Printed circuit board and printed circuit board assembly methods for testing and visual inspection: a review

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Article Info	**ABSTRACT**
	Testing and visual inspection of printed circuit boards (PCBs) and printed circuit board assemblies (PCBAs) are important procedures in the manufacturing process of electronic modules and devices related to locating and identifying possible defects and failures. Earlier defects detection leads to decreasing expenses, time and used resources to produce high quality electronics. In this paper an exploration and analysis about the current research regarding methods for PCB and PCBA testing, techniques for defects detection and vusial inspection is performed. The impact of machine and deep learning for testing and visual inspection procedures is also investigated. The used methodology comprises bibliometric approach and content analysis of papers, indexed in scientific database Scopus, considering the queries: "PCB and testing" and "PCB and testing", "printed circuit board assembly and testing" and "PCBA and testing", "PCB defect detection" and "PCBA defect detection", "PCB and visual inspection", and "PCBA and visual inspection". The findings are presented in the form of a framework, which summarizes the contemporary landscape of methods for PCBs and PCBAs testing and visual inspection.

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1. INTRODUCTION

Testing of printed circuit boards (PCBs) and printed circuit board assemblies (PCBAs) is an important procedure in manufacturing of electronic modules and devices that guarantee timely check for quality of the performed operations and finally the quality of the product. Nowadays, the manufacturing is "smart" as quality control is often performed through automatic optical inspection (AOI) to verify and validate important production tasks [1], to prevent appearance of defects in electronics production and to notify an operator [2], even for identification of micro-size defects on PCB [3]. Statistics approaches are also applied such as failure mode and effects analysis for quality control improvement [4] and statistical process control for monitoring the quality of the manufacturing process and for obtaining quality of the end product [5]. Artificial intelligence is increasingly entering for supporting conductance of different tasks such as optimization of the components position [6], as well as machine learning for detecting patterns or anomalies on PCB [7] and deep learning for defects classification in PCB production [8].

PCBs are used to provide mechanical support of mounted electronic components. They are produced from non-conductive material with conductive parts in the form of traces, pads, and conductive planes that are printed or engraved. Electronic components are mounted on the circuit board and conductive traces

connect them to create a working electrical circuit or PCBA mainly through surface mount technology [9], [10]. PCBs possess important meaning for the final electronic product, because they provide electrical connections between components, a rigid support to hold components, and a compact package that can be integrated into a final product.

PCBs testing is a crucial step of their development cycle that leads to saving time and resources and to prevent problems that could occur at the final production. These are the reasons some techniques for analysis to be performed during the early stages of PCBs manufacturing and several testing methods to be applied. These tests, conducted on prototypes or small scales, examine the potential shorts, solder joints, and solder functionality, ensuring that each tested board will not possess defects and damages.

Testing of PCBAs is also a key step addressing the check whether all components are placed and mounted correctly on the PCB and whether the assembly functions are as it is expected [11]. A wide variety of testing methods and methodologies exists in electronics as some of them are well accepted in practice, others are only in theoretical development. Anyway, new approaches also emerged to respond to the new specific characteristics of contemporary technologies and requirements to the PCBs and PCBAs. Recently, the role and contribution of artificial intelligence, machine and deep learning in PCBs and PCBAs testing is explored as solutions for minimizing the time for testing, reducing the cost of the manufactured electronic products, reducing efforts and resources and increasing the reliability of the final products [12], [13].

The goal of visual inspection is related to ensure PCBs and PCBAs quality control. The old way is based on operators nake-eyes as recently are applied several modern approaches that are classified in three groups: reference inspection methods, non-reference methods and hybrid inspection methods [14]. The research questions in this work are defined as:
− What are the most investigated methods and techniques for PCB and PCBA testing and visual inspection in the last five years? and
− What is the impact of machine and deep learning on methods for PCB and PCBA testing and visual inspection?

The answers of these questions will lead to drawing and understanding where the researchers' efforts are mainly directed recently, what are the main contemporary problems they solve and what are future trends and directions. The aim of the paper is to summarize and analyze the actual and current methods and techniques for PCBs and PCBAs testing and visual inspection as well as to outline the meaning of artificial intelligence, machine and deep learning in the testing process and visual inspection of PCBs and PCBAs. This will point out challenging problems, tendences and possible future lines for research. The contributions in this work are related to:
− Conductance of an investigation and analysis of contemporary methods for PCB and PCBA testing and visual inspection through applying bibliometric approach and examination the content of full-papers.
− Outlining the role of machine and deep learning for solving different problems in PCB and PCBA testing and visual inspection.
− Creating a framework that summarizes the current research landscape regarding the most investigated methods for PCB and PCBA testing and visual inspection.

The rest of the paper is organized as follows. In section 2 the used methodology is described. Section 3 presents an investigation regarding methods for PCB testing. The contemporary methods for PCBA testing are explored in section 4. Methods and techniques for PCB and PCBA defect detection are examined in section 5. Section 6 includes investigation concerning methods for PCB and PCBA visual inspection. In section 7 the main findings are summarized as a framework with contemporary approaches for PCB and PCBA testing and visual inspection is created. Section 8 is the conclusion.

2. USED METHOD

Analysis of the current achievements in PCBs and PCBAs testing and visual inspection, including the utilization of artificial intelligence and machine learning is performed following the several procedures and the used methodology is presented in Figure 1.
a. Queries forming and search conducting: eight different queries are formed: "printed circuit board and testing" and "PCB and testing", "printed circuit board assembly and testing" and "PCBA and testing", "PCB defect detection" and "PCBA defect detection", "PCB and visual inspection" and "PCBA and visual inspection" and submitted for searching in article title, abstract and keywords in Scopus abstract and citation scientific database. Scopus is chosen, because it includes a big amount of bibliometric data of high quality articles in engineering and informatics domains. The bibliometric data are taken on 31.07.2023.
b. Applying filters and sorting: the first applied filter concerns the investigated term that settles a five-year period: from 2018 to 2022, including the indexed papers during 2023 year. The second filter sets only scientific articles in English language to be examined. The returned results are ordered according to their relevance.

c. Bibliometric analysis: bibliometric techniques are used to outline the whole picture in the investigated area and to give an overall view on the current research. Bibliometric analysis is chosen, because it is accepted and preferred approach that is utilized in a wide variety of fields for scanning the research landscape and pointing out trend topics [15], [16] as well as for finding the most influenced journals, authors, countries and researched themes [17], [18]. For conductance of bibliometric analysis, R studio software and biblioshiny application are used [19]. The accent is given on: i) annual scientific production to understand the interest to the investigated topics, ii) the most relevant sources that publish articles in the researched topics, iii) the most frequent keyword used by authors to describe the articles content, iv) trend topics that direct the contemporary research, and v) co-occurrence network to understand the relationship between two terms and how terms are thematically organized in clusters.

d. Full-text papers analysis: analysis of the most relevant full-text papers is performed considering the obtained results after submitting eight queries. Also, the open access articles are considered for further examination, when it is possible. The analysis summarizes the used investigative approaches and obtained findings.

e. Framework development: a framework that summarizes the revealed findings is created to demonstrate the most common and contemporary researched methods and techniques for PCB and PCBA testing and visual inspection.
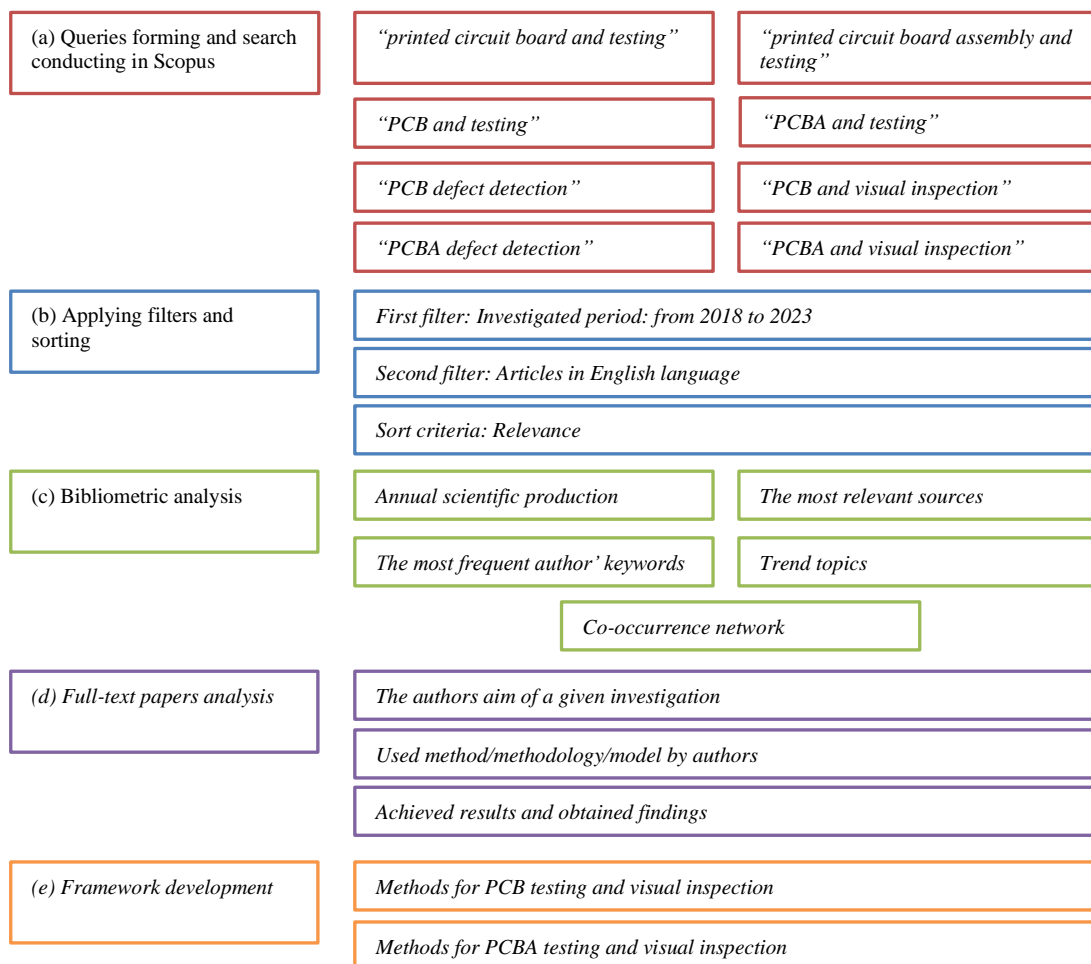

Figure 1. Used method

3. EXPLORATION REGARDING TESTING OF PCBs

For bibliometric analysis, the search is performed in Scopus scientific database as queries "PCB and testing" and "PCB and testing" are submitted. The returned results from the first query "PCB and testing" comprises 876 documents and from the second query "PCB and testing" 875 documents considering the described methodology in the previous section.

The annual scientific production is depicted on Figures 2(a) and (b) as the both curves, corresponding to the both queries, are characterized by irregularities. The published and indexed articles for 2022 are 174 and 167 for the first and second query, respectively. However, it can be noted that interest in the topic has not decreased in the last five years as the number of published and indexed articles are nearly similar. Documents so far for 2023 year are 86 for the first query and 81 for the second query.
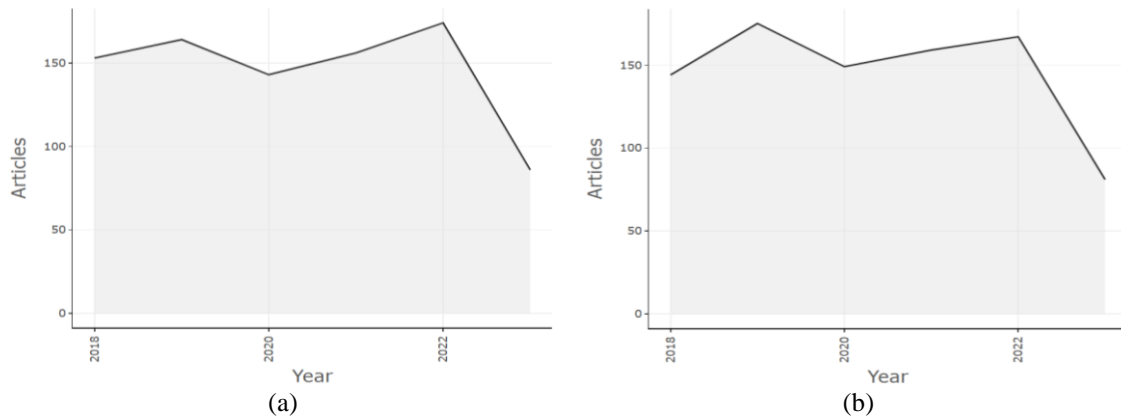

(a)   (b)

Figure 2. Annual scientific production concerning the query: (a) "printed circuit board and testing" and (b) "PCB and testing"

The articles are most often published in Proceedings of the Conference Electronic Components and Technology Conference, IEEE Transactions on Components, Packaging and Manufacturing Technology, Microelectronics Reliability, Sensors, Science of the Total Environment, Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems, IEEE ACCESS, IEEE Transactions on Instrumentation and Measurement, Journal of Physics: Conference Series as details about the publishing sources are presented through Figures 3(a) and (b). It can be seen that the papers are mainly submitted in journals and scientific conference proceedings in the field of electronics, which is understandable since testing is about ensuring quality of electronics production.
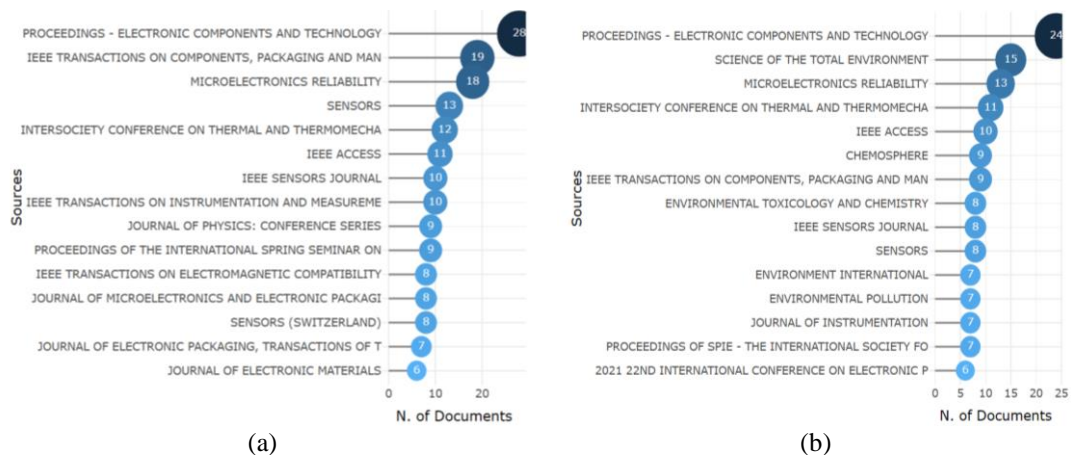

(a)   (b)

Figure 3. The most relevant sources for the query: (a) "printed circuit board and testing" and (b) "PCB and testing"

The most used keywords by authors in their papers are related to: PCB and testing and different methods for analysis like: deep learning, machine learning, failure analysis, defect detection, finite element analysis, image processing (Figures 4(a) and (b)). Another the most utilized keywords are: reliability, solder joint, eddy current, flexible PCB. In both requests, the authors describe the article content through applying almost the same keywords in their articles. Author's keywords analysis shows that in recent years the interest

related to the use of machine and deep learning in testing has grown, and this approach has developed in parallel with conventional methods.
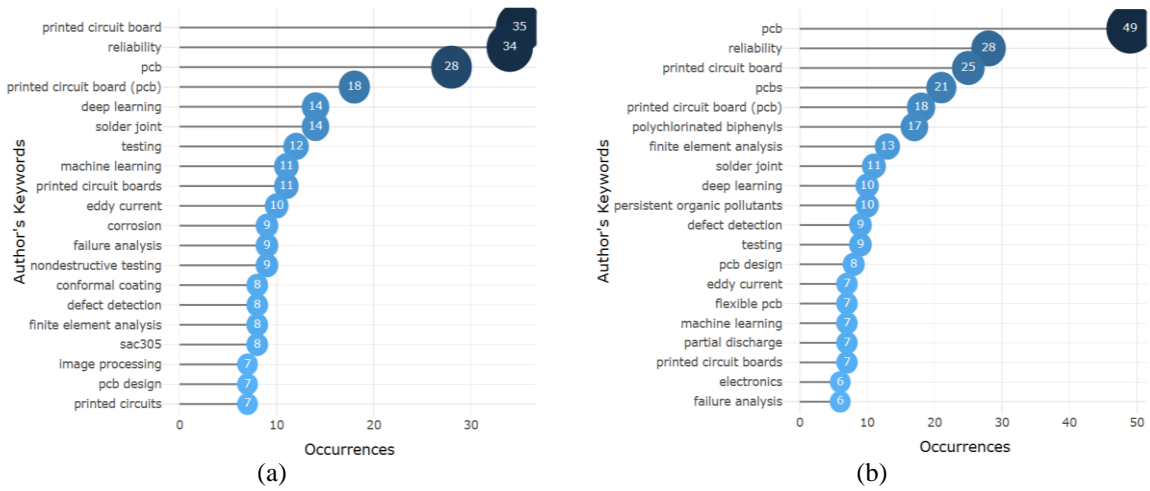

Figure 4. The most frequent keywords used by authors considering the query: (a) "printed circuit board and testing" and (b) "PCB and testing"

Considering the both queries the trend topics for 2022 years are described with the keywords: deep learning, machine learning, sensors, printed circuit board, reliability, testing, automotive, anand viscoplastic model, conformal coating (Figures 5(a) and (b)). Trend topics also confirm and outline the increased research that includes machine and deep learning at PCB testing.
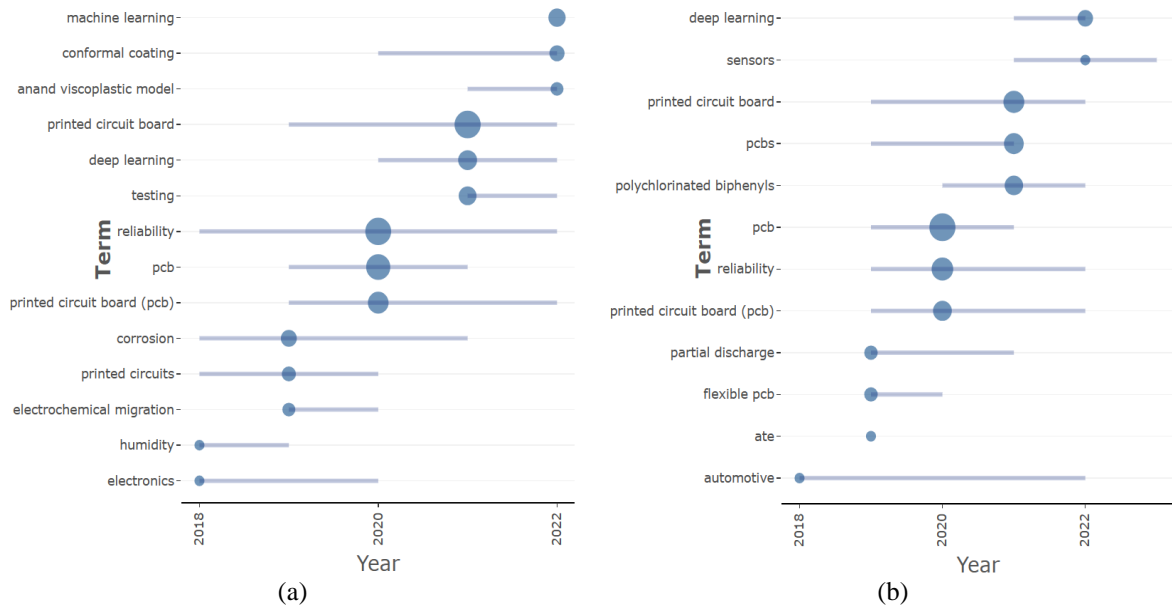

Figure 5. Trend topics regarding the query: (a) "printed circuit board and testing" and (b) "PCB and testing"

The created co-occurrence networks consist of eight and seven different clusters considering respectively the queries "PCB and testing" and "PCB and testing" (Figures 6(a) and (b)). It is noticeable that the clusters are separately formed and unconnected or weakly connected to other clusters. The biggest cluster considering the query "PCB and testing" is formed around the term reliability, which is connected with the terms solder joint, PCBs, corrosion, electrochemical migration, humidity, electronics, thermal cycling. A

separate cluster with linked terms: printed circuit board, deep learning, defect detection, and AOI also stands out. A small cluster is organized around the terms PCB and failure analysis. The biggest cluster regarding the query "PCB testing" is constructed around the core term PCB, which is connected with the terms reliability, finite element analysis, testing, FPGA, and design. Another cluster brings the terms printed circuit board, deep learning and defect detection together as this cluster is linked to a smaller cluster with the terms: PCB inspection, computer vision, image processing. It can be said that the most mentioned term at PCB testing is reliability. Also, at the both queries, clusters indicating relatedness of terms printed circuit board, deep learning and defect detection are distinguished from other clusters.
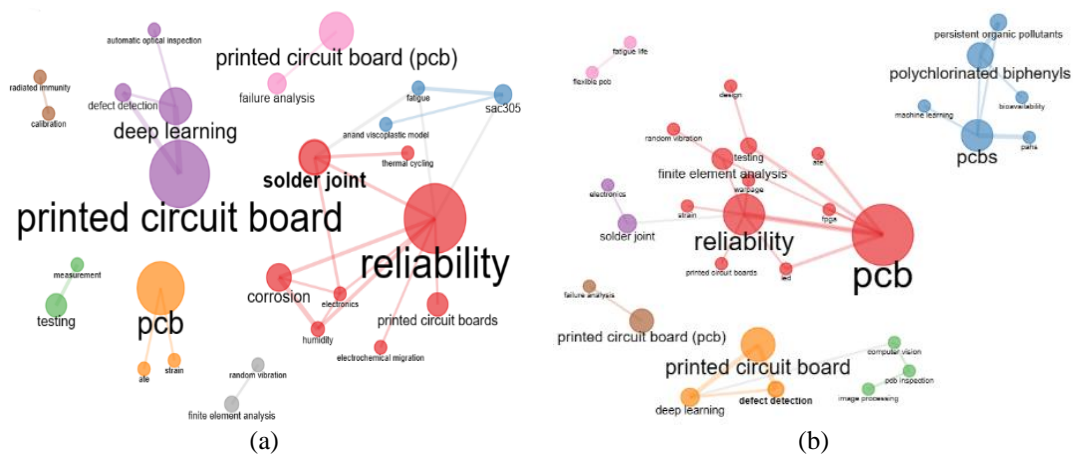

Figure 6. Co-occurrence network regarding the query: (a) "printed circuit board and testing" and (b) "PCB and testing"

The bibliometric analysis outlines the overall picture in the PCB testing and it can be summarized that the number of articles published and indexed in Scopus during the studied period is close in value, which speaks of the continuous interest in the topic by researchers. The articles are mainly published in scientific proceedings of electronics conferences and journals, which is understandable since PCB testing is a research field in electronics. It is interesting to note that among the most frequently used keywords by the authors are not only terms specific to testing and electronics, but also terms from the field of informatics, such as machine and deep learning. This leads us to the conclusion of the increased importance in our modern age of machine and deep learning for testing. This conclusion is also confirmed by the terms involved in the trend topics, as along with sensors, printed circuit board, reliability, testing, are also included deep learning and machine learning. Clusters stand out in the examined co-occurrence networks, the largest of which include terms from electronics, such as solder joint, PCBs, corrosion, electrochemical migration, humidity, electronics, thermal cycling in one cluster and printed circuit board, deep learning, defect detection, and AOI in another cluster. The meaning of the term reliability, which has the greatest frequency of usability by authors, should be emphasized. A smaller cluster is also formed, uniting the terms: PCB inspection, computer vision, image processing. It outlines the entry of machine and deep learning, as well as technologies from computer vision and image processing into PCB testing. Further exploration of the topic is performed through content analysis of relevant articles, indexed in Scopus and mainly with open access.

Azin *et al.* [20] propose a method for non-destructive testing, which combines acoustic emission technique for finding design defects on PCB and X-ray tomography for identification of the dimension of the found critical defects. Solder joints with identified defects are analyzed for understanding their stress-strain state. The method is capable of identifying PCB design defects, to analyze whether they are critical and to estimate the PCB residual usage.

The work of Elliot and Brown [21] is focused on investigation regarding the meaning of PCB traces and their angle bends (no bend, 45°, and 90°) for the maximal current conductance, location and time for possible failure. The presented methodology for testing is destructive and the findings outline that the maximal current passes PCB traces in a similar way and there is no significant difference when different angle bends are used (no bend, 45°, and 90°). The authors point out as future work an investigation regarding the influence of width, thickness, and angle bends (different of 45° and 90°) of traces on failure and reliability of PCBs.

Wileman *et al.* [22] present an approach for virtual testing of PCB and PCBA considering computer aided design (CAD) model and techniques like computational fluid dynamic and finite element analysis. Then, through simulations are tested different PCB characteristics and an assessment is performed regarding the reliability of the electronic system. The used method is called physics of failure, showing PCB behavior over time and how different mechanisms (physical and thermal) could lead to failure. This allows the risk problems to be identified during design of the electronic product and some failure issues to be removed.

Li *et al.* [23] develop a new sensor for defects detection on metal surface, which functionality is related to identified changes in frequency or magnitude. The testing is non-destructive and the sensor is capable through electrode probe to locate notch damages, their dimension and orientation.

Oliveira *et al.* [24] propose a methodology to prevent excessive bending strain in important PCB's points when in-circuit test is performed. It is based on finite element analysis and is verified through experimentation. This methodology gives the possibility PCB maximal strain at in-circuit test to be predicted and to understand whether such test could damage PCB.

Volkau *et al.* [25] present an approach for usage of unsupervised deep learning and transfer learning through deep convolutional neural network (CNN) for detecting PCB defects on images (scratch, broken PCB edge, and hole). Defects on PCB images are found considering the distance to clusters with normal PCB features as the recognition rate is high.

Nguyen and Bui [26] apply algorithms for feature extraction from images and supervised deep learning to detect defects on PCB surface in real time. The proposed system combines brute force matching technique, oriented FAST and rotated BRIEF (ORB) and random sample consensus (RANSAC) algorithms for defect detection and for testing the PCB quality. The advantages are robustness against noise, high speed computation (usage of ResNet-50), visual inspection in real time and with high precision.

Silva *et al.* [27] apply principles of transfer learning and VGG16/ResNet-50 pre-trained models for identifying the defective PCBs and also non-referential method for inspection. Findings related the queries "printed circuit board and testing" and "PCB and testing" are summarized in Table 1 as the method/methodologies for testing and their aim are presented.

Table 1. Contemporary methods for PCB testing

Paper	Method/methodology	Aim
Azin *et al.* [20]	− Non-destructive testing − Acoustic emission technique − X-ray tomography	− Finding design defects on PCB − Analyzing whether defects are critical − Estimate the PCB residual usage
Elliot and Brown [21]	− Destructive testing	− PCB bend angle traces influence on the maximal current conductance, location, and time − Possible failure
Wileman *et al.* [22]	− Virtual testing of PCB and PCBA through computational fluid dynamic and finite element analysis (physics of failure)	− Risk problems to be identified during design of the electronic product − Failure issues to be removed
Li *et al.* [23]	− Sensor identified changes in frequency or magnitude − Non-destructive	− Defects detection on metal surface − Locate notch damages, their dimension, and orientation
Oliveira *et al.* [24]	− Finite element analysis	− To prevent excessive bending strain in important PCB's points when in-circuit test is performed − PCB maximal strain at in-circuit test to be predicted − To understand whether such test could damage PCB
Volkau *et al.* [25]	− Unsupervised deep learning and transfer learning	− Detecting PCB defects on images (scratch, broken PCB edge, and hole)
Nguyen and Bui [26]	− Algorithms for feature extraction from images and supervised deep learning	− PCB defect detection − Visual inspection in real time
Silva *et al.* [27]	− Transfer learning and VGG16/resnet-50 pre-trained models	− Identifying the defective PCBs − Non-referential inspection

4. INVESTIGATION CONCERNING PCBA AND TESTING

The queries "PCBA and testing" and "PCBA and testing" return respectively 51 and 43 documents, which is significantly less than the previous request. Scientific production is characterized with irregular curves with a big distance between the minimum and maximum values (Figures 7(a) and (b)). The published and indexed in Scopus papers for 2022 year for the both queries are respectively 10 and 7. The maximal values are 14 produced and indexed in Scopus documents in 2019 year for the first query and 11 documents in 2018 year for the second query.
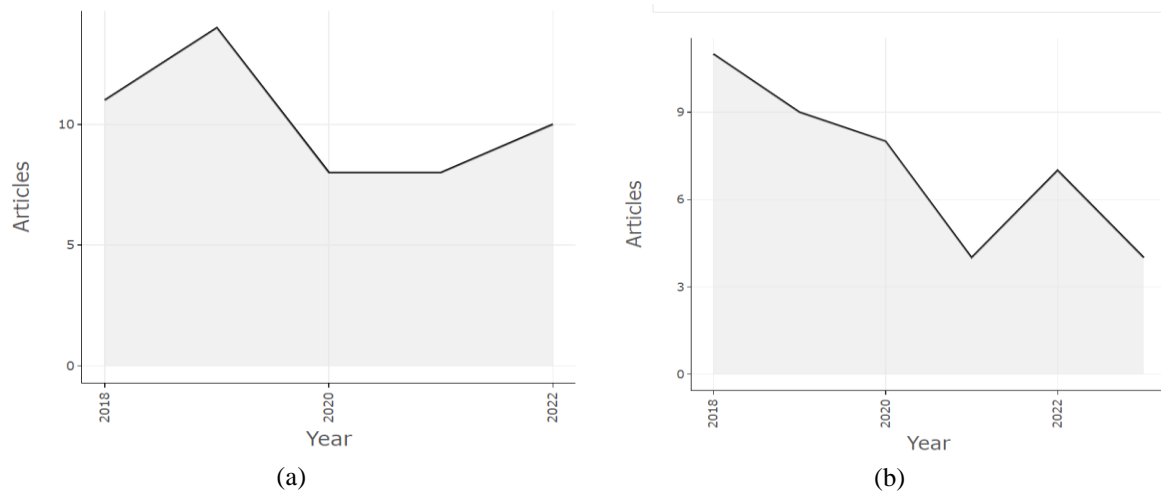
Figure 7. Scientific production for the query: (a) "printed circuit board assembly and testing" and (b) "PCBA and testing"

Among the most used keywords by authors are: printed circuit board, reliability, contactless testing, humidity and accessibility (Figures 8(a) and (b)). The terms augmented reality (AR), defect detection and automated optical inspection are also part of the keywords palette. Trend topic for the both queries is pointed out to the keyword reliability.
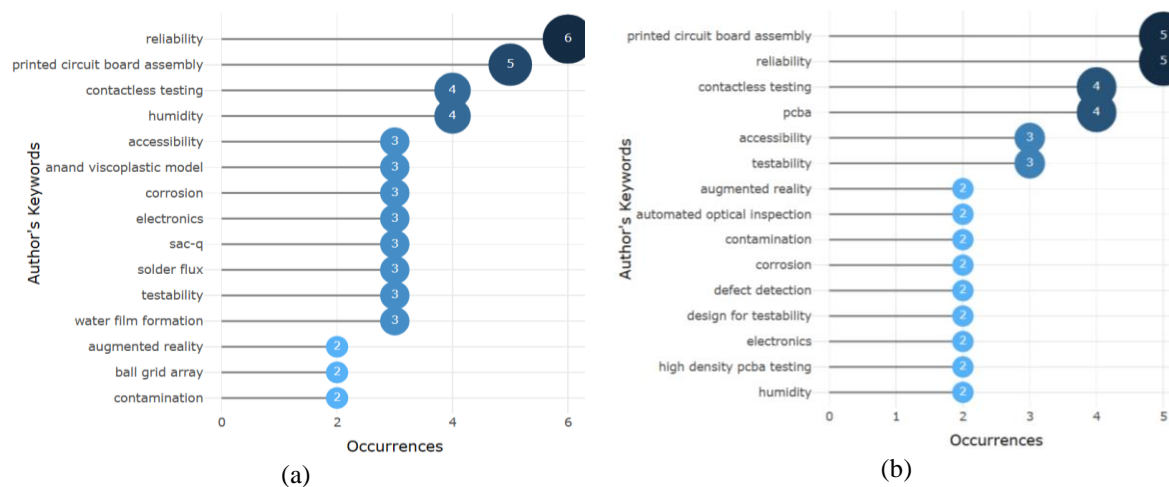

Figure 8. The most frequent keywords regarding the query: (a) "printed circuit board assembly and testing" and (b) "PCBA and testing"

Co-occurence networks are presented on Figures 9(a) and (b) as they are very similar for the both queries. Two bigger clusters are observed respectively around the term contactless testing and reliability. The cluster with the core term contactless testing also includes the terms: accessibility, testability, in-circuit test, principal component analysis, magnetic sensors, high density PCBA testing, design for testability, PCB assembly production test. A smaller cluster is formed around the keywords PCBA and smart manufacturing. Another small cluster connects terms PCBA testing, thermal signatures and defect detection. A cluster that connects the terms optical see-through and AR is also part of the networks.

If we summarize it can be said that the scientific output is significantly less for queries "PCBA and testing" and "PCBA and testing" compared to research related to PCB testing. This, however, opens up a wide field for future research and possibilities for proposing new testing approaches. Among the most frequently used keywords by the authors and related to PCBA testing are contactless testing, defect detection and automated optical inspection, which suggests that the research in the relevant articles is focused on these

themes. AR is also seen as an applicable technology in PCBA testing. The keyword reliability is indicated as a trend, which points out the main goal of the conducted research in the field of testing. The keywords around which the two largest clusters are formed in the co-occurrence networks are contactless testing and realiability, which again confirms the extremely increased importance of these terms.
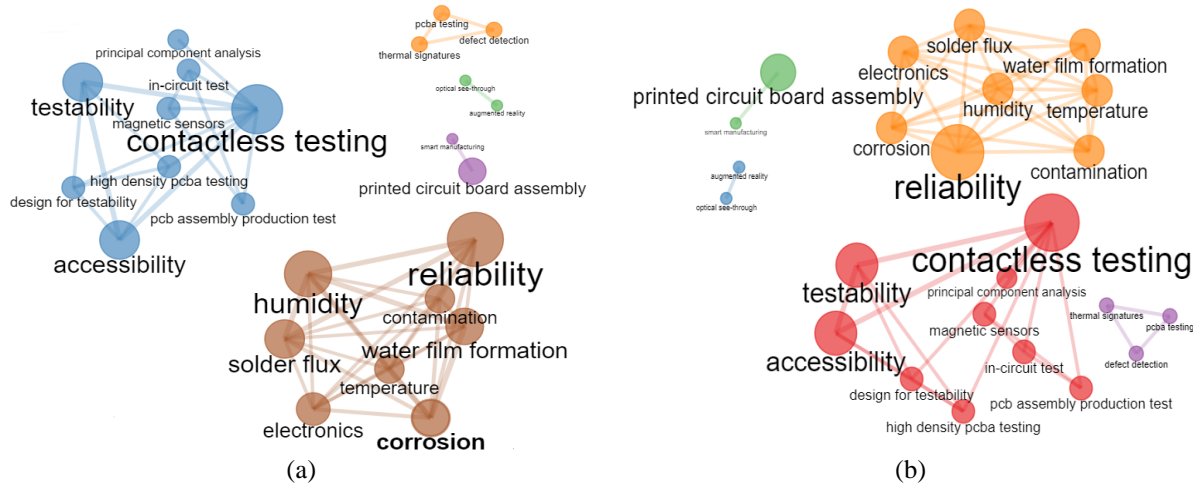

Figure 9. Co-occurrence networks regarding the query: (a) "printed circuit board assembly and testing" and (b) "PCBA and testing"

The above analysis of the full-text articles reveals in more detail the specifics of contemporary methods for PCBAs testing. It is done mainly on articles with open access.

Alaoui *et al.* [28] introduce usage of the technique infrared thermal signatures for PCBA testing regarding defects detection. This approach is capable of performing contactless diagnoses of faulty capacitors when the physical access to PCBA is limited. Other defects that could be identified are: component presence and polarity, shorts and opens. The components mounted on PCBs as well as the PCBAs are classified in three groups: reliable, less reliable and faulty. A drawback of the method is mentioning the need for more time for testing.

Qiu *et al.* [29] are developed a capacitive resonator sensor for defect detection (shorts and opens on metallic traces) on PCBAs. The structure and functionality of the sensor is explained, showing its potential for usage in manufacturing. The future work will address preparation of a sensing array with this sensor with the goal the measurement speed to be increased.

Alaoui *et al.* [30] are developed a technique for contactless diagnostics of faulty components on PCBAs applying electromagnetic signatures. Electromagnetic field probes are used for field distribution detection over PCBA components and magnetoresistance sensor for identifying changes in these components that work with low frequency. Electromagnetic signatures are taken from PCBA with correct components and are compared with PCBAs with wrong ones (with other values or removed components). According to the amplitude of a given harmonic could be identified changes in components values.

In work of Liu *et al.* [31] is talking about the application of time domain reflection (TDR) technology for failure location on PCB and PCBA. TDR is a non-destructive method and is used in different areas for failure analysis as the authors prove its suitability in the electronic industry.

Tsenev *et al.* [32] conduct functional test to measure deformation of PCBA as testing standards of mounting surface are applied. Practical experimentation is performed through an intelligent measurement system and some results are presented.

Wanchun *et al.* [33] discuss usage of resistance strain test in a PCBA process and whether strain can introduce damage of PCBA. The work shows effective identification of PCBA strain distribution and measures for strain reduction.

Runji and Lin [34] argue that AR technology can support the PCBA inspection process and present the developed markerless AR-based PCBA inspection system with features for defects identification and for safe work of inspectors.

Bonaria *et al.* [35] propose an approach for optimizing the workability of in-circuit testers through re-arranging the probes movement on PCBA and reducing testing time. It proved the effectiveness of the presented solution.

Le *et al.* [36] use image processing technique for identifying missing components on PCBAs and for inspection of solder joints. The developed AOI system is characterized with high accuracy and speed. Findings extracted from some of the most relevant papers regarding the PCBAs testing, found in Scopus for the term 2018-2023 year, are summarized in Table 2.

Table 2. Methods for PCBA testing

Paper	Method/methodology	Aim
Alaoui *et al.* [28]	– Infrared thermal signatures – Contactless diagnose of faulty capacitors	– Defects detection at PCBA testing: component presence and polarity, shorts, and opens
Qiu *et al.* [29]	– Developed capacitive resonator sensor	– PCBAs defects detection (shorts and opens on metallic traces)
Alaoui *et al.* [30]	– Contactless diagnostics of faulty components on PCBAs applying electromagnetic signatures	– Identification of changes in components values
Liu *et al.* [31]	– Non-destructive – Time domain reflection technology	– Failure location on PCB and PCBA – Failure analysis
Tsenev *et al.* [32]	– Functional test	– Measure deformation of PCBA
Wanchun *et al.* [33]	– Resistance strain test	– Identification of PCBA strain distribution and measures for strain reduction
Runji and Lin [34]	– AR technology	– PCBA inspection – Defects identification and for safe work of inspectors
Bonaria *et al.* [35]	– Re-arrangement the probes movement on PCBA	– Reducing testing time – Optimizing the workability of in-circuit testers
Le *et al.* [36]	– Image processing technique	– Identifying missing components on PCBAs – Inspection of solder joints

5. RESEARCH RELATED TO DEFECTS DETECTION ON PCB AND PCBA

The returned result regarding the query "PCB defect detection" comprises 92 documents and 4 documents for the query "PCBA defect detection" for the investigated period 2018-2023 year as the graphics of scientific production is presented on Figures 10(a) and (b). It is characterized with an increasing curve, which is an indicator of the increased interest in the subject.
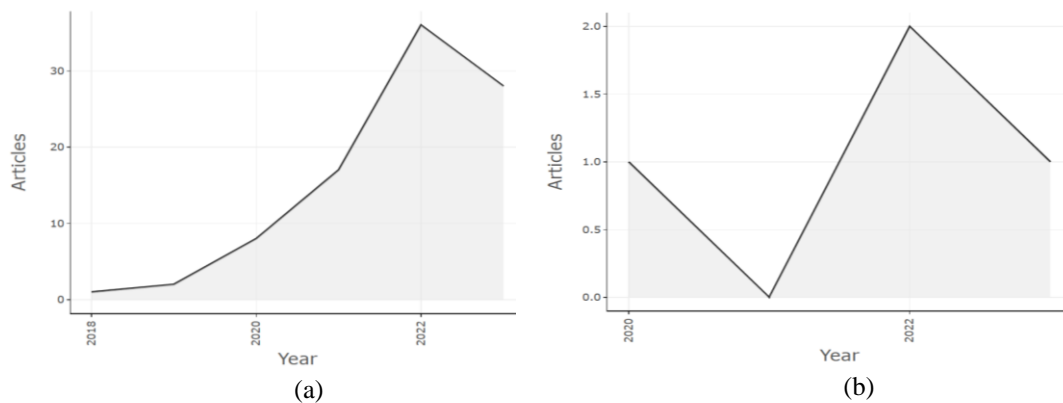

Figure 10. Annual scientific production concerning the query: (a) "PCB defect detection" and (b) "PCBA defect detection"

The research articles are published mainly in Communications in Computer and Information Science, IEEE Access, Proceedings of SPIE-The International Society for Optical Engineering, ACM International Conference Proceeding Series, IEEE Transactions on Instrumentation and Measurement, Journal of Physics: Conference Series, Sensors, Yi Qi Yi Biao Xue Bao/Chinese Journal of Scientific Instrument as it is shown on Figures 11(a) and (b). It should be noted that the articles are published not only in journals and scientific collections in the field of electronics, but also in the area of computer and information technologies. This suggests that new computer and information technologies are also involved in the PCBs and PCBAs defect detection.
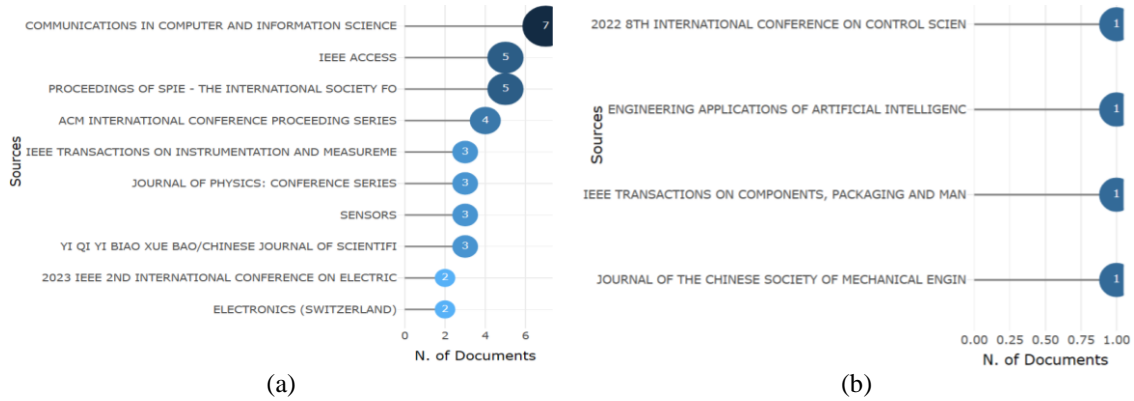
(a)

(b)

Figure 11. The most relevant sources taking into account the query: (a) "PCB defect detection" and (b) "PCBA defect detection"

The most used keywords by authors for better description of the paper's content are related to defect detection and PCB and methods used for this detection: deep learning, attention mechanism, object detection, CNN, and you only look once (YOLOv5) (Figures 12(a) and (b)).

Trend topics extracted from the author's keywords considering the query "PCB defect detection" for 2023 years are: PCBs and deep learning (Figure 13). For the query "PCBA defect detection" trend topics cannot be extracted, because of the extremily small number of returned documents.
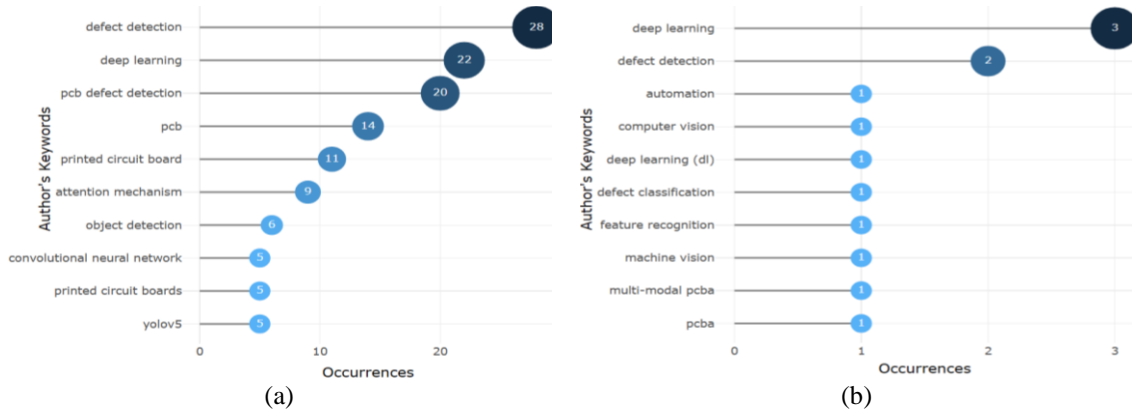

(a)

(b)

Figure 12. The most frequent author keywords for the query: (a) "PCB defect detection" and (b) "PCBA defect detection"
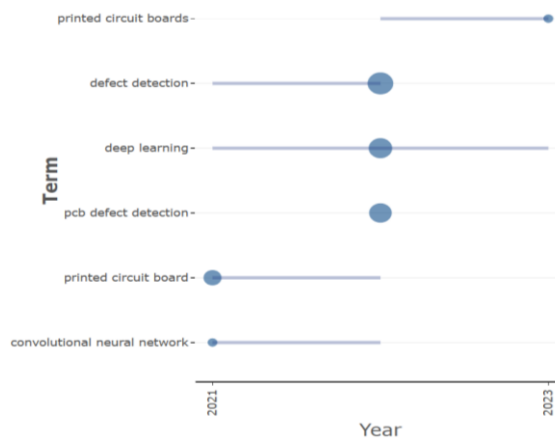

Figure 13. Trend topics for the query: "PCB defect detection"

Figures 14(a) and (b) visualizes co-occurrence networks for the results from the both passed queries. Documents obtained after the query "PCB defect detection" are characterized with a co-occurrence network with two clusters, which are closely connected. The bigger cluster is formed around the terms defect detection and deep learning. Other connected terms in this cluster are: printed circuit board, object detection, CNN, image processing, machine vision, and residual network. The second cluster links author's keywords that are often used together: PCB defect detection, attention mechanism, clustering algorithm, yolo, swin transformer, and component. The co-occurrence network for the query "PCBA defect detection" connects two terms deep learning and object detection. From the formed clusters and used terms entire them can conclude that the role of deep learning plays important role at PCB and PCBA defect detection.
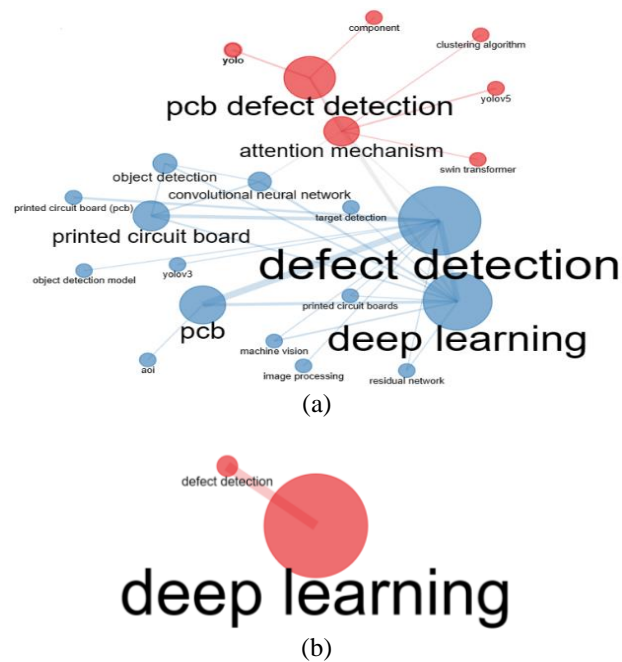

(a)

(b)

Figure 14. Co-occurrence network for the query: (a) "PCB defect detection" and (b) "PCBA defect detection"

It can be seen that more often the articles are devoted to research related to PCB defect detection and very few of the studies are focused on PCBA defect detection. Articles are published not only in conference proceedings and scientific journals in the field of electronics, but publications in those devoted to information and computer technologies are already observed. Among the most frequently used keywords by the authors are not only those in the field of electronics and defect detection topic, but also those from informatics such as deep learning, attention mechanism, object detection, CNN, and YOLOV5, which shows their application in the detection of defects. The trend is outlined through the keywords PCBs and deep learning and reaffirms the growing importance of deep learning for defect detection topic. The same is found by observing the co-occurrence networks, in which terms from defect detection topic in electronics and terms from informatics like deep learning, computer vision, and image processing together participate. Detailed examination of papers content regarding methods and models for PCB and PCBA defects detection is proposed in Table 3. The analysis is performed mainly on open access articles.

Park *et al.* [37] present an analysis regarding deep learning models and training specifics for defect detection on PCB. The characteristics of PCB images and the factors that influence on PCB image quality in the industrial environment are discussed. Methods for PCB defect detection are classified in three groups according to test data and predictions: i) test data are cropped PCB images and prediction is related to the class of the cropped image, ii) test data are whole PCB images as the prediction is the image class, and iii) direct defect detection-test data are whole PCB images and the predictions concern defects location, size, and class.

Wang *et al.* [38] propose a PCB defect detection model with a few-shot learning that gives possibilities for usage of small datasets and to achieve good performance. The model includes modules for feature enhancement and multiscale fusion with the goal the model precision to be improved and small object defects to be detected. Defects that could be recognized are: missing hole, mouse bite, open, short, spur, and spurious copper.

Yang and Kang [39] present a method for PCBs defect detection, which is based on the improved YOLOv7 network. The method uses the SwinV2_TDD module for PCB feature extraction and magnification factor shuffle attention mechanism for improving the attention mechanism adaptability. The applied activation function is Mish. The method is tested after experimentation of six PCB defects (open and short circuit, spur and spurious copper, mouse bite, and missing hole) and high average precision is achieved.

Chen et al. [40] investigate the usage of deep learning algorithm in AOI process of PCBs and especially for effective re-inspection of defects with possibility to classify them. The following defects are recognizable: missed, flipped, shifted and sideward component, tombstoning, non-wetting, and insufficient solder on images taken through AOI machines. Such approach is proved to be accurate, faster, and decreases the rate of AOI machine misjudgment.

The work of Li et al. [41] is focused on how efficiently to be detected defects on PCBAs in an automated visual inspection process as an improved variant of the YOLOv7 model is presented. The main solved challenges are related to increase the defects detection ratio considering some environmental conditions (luminance, color) and taking into account different types, sizes, and density of mounted components.

Jeon et al. [42] combine analysis of thermal images and deep learning to present a contactless method for PCBAs defect detection that supports visual inspection. Thus, in real time the defects could be located and identified with high accuracy.

Deng et al. [43] propose a new method for PCB defect detection based on finding the contour unconformity (anomaly) and energy transformation (edge-guided energy-based PCB defect detection (EEDD)). Its advantages lead to possibility for tiny defects detection and flexible definition of defect criteria taking into account the requirements of a given production.

Zakaria et al. [44] summarize and discuss some approaches for PCB defect detection such as based on multi-frequency Moiré technique, machine vision, X-ray imaging, and probabilistic techniques, as well as such as driven by machine learning and deep learning. The authors conclude that AOI successfully adopts machine and deep learning and probabilistic approaches in the field of PCB defect detection. Machine learning is also applicable for prediction purposes at defects detection on PCBs.

Table 3. Methods and models for PCB and PCBA defect detection

Paper	Method/model	Aim
Park et al. [37]	– Deep learning	– Defect detection on PCB images
Wang et al. [38]	– Model includes modules for feature enhancement and multiscale fusion	– Model precision to be improved and small object defects to be detected
		– Defects identification (missing hole, mouse bite, open, short, spur, and spurious copper)
Yang and Kang [39]	– Improved YOLOv7	– PCBs defect detection (open and short circuit, spur and spurious copper, mouse bite, and missing hole)
Chen et al. [40]	– Deep learning on images	– PCBs AOI
		– Re-inspection of defects with possibility to classify (missed, flipped, shifted and sideward component, tombstoning, non-wetting, and insufficient solder)
Li et el. [41]	– Improved variant of YOLOv7 model	– Defects on PCBAs in an automated visual inspection process
Jeon et al. [42]	– Contactless method	– PCBAs defects location and detection
	– Analysis of thermal images and deep learning	– Visual inspection
Deng et al. [43]	– Edge-guided energy-based PCB defect detection (EEDD)	– PCB defect detection (contour anomaly)
Zakaria et al. [44]	– Discussion on variety of methods: multi-frequency Moiré technique, machine vision, X-ray imaging, probabilistic techniques, as well as such as driven by machine learning and deep learning	– PCB defect detection

6. VISUAL INSPECTION AT PCBs AND PCBA

Two queries "PCB and visual inspection" and "PCBA and visual inspection" are submitted to Scopus scientific database as the returned results for the first query are 51 documents and for the second query the found documents are only 8. The annual scientific production, presented on Figures 15(a) and (b), is characterized with irregular curves with a tendency for increasing the number of indexed in Scopus papers. This is confirmed by comparing the number of indexed documents at the beginning and at the end of the investigated period as for 2018 year the obtained documents respectively for the first and the second queries are 8 and 2 and for 2022 year the returned documents are 10 and 4.
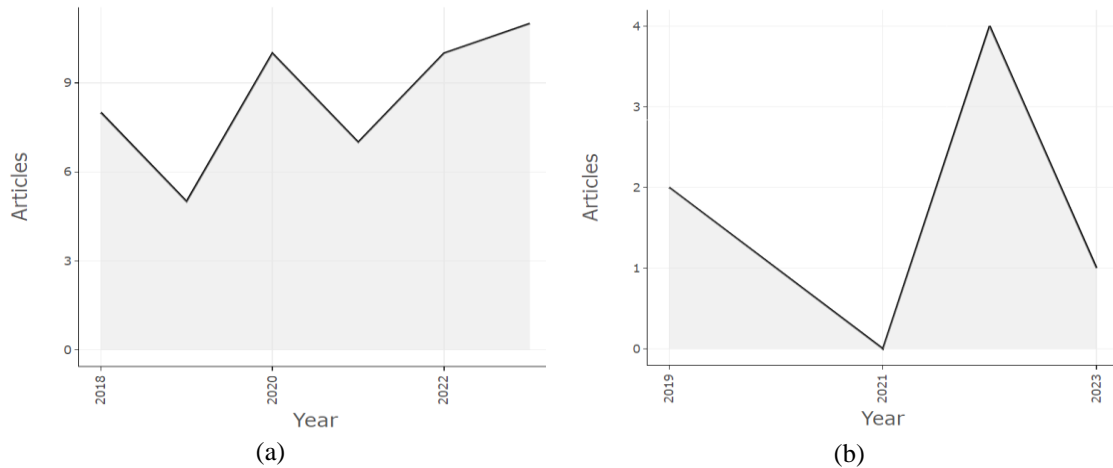
(a)   (b)

Figure 15. Annual scientific production for the query: (a) "PCB and visual inspection" and (b) "PCBA and visual inspection"

Papers are most often presented at conferences with topics in electronics and visual inspection, signal, information and image processing, artificial intelligence in engineering, computer, and information technology (Figures 16(a) and (b)). This confirms the strong penetration of new technologies and artificial intelligence in the field of PCB and PCBA visual inspection.
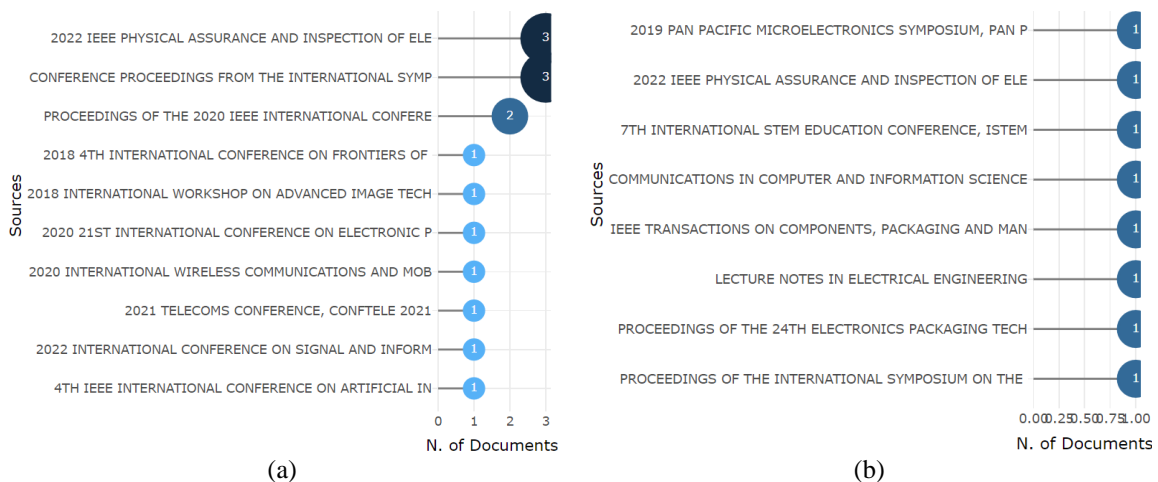

(a)   (b)

Figure 16. Annual scientific production for the quiery: (a) "PCB and visual inspection" and (b) "PCBA and visual inspection"

Figures 17(a) and (b) depicts the most utilized by author's keywords. For the query "PCB and visual inspection", the authors most often describe the papers' content with keywords like: deep learning, visual inspection, PCB, automatic visual inspection, defect detection, bill of materials, computer vision, image processing, and machine learning. The authors keywords for the query "PCBA and visual inspection" concern attribute gauge repeatability and reproducibility, automation, c3, ccga, cleanliness, co-solvent, contamination, corrosion failure, cross-section, and decision-making. Trend topics are presented on Figure 18 and includes four terms: printed circuit board, defect detection, deep learning, and visual inspection.

In the co-occurrence network is observed one main cluster, formed around the core terms: deep learning, visual inspection, defect detection, and computer vision (Figure 19). Other clusters are smaller and connect the terms image processing and quality control in one cluster, the terms automatic visual inspection, bill of materials, PCB assurance, and hardware assurance in different cluster and the terms PCB and machine learning are organized in the third cluster.
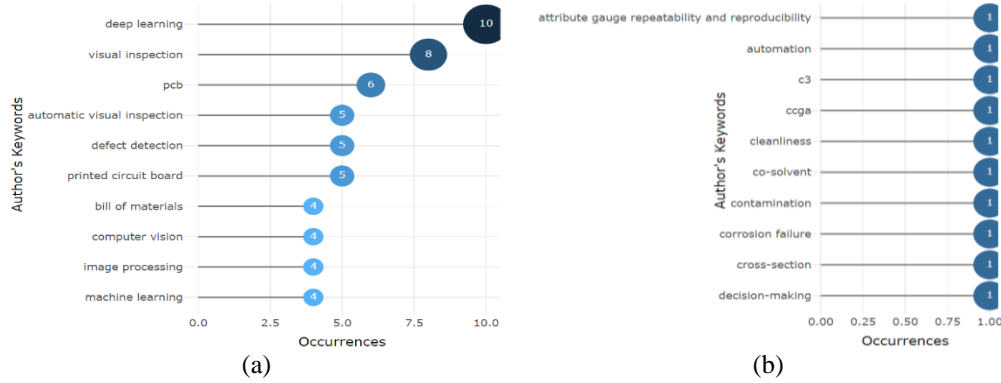
(a)   (b)

Figure 17. Author's keywords for the query: (a) "PCB and visual inspection" and (b) "PCBA and visual inspection"
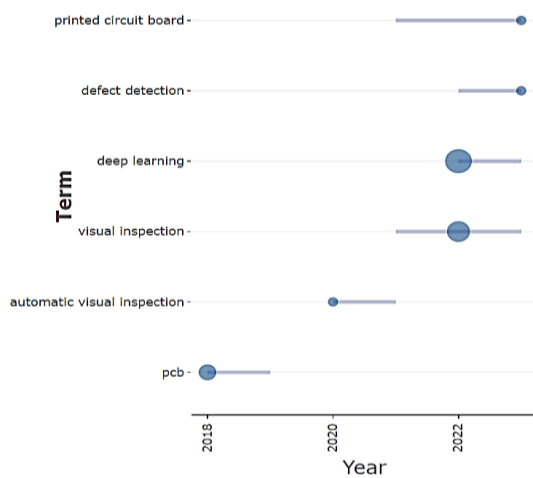

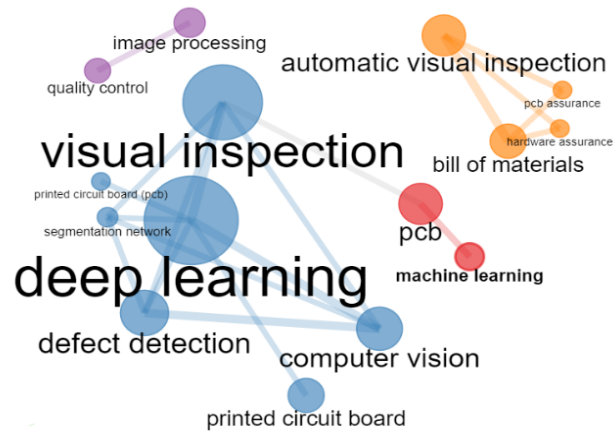Figure 18. Trend topics for the query: "PCB and visual inspection"

Figure 19. Co-occurrence network for the query: "PCB and visual inspection"

It can be said that the main research addresses visual inspection on PCB rather than visual inspection on PCBA, which is confirmed with the number of published and indexed in Scopus articles. Anyway, visual inspection is an important part of electronics manufacturing that guarantees high quality production. In this way it will continue to evolve and to grasp new technologies as it is seen through the name of sources that publish such papers. Considering the author's keywords and trend topics it is obvious the big role of deep learning for visual inspection. Other important terms are computer vision, image processing, and machine learning. The co-occurrence network once again confirms the application of contemporary technologies for the purposes of visual inspection. More detailed view is created after analyzing the content of relevant papers, mainly with open access.

Cao [45] presents a real-time visual inspection system to facilitate the identification of missing component on PCB. The solution is complex and consists of hardware and software part. The created software framework is based on image processing technique, analysis of region of each component, cross-correlation technique, and consideration of production rules. The author confirms the workability of the system after experimentations and points out its advantages for manufacturing quality control.

Glue control process in PCB manufacturing through applying visual inspection is discussed by Iglesias *et al.* [46]. In this way the human operator is notified when to change the glue tube. Machine learning algorithms random forest, polynomial regression and neural network are used for solving a regression task at estimation of the glue level. Robustness of the presented approach is proved even at adding noise on collected images.

Zhang [47] proposes a method for automatic inspection of PCBs that comprises YOLO deep learning algorithm, image processing technique and an algorithm for position correction. The recognition rate

of three defect types: wrong component, missing component and multiple parts is very high. It is argued that this method is effective, automating visual inspection, and decreasing manufacturing costs.

Sathiaseelan *et al.* [48] are developed the electronic component localization and detection network (ECLAD-Net) for identification and classification of resistors and capacitors on a PCB and in this way to detect malicious and reused components. The proposed novel method is compared with existing ones and the results point out that the learning model has to possess more than one hidden layer in a neural network, the number of layers in CNN has to be not more than in VGG-16 and it should be non-linear.

The work of Adibhatla *et al.* [49] is focused on anomaly detection (defects) with different sizes on PCBs through unsupervised machine learning (deep learning), which advantages in comparison to supervised machine learning algorithms, are usage of less data and time reduction for pre-processing. A student-teacher feature framework is used for image classification and for the distribution learning of images without defects as ResNet-18 for speeding inference is utilized. The effort of human operators for labeling images is decreased. The method is characterized with high accuracy and efficiency.

According to Chiun and Ruhaiyem [50] through automated visual inspection of PCBAs components, time and cognitive load of operators can be reduced and the process of quality control can be improved. Experimentation with three deep learning algorithms: R-CNN, YOLOv3, and SSD FPN is performed as the last one is seen as the best solution for objects (components from different types) localization and detection on images. Deep learning models are created through ResNet-50 (for R-CNN and SSD FPN) and Darknet-53 (for YOLO network).

Malin *et al.* [51] compare several techniques: near infrared wavelengths, X-ray and visible light for image analysis of PCBAs and defects detection in a process of visual inspection. The authors conclude that X-ray technique should be avoided, because of health risks. Instead, it is good to use more health-safe approaches as this investigation identifies features of the compared techniques regarding detect defects at given wavelength. A summarization of contemporary methods and models utilized in PCB and PCBA visual inspection is presented in Table 4.

Table 4. Methods and models in PCB and PCBA visual inspection

Paper	Method/model	Aim
Cao [45]	– Complex solution with hardware and software part – Software framework with image processing technique, analysis of region of each component, cross-correlation technique and consideration of production rules	– Identification of missing component on PCB
Iglesias *et al.* [46]	– Machine learning algorithms: random forest, polynomial regression and neural network	– Regression task at estimation the glue level in PCB manufacturing
Zhang [47]	– YOLO deep learning algorithm, image processing technique, and an algorithm for position correction	– Recognition of three defect types wrong component, missing component and multiple parts on PCBs
Sathiaseelan *et al.* [48]	– ECLAD-Net	– Identification and classification of resistors and capacitors on a PCB – Detect malicious and reused components
Adibhatla *et al.* [49]	– Unsupervised machine learning method (deep learning) – Student-teacher feature framework – Resnet-18 for speeding inference	– Defects detection (anomalies with different sizes) in PCBs – Image classification
Chiun and Ruhaiyem [50]	– Deep learning: R-CNN, YOLOv3, and SSD FPN	– Objects (components from different types) localization and detection on images of PCBAs
Malin *et al.* [51]	– Near infrared wavelengths, X-ray and visible light techniques comparison	– Image analysis of PCBAs and defects detection

7. RESULTS AND DISCUSSION

The findings from performed investigation of relevant documents, indexed in Scopus, regarding eight different queries "PCB and testing" and "PCB and testing", "PCBA and testing" and "PCBA and testing", "PCB defect detection" and "PCBA defect detection", "PCB visual inspection" and "PCBA visual inspection" are summarized through created framework, presented on Figure 20.

The framework outlines the current landscape of the most researched methods, methodologies, and models for PCB and PCBA testing and visual inspection. It can be seen that alongside conventional methods that are continuously being improved, new sensor solutions have recently been created to conduct non-destructive and contactless tests. The role of machine, deep and transfer learning in automating testing and visual inspection tasks is growing significantly in our contemporary ages.

The most investigated recently trending methods for PCB testing and visual inspection are classified in:

– Destructive methods that are less often investigated, perhaps due to the destructive nature and removing a part of the prototype. Anyway, such methods are applied for identification of possible PCB failure.

− Non-destructive methods that include a wide variety of techniques for PCB testing like acoustic emission, X-ray tomography, frequency/magnitude sensing, time domain reflection as often they are used in different combinations to locate and evaluate PCB defects and damages.
− Virtual methods, which are based on simulations applying some analytical techniques such as finite element analysis to identify risk problems and ro remove failure issues.
− Algorithms from deep learning and transfer learning for PCB and PCBA defects detection and real time visual inspection are the most utilized contemporary approaches.
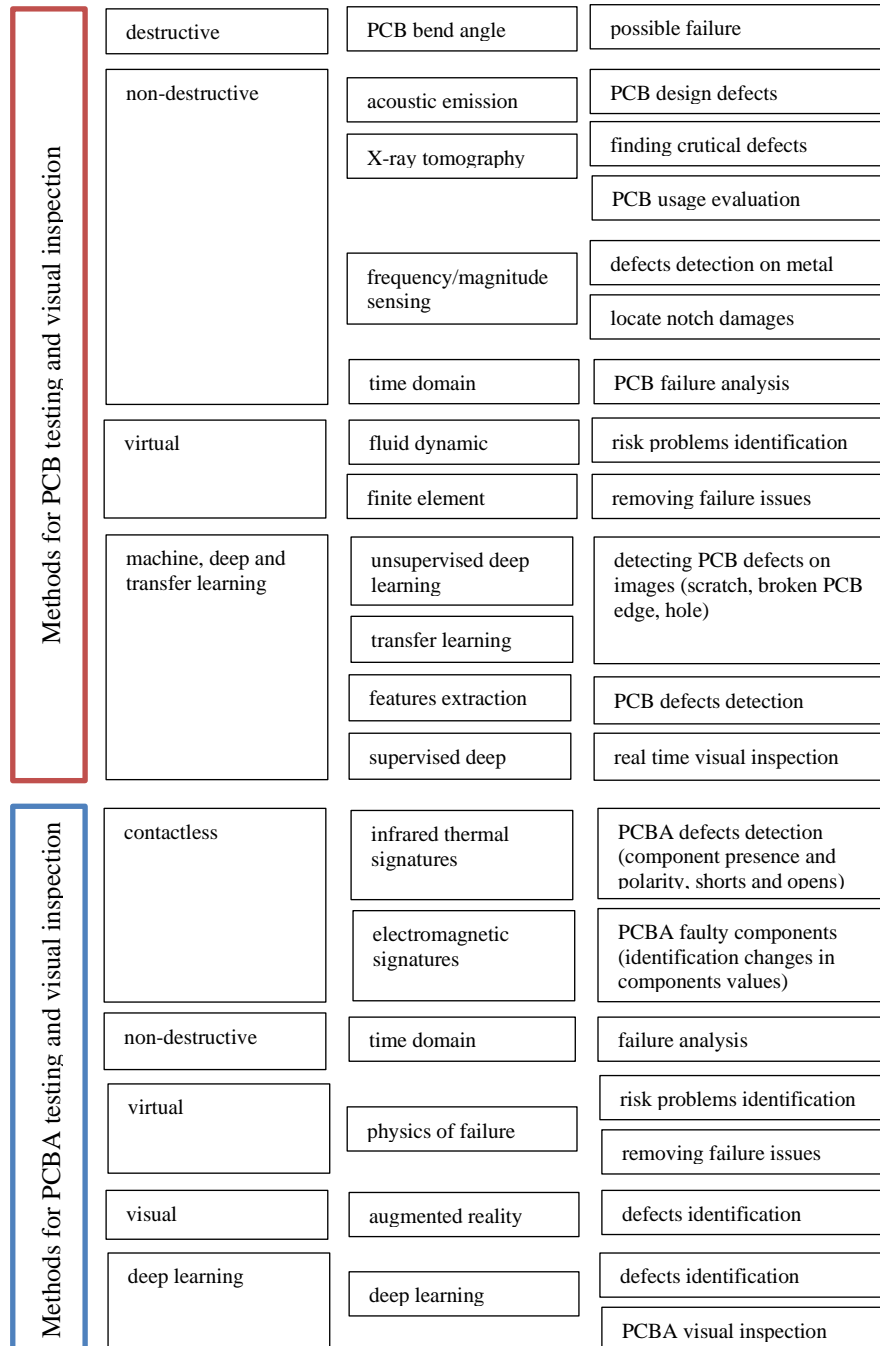

Figure 20. Framework, summarizing the most investigated methods for PCB and PCBA testing and visual inspection

The most often researched methods for PCBA testing in the last five years could be classified in:
− Contactless methods for defects detection on PCBAs such as: infrared thermal signatures, electromagnetic signatures.
− Non-destructive methods for failure analysis.
− Virtual methods, which are based on performed simulations for identification of risk problems in PCBAs and for solving some failure issues.
− Visual methods based on AR technology, which is used in support of defects detection on PCBAs and in assistance of quality control inspectors.
− Machine and deep learning algorithms as mainly are discussed deep learning algorithms for PCBAs defects detection and in facilitation of visual inspection.

The created framework answers to the posed research questions: what are the most investigated methods and techniques for PCB and PCBA testing and visual inspection in the last five years? and what is the impact of machine and deep learning on methods for PCB and PCBA testing and visual inspection? non-destructive and non-contact testing methods are seen to be preferred for examination and implementation. Testing in a simulation environment is also a preferred method for investigating defects and failures. Bibliometric analysis and article content analysis confirm the growing role of machine and deep learning to detect defects and to support visual inspection.

8. CONCLUSION

The findings of this paper reveal the most often recently investigated topics related to PCB and PCBA testing and visual inspection methods as these methods are classified in groups for better understanding of their nature. The data are taken from scientific database Scopus for a term from 2018 to 2023 year. The most relevant papers mainly with open access are explored and on this basis a framework that summarizes the contemporary landscape in the PCB and PCBA methods for testing and visual inspection is developed.

Bibliometric analysis is also applied to understand: i) the interest to the researched topics, which has been steady for the past 5 years; ii) the sources that published these papers, which are recently not only in the domain in electronics, but also in the field of computer and information technologies; iii) the most frequent author's keywords that describe in the best way the papers content as in this case they are related to contemporary technologies, methods, and models for PCB and PCBA testing and visual inspection; and iv) trending topics, which point out the growing impact of machine and deep learning algorithms for improving the reliability of printed circuit board assembly and PCBA testing and visual inspection.

The limitation of this study concerns the following issues: i) the used literature sources and their bibliometrics are taken from Scopus scientific database and ii) mainly are examined papers with open access. Anyway, we believe that these limitations in no way diminish the importance of the study, as Scopus is a large scientific database indexing high-quality articles. Open access papers are published in scientific collections or journals with an impact rank/impact factor, which also does not decrease their significance. The future work is focused on further exploration of the application of machine learning and deep learning in the processes of PCB and PCBA testing and visual inpection.

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