective optimization algorithm	Topic23	optimization, algorithm, genetic, optimal, parameters, algorithms, multi-objective, objectives, optimized, problem, optimize, evolutionary, performance, evolution, search
genetic algorithm	Topic24	algorithm, genetic, local, search, problem, global, modified, operator, convergence, solution, optimal, initial, algorithms, solve, space
profile control	Topic25	measuring, measurement, inspection, coordinate, probe, measured, accuracy, machine, system, cmm, data, model, on-machine, error, profile
CNC machine center	Topic26	machining, center, vertical, cnc, centers, piece, horizontal, centre, test, analyzed, identifying, relation, evaluation, disadvantages, direction
robust control of machine tool	Topic27	robust, uncertainty, robustness, effective, parametric, method, conditions, model, uncertain, complexity, task, deal, handle, parameter, performance
process planning	Topic28	process, planning, manufacturing, plan, plans, machining, operations, capp, operation, part, sequence, environment, selection, tools, computer-aided
evaluation method	Topic29	decision, process, selection, evaluation, criteria, problem, fuzzy, decision-making, analysis, similarity, alternative, theory, weights, ahp, hierarchy
cost management of machine tool	Topic30	production, cost, manufacturing, demand, line, productivity, batch, product, high, capacity, reduction, economic, lifespan, economical, customization
polishing process	Topic31	polishing, surface, abrasive, diamond, tool, process, optical, aspheric, freeform, mirror, workpiece, quality, precision, lens, roughness
gear of machine tool	Topic32	tooth, modification, method, bevel, gear, contact, machine, modified, settings, spiral, hypoid, machine-tool, pinion, profile, transmission

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model calibration of NT	Topic33	mechanism, method, identification, model, calibration, theoretical, parameter, simulation, experiment, effective, accuracy, decoupling, coupling, identifiability, kinematical
neural network	Topic34	network, neural, networks, learning, training, radial, function, propagation, rbf, prediction, trained, weights, conditions, predict, back-propagation
frequency domain analysis	Topic35	frequency, domain, analysis, spectrum, signal, spectral, components, envelope, frequencies, characteristic, phase, synchronous, bands, presence, band
adaptive control of machine tool	Topic36	control, controller, adaptive, system, pid, gain, performance, tuning, process, servo, simulation, stability, robustness, dynamics, self-tuning
loading analysis	Topic37	load, operating, condition, measured, speeds, running, operation, fluctuating, changes, time-varying, variable, loading, simulated, steady-state, response
efficiency improvement	Topic38	increase, effect, decrease, improve, efficiency, effects, reduced, negative, productivity, improvement, improves, influence, trend, dramatically, properties
performance optimization	Topic39	optimization, optimal, constraints, cost, maximum, function, optimum, minimize, optimized, constraint, criterion, value, problem, effectiveness, productivity
protocol and security of IoT	Topic40	IoT, devices, internet, protocol, security, coap, things, protocols, communication, networks, web, network, mobile, message, mqtt
impedance analysis	Topic41	variation, effect, changes, analyzed, dimensional, reduction, effective, space, causes, propagation, analysis, evaluation, manifold, inherent, impedance
guideways friction	Topic42	friction, coefficient, effects, sliding, yarn, velocity, mechanical, frictional, properties, guideways, rotor, ratios, tribological, reliable, analysis
performance improvement	Topic43	performance, improve, evaluation, measures, effective, enhance, improvement, superior, comparative, high, excellent, action, high-performance, analyzed, modifications
kinematic analysis of machine tool	Topic44	parallel, kinematic, workspace, stiffness, mechanisms, machine, mechanism, design, kinematics, synthesis, redundant, pkm, performance, redundancy, structure
material removal rate	Topic45	material, removal, rate, process, mrr, parameters, metal, volume, tool, effect, maximum, higher, predicted, pmnd-edm, optimizing
ball screw feed system	Topic46	ball, screw, system, linear, machine, positioning, accuracy, drive, slide, moving, guideway, preload, roller, ball-screw, high-precision
interpolation algorithm	Topic47	curve, interpolation, nurbs, curves, points, b-spline, parametric, interpolator, spline, algorithm, real-time, non-uniform, cnc, line, fitting
production scheduling	Topic48	scheduling, flexible, manufacturing, machine, operation, production, capacity, allocation, tools, flexibility, processing, planning, resources, schedule, assignment
surface quality	Topic49	surface, machined, quality, roughness, topography, process, influence, workpiece, integrity, parameters, effect, electron, scanning, analyzed, mechanism
parameters optimization	Topic50	parameters, analysis, optimal, grey, orthogonal, performance, relational, method, process, ratio, variance, optimization, rate, combination, optimum
stability theory of machine tool	Topic51	phase, stability, delay, system, periodic, nonlinear, theory, numerical, equation, stable, differential, regenerative, dynamics, linear, vibrations
particle swarm optimization	Topic52	optimization, particle, parameters, swarm, pso, optimize, performance, model, improve, algorithm, optimizing, particles, multi-objective, improved, optimal
cutting machining of machine tool	Topic53	chip, cutting, formation, tool, thickness, forces, edge, process, machining, shear, conditions, orthogonal, interface, zone, tool-chip
automatic tool change algorithm	Topic54	algorithm, efficient, automatic, discrete, fast, effective, cycles, suitable, matching, efficiency, automatically, slow, atc, time-consuming, manually
process sequence optimisation	Topic55	optimisation, operation, constraints, line, sequence, graph, case, balancing, feasible, optimised, precedence, analysed, transfer, cycle, machining
reliability technology	Topic56	reliability, failure, analysis, degradation, method, assessment, modes, failures, allocation, case, information, field, mode, comprehensive, function
Internet of things	Topic57	energy, wireless, IoT, devices, access, channel, transmission, network, consumption, communication, networks, performance, internet, things, power
signal analysis	Topic58	wavelet, transform, signals, signal, vibration, time-frequency, analysis, fourier, discrete, feature, processing, technique, fast, features, extraction

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electric discharge machining	Topic59	electrode, edm, machining, discharge, electrical, material, process, removal, wear, surface, mrr, electrodes, powder, gap, pulse
kinematics modeling of five-axis machine tool	Topic60	machine, five-axis, tool, coordinate, kinematics, kinematic, transformation, axes, tools, matrix, simulation, location, function, model, coordinates
maintenance of machine tool	Topic61	maintenance, source, cost, failure, replacement, policy, separation, preventive, optimal, availability, independent, component, downtime, repair, economic
neural network	Topic62	neural, network, artificial, ann, data, training, input, prediction, output, predict, algorithm, intelligence, parameters, multilayer, back-propagation
numerical control system	Topic63	cnc, control, numerical, computer, controlled, numerically, machines, lathe, computerized, aided, program, machine, numeric, contribution, perform
tool path planning	Topic64	tool, cutter, surface, path, machining, orientation, five-axis, method, contact, paths, orientations, point, location, positioning, generate
machine learning	Topic65	model, prediction, predict, regression, accuracy, modeling, data, predictive, conditions, validation, accurately, linear, support, correlation, ls-svm
micro electric discharge machining	Topic66	process, machining, micro-edm, fabrication, electrochemical, high, fabricated, ratio, effect, electrode, voltage, etching, microstructures, capacitance, micro-electrical
thermal error compensation	Topic67	error, machine, accuracy, compensation, tool, induced, dimensional, deviation, position, deviations, thermally, compensate, reduced, adjustment, precision
adaptive control	Topic68	scheme, adaptive, performance, adaptation, transmission, improve, predictor, efficiency, effectiveness, reliable, simulations, update, simulation, enhance, adapt
machining surface roughness	Topic69	machining, surface, surfaces, blade, rough, tool, sculptured, five-axis, method, blades, path, paths, convex, efficiency, tool-path
tool path planning	Topic70	path, tool, machining, offset, algorithm, generate, planning, curve, method, boundary, spiral, points, offsetting, smooth, tool-path
welding machine	Topic71	welding, device, variable, mass, preload, automatic, weld, arc, high, seam, metal, pressure, eccentric, gap, welded
stamping technology	Topic72	forming, process, metal, sheet, bending, thickness, cold, steel, tube, flatness, punch, strain, stamping, punching, deformation
bearing	Topic73	bearing, bearings, ball, shaft, preload, contact, rotor, element, inner, outer, angular, race, elements, rotating, roller
measurement technology	Topic74	measurement, laser, optical, device, displacement, technique, precision, sensor, instrument, fiber, accuracy, positioning, tracker, calibration, non-contact
dynamic characteristic analysis	Topic75	state, transient, continuous, dynamic, steady, dynamical, changes, patterns, threshold, space, discrete, temporal, intervals, stable, characterize
dynamic modeling of machine tool	Topic76	stability, dynamic, frequency, dynamics, response, modal, milling, natural, damping, method, stable, modes, frequencies, structural, stiffness
state evaluation of machine tool	Topic77	test, data, indicator, lifetime, residual, technique, analysis, accelerated, assess, deterioration, measure, rig, condition, criterion, validation
forward transfer function	Topic78	function, transfer, approximation, case, method, coefficients, parameter, complicated, efficiently, degree, forward, numerical, expression, computing, polynomial
feature Engineering	Topic79	feature, extraction, information, selection, classification, recognition, method, reduction, domain, original, effectiveness, represent, robustness, classify, preprocessing
modeling theory of machine tool	Topic80	model, modeling, models, accurate, mathematical, built, build, system, theory, modeled, analyzing, principle, represent, cutterhead, damped
machining process	Topic81	milling, process, machining, cutting, processes, parameters, quality, operations, cutter, operation, experiment, tests, slot, workpiece, tool-workpiece
conditions monitoring	Topic82	signal, acoustic, signals, emission, analysis, sound, technique, techniques, monitoring, processing, conditions, information, level, recorded, estimation
data sampling method	Topic83	variable, variables, method, interval, correlation, sampling, points, analysis, independent, selected, sample, data, distortion, window, eliminate
cooling and lubrication system	Topic84	cooling, cutting, dry, fluid, machining, air, lubrication, minimum, coolant, quantity, mql, temperature, environment, liquid, lubricant

linear interpolation algorithm	Topic85	feedrate, acceleration, trajectory, algorithm, velocity, jerk, linear, machining, smooth, profile, interpolation, planning, smoothing, efficiency, path
tool condition monitoring	Topic86	tool, monitoring, condition, cutting, wear, on-line, signals, breakage, system, process, detect, operations, online, reliable, real-time
computer aided design	Topic87	design, engineering, analysis, computer, prototype, designs, manufacture, cad, synthesis, mechanical, computer-aided, evaluation, redesign, built, requirements
HMI	Topic88	software, system, module, interface, platform, hardware, modular, electronic, interfaces, hmi, human, package, operating, post-processing, human-machine
micro-milling	Topic89	micro, diameter, micro-milling, small, size, micromachining, miniature, lapping, tools, precision, grooves, cylindrical, precise, mems, miniaturization
rotary axis movement of five-axis	Topic90	rotary, axis, machine, axes, angular, linear, head, position, rotational, five-axis, tools, movement, orientation, rotation, multi-axis
service manufacturing	Topic91	product, design, products, quality, service, requirements, process, cycle, customer, manufacturing, requirement, satisfy, association, feasibility, model
vibration suppression	Topic92	vibration, ultrasonic, frequency, amplitude, mode, high, frequencies, reduced, analyzed, reduction, resonance, forced, suppression, excitation, self-excited
remote control of machine tool	Topic93	industrial, control, systems, communication, real-time, network, automation, fieldbus, remote, networks, distributed, ethernet, requirements, protocol, safety
cutting force measurement	Topic94	cutting, force, forces, measured, coefficients, conditions, process, machining, feed, dynamometer, milling, resultant, mechanistic, estimate, end-milling
manipulator kinematic analysis of machine tool	Topic95	parallel, manipulator, kinematic, platform, freedom, kinematics, degrees, dof, hybrid, mechanism, dynamic, joint, space, degree, analysis
finite element analysis	Topic96	element, finite, analysis, method, simulation, fem, numerical, model, distribution, analyze, simulations, simulated, predict, modeling, three-dimensional
gear fault diagnosis	Topic97	gear, fault, vibration, planetary, gearbox, frequency, signals, faults, diagnosis, modulation, signal, planet, amplitude, components, analysis
wire cutting machining	Topic98	wire, machining, process, discharge, wedm, pulse, parameters, voltage, tension, gap, kerf, roughness, electrochemical, wire-edm, electro-discharge
motor	Topic99	motor, torque, mechanical, drive, linear, rotor, induction, synchronous, system, driven, stator, currents, voltage, electromechanical, coupling
adaptive tracking and disturbance rejection	Topic100	control, controller, tracking, system, disturbance, performance, adaptive, nonlinear, disturbances, law, linear, mode, dynamics, robustness, stability
distributed platform	Topic101	framework, information, integration, requirements, support, distributed, platform, environment, execution, software, collaborative, heterogeneous, prototype, interoperability, sharing
multifunctional machine tool	Topic102	systems, industrial, processes, components, tools, modern, industry, complexity, domains, applicability, adapted, handling, suggest, multifunctional, evolved
prognostics and health management of machine tool	Topic103	monitoring, condition, health, machine, data, status, degradation, diagnostic, machinery, maintenance, effective, assessment, prognostic, information, collected
statistical method	Topic104	distribution, density, probability, stochastic, threshold, random, statistical, gaussian, deterministic, value, function, distributions, normal, assumption, likelihood
hydraulic system reliability	Topic105	system, automatic, built, reliable, off-line, hydraulic, on-line, enhancement, determines, reliability, details, adapt, automated, specification, database
machine tool fixture	Topic106	workpiece, machining, setup, fixture, process, clamping, fixturing, case, locating, layout, position, machined, holding, clamped, location
spindle thermal deformation	Topic107	thermal, temperature, heat, deformation, rise, modeling, transfer, accuracy, spindle, robustness, field, points, expansion, regression, linear
surface roughness optimization	Topic108	surface, roughness, parameters, feed, cutting, rate, depth, values, burnishing, quality, spindle, turning, average, predicted, optimum
turbine blade processing	Topic109	analysis, wind, turbine, method, dimension, nonlinear, kernel, operation, sensitive, component, principal, linear, fractal, turbines, components

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damping design	Topic110	structure, machine, tool, damping, design, mechanical, hierarchical, large, symmetrical, generalized, flexibility, capability, heavy-duty, rigidity, theoretical
gear failure	Topic111	gear, tooth, crack, teeth, mesh, spur, transmission, damage, pitting, pair, hobbing, helical, cracks, fatigue, failures
CNC	Topic112	control, system, feedback, active, loop, actuator, piezoelectric, dynamic, real-time, subsystem, flexible, controlling, mechatronic, closed-loop, hysteresis
process parameter optimization	Topic113	process, parameter, influence, values, combination, setting, optimum, effect, analyzed, determining, optimal, suitable, measured, appropriate, optimizing
anti-collision algorithm	Topic114	space, collision, interference, multi-axis, algorithms, area, detection, simulation, avoidance, trajectory, collisions, efficient, accessibility, safe, collision-free
gear fault diagnosis	Topic115	fault, diagnosis, vibration, faults, detection, gearbox, gear, signals, machinery, condition, signal, rotating, diagnostic, monitoring, early
metal-based particle materials	Topic116	analysis, metal, principal, component, effective, hybrid, pca, multivariate, effect, particles, reinforced, properties, mechanical, mmcs, machinability
lubrication technology	Topic117	oil, film, pressure, hydrostatic, lubrication, flow, bearing, gas, aerostatic, lubricant, thickness, capacity, pump, performance, thrust
kalman filter method	Topic118	filter, loss, performance, filters, response, kalman, bandwidth, frequency, impulse, waveguide, insertion, suitable, filtering, coupling, low-pass
hob	Topic119	angle, rotation, tilt, model, pitch, degrees, helical, conical, inclination, mathematical, analyzed, simulation, hob, profile, edge
tool health management	Topic120	wear, tool, measured, diffusion, influence, cutting, affects, tool-wear, worn, severe, edges, crater, tool-life, predicting, estimate
error compensation	Topic121	error, compensation, accuracy, method, machine, precision, improve, reduced, experiment, positioning, measurement, straightness, volumetric, prediction, high-precision
machine learning	Topic122	classification, features, support, machine, classifier, svm, conditions, accuracy, extracted, data, recognition, feature, condition, classifiers, statistical
big data	Topic123	data, information, acquisition, real-time, collect, amount, collection, large, system, mining, huge, processed, management, database, data-driven
machine tool flexibility	Topic124	manufacturing, processes, systems, industry, tools, production, modern, automated, environment, integration, flexible, machine, global, productivity, flexibility
CNC	Topic125	program, cnc, programming, data, step-nc, iso, software, code, language, systems, file, cadcam, manufacturing, interface, step-compliant
MT technology forecasting	Topic126	future, industry, trends, techniques, field, analysis, developments, purpose, understanding, findings, aspects, comprehensive, areas, reviews, contribution
heuristic algorithm	Topic127	problem, solve, solution, optimal, heuristic, algorithm, programming, processing, search, minimize, sequence, formulated, machines, computational, parallel
open CNC system	Topic128	system, cnc, architecture, control, open, real-time, controller, software, computer, numerical, embedded, kernel, pc-based, remote, intelligent
part surface defect detection	Topic129	detection, defect, detect, damage, analysis, test, localized, processing, case, early, on-line, location, anomalies, identifying, serious
ultrahigh-speed machining	Topic130	machining, process, quality, productivity, efficient, work-piece, parameters, cost, essential, conditions, ultrahigh-speed, multi-tool, economics, powerful, high-efficiency
machine tool condition monitoring	Topic131	process, quality, control, manufacturing, chart, monitoring, statistical, variables, improvement, product, monitor, improve, productivity, adaptive, actions
image recognition	Topic132	image, vision, object, processing, spatial, visual, camera, recognition, area, digital, automatic, tracking, video, three-dimensional, vision-based
structure design	Topic133	component, structural, structure, design, mechanical, performance, topology, essential, weight, interaction, case, aspects, reasonable, inherent, topologies
cutting tool wear	Topic134	cutting, tool, tools, carbide, wear, steel, machining, materials, coated, hard, inserts, turning, conditions, inconel, machinability
expert system	Topic135	knowledge, system, expert, process, information, base, database, engineering, reasoning, case, rules, experience, human, data, knowledge-based

CNC system	Topic136	digital, unit, system, hardware, processing, processor, field, programmable, signal, fpga, array, gate, structure, plc, dsp
machine tool kinematics modeling	Topic137	motion, direction, circular, axis, method, vertical, tests, trajectory, linear, planar, rotational, double, three-axis, longitudinal, horizontal
efficiency improvement	Topic138	efficiency, processing, high, quality, improve, improved, increase, amount, enhance, feasibility, analyzing, situation, plane, maintaining, superiority
deep learning	Topic139	learning, deep, algorithms, cluster, representations, online, framework, datasets, clusters, supervised, unsupervised, dataset, classification, convolutional, temporal
surface 3D reconstruction	Topic140	surface, point, free-form, method, mesh, sampling, engineering, reconstruction, reverse, cad, distance, shape, subdivision, three-dimensional, boundary
grinding process	Topic141	grinding, wheel, process, workpiece, ground, surface, machine, diamond, grinder, profile, belt, cylindrical, efficiency, abrasive, micro-grinding
virtual reality and augmented reality	Topic142	virtual, reality, environment, augmented, industrial, task, training, interaction, display, visualization, cognitive, scenario, interface, operator, intuitive
high speed and high precision machine tool	Topic143	high, accuracy, precision, improve, dimensional, higher, productivity, high-precision, resolution, parts, requirements, performance, machining, cost-effective, high-quality
laser interferometer	Topic144	laser, beam, zone, scanning, quality, continuous, taper, interferometer, width, cnc, power, direction, materials, laser-assisted, heat-affected
electric discharge machining	Topic145	discharge, edm, machining, pulse, electrical, process, gap, plasma, duration, voltage, workpiece, crater, spark, arc, dielectric
cutting process	Topic146	cutting, depth, cut, radial, axial, milling, feed, width, high-speed, process, machining, maximum, groove, tangential, immersion
residual stress	Topic147	stress, residual, fatigue, material, alloy, strength, stresses, titanium, high, properties, resistance, mechanical, aluminum, materials, effect
lathe machining process	Topic148	turning, tool, cutting, lathe, machining, process, workpiece, machine, operation, ultra-precision, cylindrical, roundness, diamond, turned, flycutting
drilling	Topic149	drilling, hole, drill, holes, thrust, process, diameter, force, burr, feed, deep, drills, spindle, quality, steel
digital modeling of machine tool	Topic150	simulation, model, numerical, mathematical, modelling, dynamic, verification, simulate, purpose, simplified, matlab, simulator, software, finite-element, comprehensive
contour error control	Topic151	contour, error, tracking, control, controller, trajectory, motion, position, accuracy, axis, cnc, multi-axis, desired, cross-coupled, reduced
tool path planning	Topic152	machining, toolpath, corner, high-speed, length, sharp, toolpaths, corners, curvature, hsm, height, continuous, path, zones, lengths
cloud computing and Cyber-physical system	Topic153	cloud, computing, service, internet, architecture, devices, physical, fog, resources, things, industrial, platform, IoT, cyber-physical, cyber
machine tool fixture	Topic154	tool, machine, holder, tools, tests, equipped, productivity, part, simplified, avoiding, incorporate, amplification, tool-setting, test, installed
reconfigurable machine tool	Topic155	configuration, design, machine, reconfigurable, systems, requirements, manufacturing, changes, flexible, flexibility, machines, reconfiguration, modular, rapid, scalability
efficiency improvement	Topic156	method, effectiveness, accuracy, efficiency, efficient, characteristic, improve, combines, experiment, suitable, efficiently, acquire, first-order, off-line, repeated
machining process	Topic157	milling, cutting, tool, cutter, deflection, edge, workpiece, mill, ball-end, forces, engagement, angle, surface, direction, ball
hidden markov model	Topic158	estimation, model, state, method, markov, hidden, prediction, accurate, remaining, parameters, estimator, online, bayesian, algorithm, hmm

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