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A Novel Process to Setup Electronic Products Test Sites Based on Figure of Merit and Machine Learning

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ABSTRACT Consumer electronic manufacturing (CEM) companies maintain a range of electronic products that are designed and tested according to the type and end-user requirements. These electronic products go through a validation and verification test for proof of design and a manufacturing test for checking reliability, quality, and manufacturing defects. Testing is carried out using test sites, designed based on the electronic product type. Currently, there is no standard approach for setting up a test site for electronic products. In this research, two processes are presented, for setting up new test sites and optimization of existing test sites for consumer and other electronic products. The proposed processes include a voice of customer (VoC) interface, that is based on a unique dataset and through machine-learning technique automatically translate customer information into customer requirements, and a figure of merit (FoM) presented as an outcome of this research using several key test-related parameters. These proposed processes are an important step towards defining a standard approach for setting test sites for consumer and other electronic products. The processes are implemented using a software application developed in LabVIEW, which is linked to a database containing test data for around 400 products collected as part of this research and form a knowledge base for the proposed processes. Finally, the processes are validated by setting up a new experimental test site for an RF receiver and optimization of an existing test site of an antenna system.

INDEX TERMS Consumer electronic manufacturing (CEM), electronic product test, figure-of-merit (FoM), LabVIEW, machine-learning, voice of customer (VoC).

I. INTRODUCTION

The consumer electronics manufacturing industry is considered one of the main industries forming the country's economic backbone. The testing of manufactured electronic products is an important stage in the manufacturing process and is usually done towards the end of the process. Testing is carried out by setting up a test site for the product under test and the pre-requisite for this is the understanding of how a test site can be setup.

The consumer electronic manufacturing (CEM) industry includes two main companies which are the original electronic manufacturing (OEM) and the CEM companies. These companies carry out various activities, some of these are discussed in this section. Figure 1 shows the roles of these companies within the CEM industry. Consumer electronic products (CEPs) are mostly manufactured by OEM and CEM companies while other companies use OEM and CEM companies to get their products manufactured and tested. Manufacturing and testing of CEPs rely on design for manufacturing and design for testability tools and techniques.

OEM companies design and manufacture their products, process customer returns, and cover all aspects and stages of manufacturing. Some customers of OEM companies buy products from them and sell these products with their labels. Further, OEM companies provide all after-sales for the end-users of their customers, as well as perform all aspects of design for manufacturing and design for testability activities.

CEM companies manufacture electronic products for their customers only. Their focus is on manufacturing and

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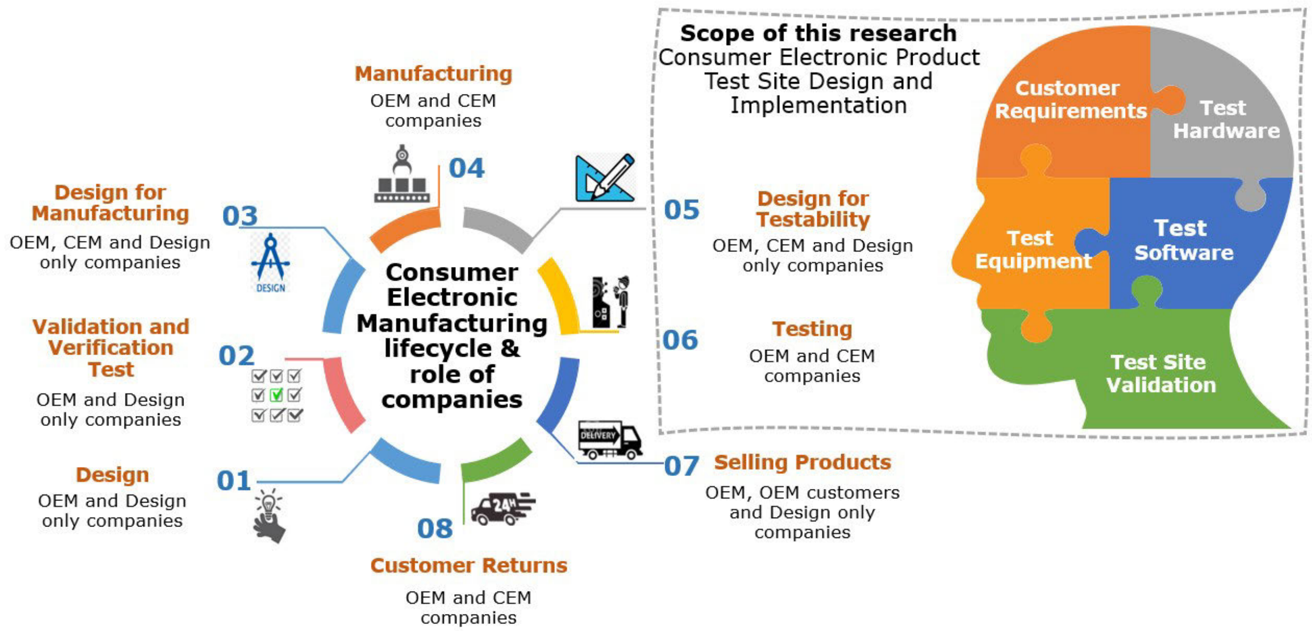

FIGURE 1. Scope of the research within CEM lifecycle.

testing products. As these companies do not have their product range hence, they normally do not have product design expertise. CEM companies carry out design for manufacturing and design for testability activities for some of their customers. Some companies design their electronic products but use CEM companies for manufacturing. These electronic product companies normally perform design for manufacturing and design for testability for their products but sometimes subcontract these activities to CEM companies

The rest of the article is structured as follows. Related work and review of existing electronic products and their test sites, limitations of existing test site setup processes, and machine-learning techniques are discussed in Section II. Section III presents the novelty of the research work. Section IV discusses the research methodology which includes four steps. Details of each step are presented in this section. Next is section V, which presents the proposed process through block diagrams and a flowchart. The implementation of the proposed process is discussed in section VI. After the implementation, the next is the validation stage which is discussed in section VII where two experimental test sites are considered. The first one is a new test site setup using the proposed process while the second one is an existing test site that is optimized using the proposed process. Section VIII is a discussion related to the proposed process. Finally, section IX presents the conclusions.

II. RELATED WORK

In this section, a review is carried out for electronic product types and their variants followed by the study of various aspects of electronic product test sites. Some of the key parameters for setting up a test site include the type of testing required, test coverage, test equipment required, number of test stages, test jigs, test software, etc. The overall decision and selection of these parameters are mainly based on the type of electronic product and allocated budget. Section II-A and II-B present the details of some electronic products and existing test sites which are reviewed. Limitations of existing test site setup processes are discussed in Section II-C and Section II-D discusses some machine learning techniques reviewed as part of this research.

A. REVIEW OF ELECTRONIC PRODUCTS

For this review, around 400 different CEPs and their variants are reviewed, and data is collected. These products range from simple to complex electronic devices that are deployed on land, underwater, and in space. Table 1 lists some of the CEPs reviewed. Product type is listed in the second column while basic specifications are mentioned in the last column.

Some customers modify their products to add new features or upgrade due to obsolete components. In this review, these modified products are referred to as variants of consumer and other electronic products. Depending on the level of modification, some products require a new testing strategy.

Some products overlap multiple categories i.e., an RF transceiver with a digitally controlled attenuator or an audio amplifier with digital gain control.

B. REVIEW OF EXISTING ELECTRONIC PRODUCT TEST SITES

In this section existing electronic product test sites are reviewed. These electronic test sites can be used for testing a prototype, a batch for design proving purposes, or can be deployed in a manufacturing environment. The authors in [1] used a standard continuity tester to check the short circuit between tracks and connectors for a backplane. The important aspect of this test site is the use of general-purpose connectors

TABLE 1. Details of some consumer electronic products reviewed.

Category	Product Type	Details
1	Audio Equipment	Low frequency, measurements like harmonic distortion, gain, phase difference, etc.
2	Basic and Complex Digital Equipment	Design based on gates, multiplexers, decoders, programmable chips (PIC controllers), FPGA, DSP, JTAG, etc.
3	Cable assemblies	Various cables used in electronic products
4	Cameras	Image detection and processing required Windows or Linux operating systems.
5	High Voltage / Power Equipment	1000V or above, safety required
6	Medical Equipment	Low frequency, high reliability required image, and signal processing.
7	Power Supplies	DC or AC power supplies, low and high wattage
8	Radar systems	Including ground penetrating radars
9	RF Equipment	Up to 3GHz
10	Satellite Communication Equipment	950MHz to 36 GHz
11	Sensors and transducers	Internet of things devices, digital control using IP address, etc
12	Underwater Equipment	Maximum test coverage and high reliability are required.

between the unit under test and the test equipment. This type of test site is normally the first of several stages setup for testing an electronic product.

In [2] a complex digital circuit board is validated i.e., checked for open and short circuit nets using a joint test action group (JTAG) interface. The authors performed a boundary scan test where the unit under test is powered using the JTAG port. This test is carried out before the functional test. The authors highlighted the problems with the traditional test process for a satellite control system in [3]. They designed an automated test equipment (ATE) system to improve efficiency and accuracy. In [4] the author discussed the importance of design for testability techniques which can help in achieving an optimized test solution. Some of the points mentioned are to run a boundary scan test, adding more test points on the Printed Circuit Board (PCB) to increase test accessibility and help in improving test coverage. The author also discussed the use of ATE. The authors in [5], presented a universal platform to test PCBs. They have used the National Instrument PCI eXtensions for Instrumentation (NI PXI) system, bed of nails jig, and interconnections to setup the test site. A test site for an RF product is presented in [6] and [7]. They used a vector network analyzer to measure return loss and voltage standing wave ratio.

A wireless system for temperature measurement is presented in [8]. The authors discussed how this setup can be deployed in different scenarios. In [9] authors presented a framework for testing the internet of things applications. This test site can be setup in a manufacturing test environment where the internet of things based devices can be tested for manufacturing defects or validation of some functionality. An automated test system is developed in [10] for an aerospace product. The authors used simulation techniques for troubleshooting. In [11] a web-based monitoring and control technique is presented which can be applied to control and monitor test sites for electronic products. The authors used LabVIEW [12] for image processing in [13] which can be used for performing an automated optical inspection on PCBs. A configuration tool to download firmware at high speed using the JTAG port is presented by the authors in [14]. Using this technique, a boundary scan can also be performed on the PCB assemblies. In [15] some standard measurements are performed on an audio product. These measurements include total harmonic distortion and signal-to-noise ratio.

A data acquisition application is developed in LabVIEW using an open-source instrument control tool in [16]. The unit under test is an optical device used for profiling depth. An induction motor control test site is setup by authors in [17]. They used LabVIEW as a software platform to acquire data and hardware control. Finally, in [18] the authors used a general-purpose interface bus (GPIB) to control a bench power supply and a digital multimeter and acquired measurements. ATE performance, obsolescence, and compatibility issues are discussed in [19]. The authors discussed a systematic design approach that covers both software and hardware architecture.

In [20] the authors analyzed low-frequency signals using LabVIEW and extracted some features from the acquired signal. An eddy current measurement system is developed by authors in [21] using NI myRIO data acquisition system controlled using LabVIEW. A high-speed data acquisition system is developed by authors in [22]. They used the NI DAQ system controlled through LabVIEW. In [23] authors controlled GPIB based commercial off-the-shelf (COTS) test equipment remotely using TCP/IP protocol.

A low-frequency signal processing system is developed by authors in [24] using LabVIEW and NI Elvis. The authors presented an automated system for electronic circuit testing in [25]. In [26] an RF circuit test method using a signal generator and PXI system is proposed by the authors. A Low-frequency signal acquisition and analysis system is developed by the authors in [27] using an analog to digital, conversion. The authors used a LabVIEW toolkit for processing the acquired signal. In [28] the authors used LabVIEW to acquire signals from exiting interfaces used for spacecraft equipment. A data acquisition system is presented in [29] where the authors acquired analog signals from a storage oscilloscope controlled by a GPIB interface. The authors used low-level programming commands for data acquisition.

In [30] the authors developed a portable system for testing antennas using an Arduino board. The authors proposed architecture for automatic hardware that includes most of the common interfaces including GPIB in [31]. In [32] the authors used a PIC microcontroller to acquire data from a transducer. The test software is developed in LabVIEW. A cable test setup is presented in [33] where authors used the NI DAQ system for automated testing. In [34] authors presented an automated test system for an avionics system. Authors in [35] presented the architecture of GPIB and highlighted the pros and cons. A test site for remotely controlling and monitoring a motor is discussed in [36]. The setup presented in [37] is used for controlling a temperature chamber. This test site is very useful for doing environmental testing on different electronic products. In [38] the authors used COTS test equipment and LabVIEW to test an RF current probe. An automated test setup for low-frequency medical devices is presented by authors in [39]. They also performed a comparison between manual and automated tests. The authors discussed PCB diagnostic and troubleshooting techniques in [40].

An automated test system for an RF device is presented by the author in [41] and carried out various RF tests including spurious test and automatic gain control. In [42] the authors presented a technique for automated testing for an electronic control unit using a CAN bus. The authors in [43] demonstrated the use of GPIB to automatically control and configure COTS test equipment.

A power supply output voltage calibration process is presented in [44] where the authors controlled a power supply using a GPIB interface and a digital multimeter to monitor power supply voltage. The authors in [45] designed a test jig and used ATE to test a PCB. An automated test site for testing a software-defined radio operating is presented in [46]. A summary of the above review is presented in Table 2 which includes both hardware and software information.

C. LIMITATIONS OF EXISTING TEST SITE SETUP PROCESSES

The main limitation of the existing electronic products test site setup processes is the lack of standards or the absence of a common approach. The standard used in the CEM industry is for manufacturing and not specifically for CEP testing. An example is the CE marking for CEPs manufactured for the European market. This regulation is simply a confirmation that the CEPs which are manufactured outside the European Union are built to their standards. Like other similar standards, this does not include how and at what standard the CEPs should be tested.

The next problem is related to customer requirements. Currently, there is no standard procedure for collecting customer requirements. Customers use different terminologies and provide information at different stages of CEP manufacturing and often it is seen that some important information is overlooked. These issues can have a direct impact on product quality. As an example, a customer may want a thermal test but not sure about the temperature range. Selecting a higher temperature range can reduce the product lifetime while the product may not work properly at extreme temperatures if the temperature range is less than the optimum. This example highlights the importance of generating customer requirements correctly.

There is a huge variety of CEPs manufactured and new variants are launched continuously so it is very difficult for CEM companies to maintain the required expertise to cater to this. Having good product knowledge is essential for setting up a good test site. These product types and their variants include medical devices, sensors, RF-based products, complex digital products based on Field Programmable Gate Array (FPGA), radars, products deployed underwater, aerospace systems, fiber optic products, etc. The problem is that a test system design engineer can be an expert in understanding and testing RF products but not necessarily have the same knowledge when it comes to an image processing device. Similarly, an expert in FPGA-based products may not be able to setup a test site for an underwater communication system.

Finally, no database contains technical data of existing test sites and information about different techniques that can be used for designing new test sites. There is no knowledge base of how different CEPs can be tested.

D. MACHINE LEARNING TECHNIQUES

In this section, some machine learning applications are reviewed. The use of machine learning is increasing manifolds and is being applied to various areas and industries. In [47] the authors reviewed some machine learning techniques to predict the performance of the soldering system used for both through-hole and surface mount components. Some limitations of machine learning algorithms are discussed in [48]. The authors used historical data to estimate the deviation from the required performance. Scikit Learn, a Python [49] module is used by authors in [50] for implementing a machine learning algorithm.

In [51] the authors reviewed some machine learning algorithms and presented their findings which include some limitations. The focus of research is to maintain quality control for production lines and the authors reviewed machine learning techniques to achieve this in [52]. The authors reviewed supervised and unsupervised machine learning algorithms in [53]. They further explored the use of internet of things related applications. A review of some standard supervised machine learning algorithms is presented in [54]. The authors also highlighted the main features of each algorithm reviewed.

In [55] the author surveyed supervised machine learning algorithms which included text classification. The authors reviewed security issues and limitations for machine-learning-based implementations in [56]. They also presented various trends where further research can be carried out. Finally, text data extraction and analysis are discussed by the

TABLE 2. Summary of existing test sites reviewed.

Product type	Software	Hardware
	Aerospace products	
Aerospace [10]	Visual basic	ATE, cables
Avionics system [34]	Details not provided	GPIB, PXI system
Satellite control system [3]	Java	ATE, CAN, and RS232 interfaces
Spacecraft interfaces [28]	LabVIEW	COTS hardware, MIL-1553, and SpaceWire
	Low frequency and biomedical electronics products	
Analog audio device [15]	Matlab	ADC, DAC
Wireless Audio product [25]	LabVIEW	NI PXI, bed of nails jig
ECG system [24]	LabVIEW	NI Elvis
EEG Headset [20]	LabVIEW	Transducer and Bluetooth
Low-frequency product [27]	LabVIEW	COTS ADC
Medical devices [39]	Python, LabVIEW	DAQ
	Digital electronic products	
Complex digital [2], [14]	COTS	JTAG, pods, cables
	Data acquisition products	
DAQ system [22], [29], [32]	LabVIEW	NI DAQ devices, GPIB interface, Oscilloscope, PIC microcontroller, transducer
	Motor control circuits	
DC motor driver [21]	LabVIEW	NI myRIO, DC motor driver
Induction motor [17]	LabVIEW	Data acquisition (DAQ) and control
Motor control [36]	LabVIEW	Camera, Arduino
	Internet of things-based products	
Internet of things [9], [23]	LabVIEW / COTS	Network switch, Oscilloscope. waveform generator
	Various circuits and products	
Printed circuit board (PCB) [5]	LabVIEW	PXI system, Bed of Nails (BoN) fixture
Backplane [1]	COTS	COTS cable tester, connectors
Cable assembly [33]	LabVIEW	NI DAQ
The electronic control unit [42]	LabVIEW	CAN bus, Power supply
GPIB based system [35]	HP VEE Pro	GPIB interface
Microfluidic device [13]	LabVIEW	Camera and accessories
Optical device [16]	LabVIEW	Data acquisition (DAQ)
Power supply control [44]	LabVIEW	Power supply, digital multimeter, GPIB
Underwater modem [11]	LabVIEW	Sensors, cables
Thermal cycle for the unit under test [37]	LabVIEW	Environmental test chamber interface
Temperature probe [8]	COTS	Analyzer, antenna
Refrigerator [45]	LabVIEW	ATE, test jig, RS232, ADC, and sensors
	RF circuits and products	
Antenna [30]	LabVIEW	Arduino, Stepper motors, and drivers
Antenna [6], [7]	COTS	Analyzer, cables
RF circuit [26]	LabVIEW	NI PXI, Signal generator,
RF current probe [38]	LabVIEW	Spectrum analyzer, Signal generator
RF device [41]	LabVIEW	SPI, I2C, HPIB
Software-defined radio [46]	LabVIEW	Signal generator, Spectrum analyzer, RS232, GPIB
Wireless sensor network [18]	LabVIEW	Digital multimeter, Power supply, and GPIB

authors in [57]. The focus of their research is data analysis and mining. They presented their work through three stages.

III. THE NOVELTY OF THE PROPOSED RESEARCH WORK

In this manuscript, two automated machine learning-based processes are presented. The first process is for setting up a new test site and the second process is for optimization of an existing test site, both for testing CEPs at PCB assemblies and as finished products within the manufacturing environment of the CEM industry. The two processes comprise three main building blocks which are the proposed unique voice of customer (VoC), figure of merit (FoM) interfaces, and

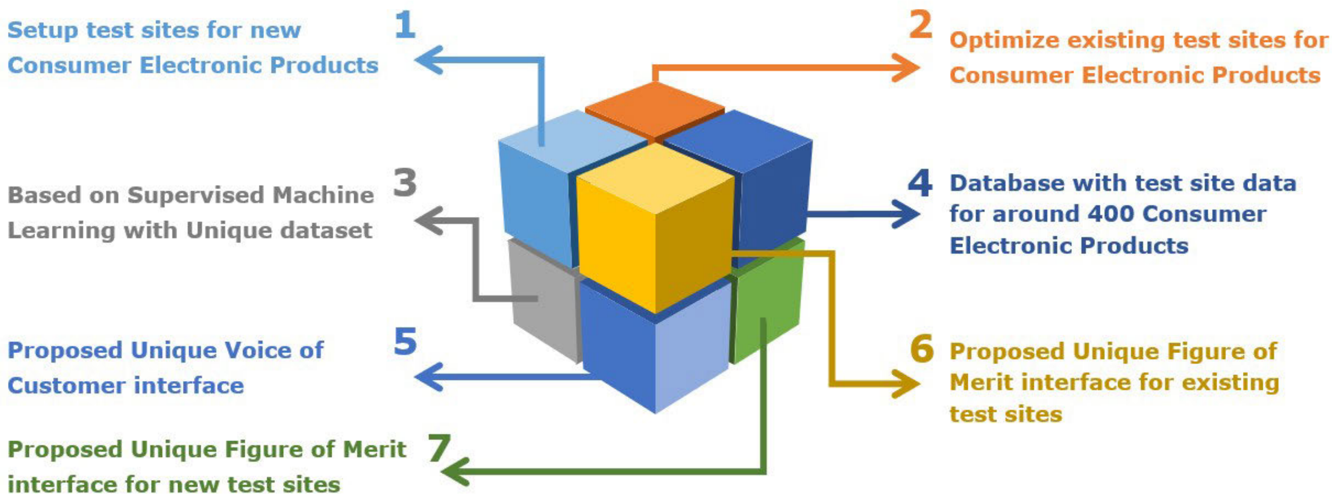

FIGURE 2. Novel features of the proposed process.

a database that contains manufacturing and test data for existing test sites.

The first process for setting up a new test site for CEPs is based on VoC and FoM interfaces. The second process is for optimization of an existing test site for CEPs, based on FoM and existing manufacturing and test sites' historical data.

The proposed process is implemented using a software application developed in LabVIEW which provides graphical user interfaces (GUIs) for the two processes. The interface for setting up new test sites includes the proposed VoC and FoM interfaces. The proposed software application generates reports which are used for setting up new test sites and optimization of existing test sites. The application is also linked to a database that includes test site data for around 400 products which are collected as part of this research. The database also includes existing test sites data, COTS test equipment details, and fault and repair details. There is an interface provided through which new data can be added within the categories mentioned here. The database is discussed in detail in section V-C.

The VoC interface takes customer information and automatically converts it into customer requirements using supervised machine learning. The proposed FoM interface takes customer requirements and other test data to automatically generate reports which are used for setting up test sites. The reports include details of test software requirements, COTS test equipment, test stages, estimated test times, etc.

Using the proposed process, a test site can be setup or optimized for any CEP quickly, using the unique VoC and FoM interfaces. The CEM companies can save time and resources and can setup test sites with limited technical expertise.

Finally, a unique test set is created using the data collected, and this test set forms the basis of effective machine learning implementation. More data can be added to improve the dataset as and when needed. Figure 2 provides a graphical summary of the novelty of this research.

The process presented here can be applied to any electronic product that requires either testing during manufacturing or proof of design stage.

IV. RESEARCH METHODOLOGY

There is currently no universal approach or standard process when setting up sites for testing electronic products within or outside the manufacturing environment. CEM, OEM, and other companies implement and follow their standards, and have both advantages and limitations. The driving force behind this research is to come up with a standard and universal approach which can be used for setting up a consumer electronic product test site within the CEM industry. Figure 3 presents the research methodology through four steps.

A. DESIGN RESEARCH

The first step is to define the scope of this research. For this purpose, few categories are identified which include a review of existing test sites, machine learning algorithms, and how customer information can be collected. To review test sites of CEPs, a criterion is also required i.e., how and what information related to CEP test sites is to be collected.

B. CONDUCT RESEARCH

The first step of the second activity is to select some CEPs and variants to understand and accumulate product knowledge. This is necessary for setting up test sites. The details of these electronic products and their variants are listed in section II-A.

The second step is to review how test sites are designed. This includes reviewing both the pre-requisites and the existing approach used for setting up test sites. Several parameters need to be considered and evaluated before setting up a test site for electronic product testing. The first parameter is the type of test site that can be manual, semi-automated, or fully

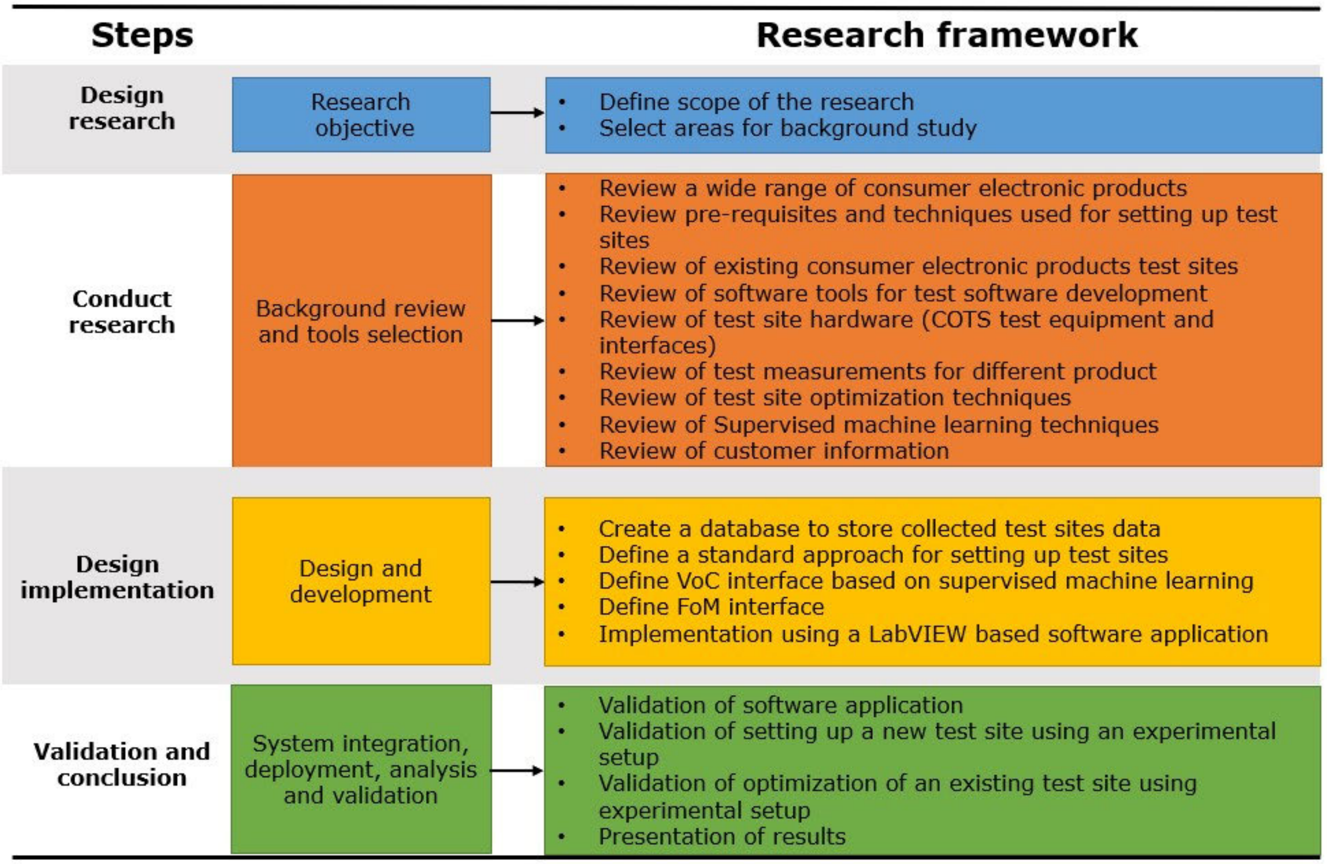

FIGURE 3. Research methodology.

automated depending on the requirements. The next is to evaluate what measurements are to be taken, focusing on the unit under test type, and functionality to be checked. Once the measurements are identified, the test equipment is then selected. The test equipment can be COTS or developed in-house. After that, the number of test stages is finalized considering the product handling and how the test site is physically setup. Finally, the system site development team can design test jigs based on the type of product and tests required. The last step is to develop test software to control the test site. Test software features depend on all the options discussed in this section. The test sites should be designed keeping in mind the future upgrade in case of obsolescence or change in the unit under test batch size.

Test sites are setup using design for testability information provided by the design team. Electronic product testing is carried out by setting up a test site for the unit under test. The test site includes test software, test equipment, test jigs, etc. Electronic product manufacturers use different techniques to test electronic products. Some of the common techniques used are discussed in this section. The unit under test goes through a simple go/no go test which is also called a health check where the unit under test is switched ON to check if it is working. Normally a power supply is required for this test. Other units under test go through more extensive testing where a special signal/waveform is generated using hardware or test software and applied to the unit under test input. For advanced RF testing, an arbitrary waveform generator can also be used. Depending on the product type, a more specialized test setup is required where the test system development team design a circuit or use COTS test equipment for testing unit under test.

As an example, a COTS transmitter can be used for testing an RF receiver. Some electronic products comprise of multiple PCBs. To test these PCBs, individually or combined, manufacturers use a golden unit under test or a known good unit. For example, if the electronic product under test comprises of 3 PCBs, to test PCB 1, the other two PCBs are golden boards. The advantage of this approach is that it reduces the test development time but at the same time it is important to make sure the golden unit under test does not become faulty. Some manufacturers use laboratory equipment like function generators and oscilloscopes to acquire measurements from the unit under test. Test equipment are controlled by test software through control ports like LAN, GPIB, etc. The unit under test also undergoes a full test and for it to pass the test, all the individual tests should pass.

Depending on how the test software is written, this technique can be more time-consuming as the whole test may be required to be run even though only one subtest fails.

After the test sites are setup, there is a review process to try and avoid the possibility of over or under-testing. This can be achieved through a few iterations and evaluation of design for testability. This step is very important and often the companies end up shipping products that are not fully tested and have low-test coverage. Another problem is high customer returns. For high-volume products, the manufacturing companies explore designing and developing ATE systems which result in overall efficiency due to reduced testing time.

The third step is to review existing test sites of consumer and other electronic products. This includes reviewing specific aspects of test sites which include test software, test hardware, and COTS test equipment. The details of this review are covered in section II-B.

The fourth step is to review applications used for developing test software. CEM companies use different software and tools such as LabVIEW, Python, Visual Basic, etc. to develop their test application. Python is one popular application used by CEM companies for test software development. Python provides a complete solution that includes data acquisition, storage, analysis, and report generation. The other popular tool is LabVIEW which provides several important features like built-in maths and signal processing functions, custom GUI and data storage, source code control, validation and management tools, report generation using MS Office, and database interface. LabVIEW also provides functions to control applications remotely. At the end of the review, LabVIEW is selected due to its quick development and debugging features on top of the features mentioned here.

The fifth step is to review test site hardware which includes test jigs, COTS test equipment, and interfaces. The key hardware categories for testing electronic products include test equipment which can be either COTS or in-house designed test equipment and various types of test jigs. The test equipment depends on product type; for testing an audio product an audio signal generator and audio analyzer are used. For RF product testing a signal generator with the required frequency range, spectrum analyzer and network analyzer can be used. For complex digital products, programming tools are mostly used. There are different test jigs used which include a bed of nails test jigs, programming jigs, functional test jigs, or a simple mount for fitting the unit under test. CEM companies design these test jigs based on the type of CEP, unit under test batch size, and budget.

The sixth step is to review different test measurements taken for the CEPs. A further review was carried out for different measurements that can be taken using the above COTS test equipment discussed. The measurements are selected depending on customer requirements and the level of testing needed. Some measurements reviewed include image processing, harmonic analysis, return loss, insertion loss, bit error rate, etc.

The seventh review step is the optimization of existing test sites where certain parameters like increasing test coverage, reducing unit under test's test time, increasing throughput, and reducing or increasing test stages are considered. Test sites can be optimized by doing various activities such as record test results automatically reduces unit under test's test time, automatic analysis can help in quick troubleshooting for the failed unit under test, changing test sequence, or removing certain tests where the failure rate is very low, reducing operator handling, etc.

The eighth step is the review of machine learning techniques. For this review, some supervised machine learning techniques are studied, and their details are discussed in section II-D.

The ninth step is the review of information provided by customers for testing their products. For collecting this information several customers are interviewed and the information they provided is reviewed. The review is focused on what information customers generally provide, what information is not provided, and at what stage of the process the information is provided.

C. DESIGN IMPLEMENTATION

The first step of the third activity is to analyze the reviewed and collected data. This data is the knowledge base and is stored in a database created for this purpose. The collected data includes product and customer information, level of testing, details of individual tests, test equipment used, documentation including test plans and detailed test procedures, test jigs, measurements taken, test software, test time, test sequence, faults, etc. This step is vital and critical for this research.

The second step is to define a standard approach. CEPs go through several stages during manufacturing. Once the product is manufactured, they go through testing to verify the functionality and pick up any manufacturing defects. This testing can be a basic power ON test or an extensive functional test. The research is initiated to come up with a standard approach for setting up test sites for electronic products. This is a huge task considering the already available number of CEPs and their variants, and the frequency of new products being launched. CEM companies, depending on the CEP type and available expertise, have defined their standards. There are advantages and disadvantages to these standards.

The third step is to define a VoC interface based on what and how the customers provide information and how the CEM companies use this information to setup their test sites. A process is defined to translate customer information into requirements that the test system development team can use. It is important to ensure the customer requirements are generated as early in the process as possible. For this purpose, a machine-learning algorithm is created, based on the historical data collected and stored in the database. This VoC interface includes a process to collect customer information from various sources and using questionnaires and templates which is then converted into test requirements, using a supervised machine-learning technique, and the decision-making is based on comparing the new customer requirements with the historical information stored in the database.

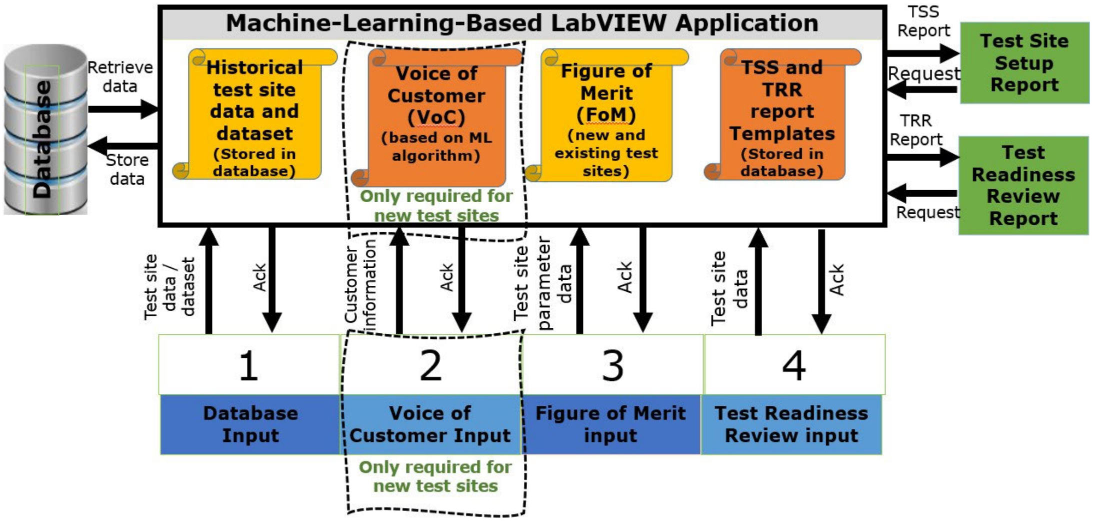

FIGURE 4. Block diagram of the proposed processes.

The fourth step is to define the FoM for setting up test sites for CEPs. The FoM which is the backbone of this research is defined based on the conclusions drawn after reviewing test site data collected which includes common steps in setting up test sites, various test-related parameters, certain trends, etc. The selected parameters are assigned weightage and the FoM is then calculated using these parameters. To improve the effectiveness of FoM, test system design engineers and test operators are observed and interviewed to collect more data which includes whether they found a certain test site easy or difficult to use, what approach they use to design the test site, how did they select test equipment, what test sequences they used.

The fifth step is implementation. A software application is created in LabVIEW which provides both VoC and FoM interfaces and connects to the database. This application generates the required outputs in the form of reports which are discussed in section V. Two scenarios are considered and implemented i.e., setting up new test sites and optimization of existing test sites for testing electronic products during manufacturing. The software application provides two GUIs for the two processes. The first process i.e., setting up new test sites is based on VoC and FoM while the second process for optimization of existing test sites is based on FoM and existing test and manufacturing data. The process shows how customer information is translated into detailed specifications for setting up the test site. The results also highlight that in certain cases where customer information is not complete, the historical data from other test sites can be used.

D. VALIDATION AND CONCLUSION

The final step of the methodology is the validation of the process implemented using a LabVIEW based software application. The two processes i.e., setting up a new test site and optimization of the existing test are validated through two experimental setups. An experimental test site is setup for an RF product and its implementation using the proposed process is presented in section VII-A. For validation of the second process, an existing test site for an antenna product is optimized using the proposed process, and results are presented in section VII-B.

The outcome of this research is a proposed standard method based on VoC, FoM, and existing manufacturing and test data, which can be used by CEM companies to setup test sites for testing electronic products.

V. PROPOSED MACHINE-LEARNING BASED AUTOMATED PROCESS

In this section, the block diagram and flowchart of the proposed process being presented. The details of the machine learning algorithm for converting customer information into customer requirements are also discussed here.

A. PROCESS BLOCK DIAGRAM

The proposed process to setup a test site for a new product is presented in figure 4. The block diagram shows the four inputs to the system which are 1) Database input interface, 2) VoC [58], [59] input interface, 3) FoM [60], [61] input interface, and 4) the Test Readiness Review (TRR) interfaces. The system generates two reports.

The database interface is independent of other interfaces and is used when new information is required to be added to the database. The process for setting up a test site for a new electronic product is initiated when the customer requirements are entered through the customer interface. This interface is also referred to as the VoC interface [62]. The test site design authority (TSDA) kick starts the process with the customer information available at the start of the process entered through the VoC interface. If the VoC threshold value is below the required level, then the software application will prompt to add more data.

This interface is not required for existing test sites that require optimization. The VoC threshold includes basic

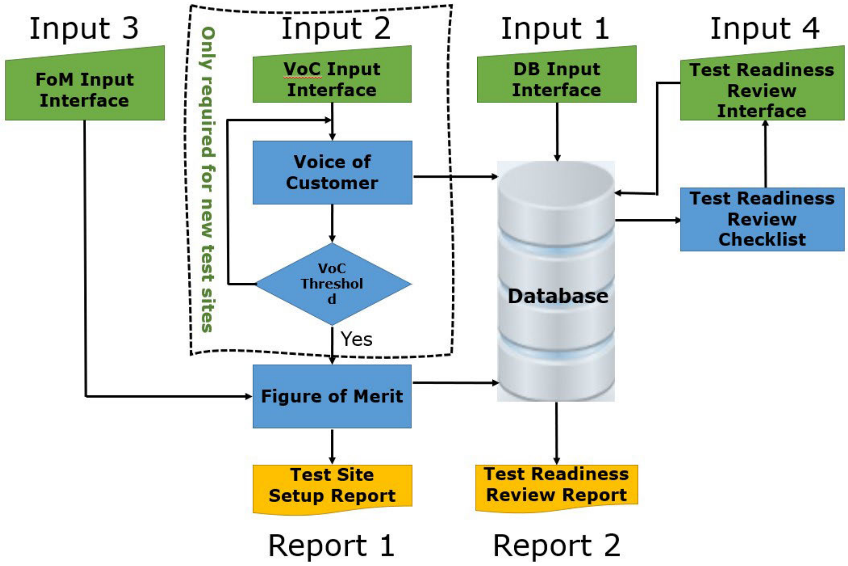

FIGURE 5. The flowchart of the proposed processes.

electronic product information, the number of test stages required or requested by the customer, any specific test requested by the customer, budget, etc. while other parameters such as test coverage, use of any specific software or hardware tool, use of specific COTS test equipment is optional.

For setting up new test sites, the customer information which is made available at a later stage can also be entered through the third interface i.e., the FoM interface. The customer information added through the FoM interface is usually missing information without which FoM cannot be calculated. The process of optimization of the existing test site starts from this input. The software application calculates the FoM using the information acquired through the VoC interface when setting up a test site for new products, and the FoM interface both new and existing test sites. The first report i.e., the Test site setup report is generated using the inputs mentioned so far.

The fourth interface is the TRR interface which is used towards the end of the process. This input is used as a failsafe step to make sure everything is required to setup the test site is available.

Two reports are generated by the application. The first is the 'Test Site Setup report' which is used by the TSDA to understand and finalize the requirements and procure the items required. The second is the 'Test Readiness Review (TRR) Report' which confirms if the test site can be setup and that everything required is available.

B. PROCESS FLOWCHART

Figure 5 shows the flowchart of the process. The process is initiated and authorized by TSDA. The process of setting up a test site for a new electronic product starts by entering information through the 'VoC input interface' while the process of optimization of an existing test site starts at the 'FoM input interface'. All information received through the interfaces is stored in the database and assigned a unique ID. For setting up a new test site, the information entered through the VoC input interface is used to calculate a threshold which is called the ''VoC threshold''.

The TSDA continues to add more requirements by contacting the customer until this threshold is reached. A calculated value less than this threshold means that there is not enough information available to design the test site. The threshold is a fixed value that is set by the TSDA. The next step is to enter FoM details using the FoM input interface. As mentioned previously this is mandatory for both new test site design and existing test site optimization. Once all the FoM details are acquired then the first report i.e., 'Test site setup report' can be generated. The 'Database input interface' or the database input is an independent and useful interface that can be used to add information which in a way is equivalent to a system upgrade. Adding more historical data or test equipment details through this interface will improve the quality of the system.

The next step is for the TSDA to confirm if the test site can be setup physically. To do this the details are entered through the 'Test readiness review (TRR) interface'. Depending on the product type and customer requirements, the TSDA is presented with a template which, once filled or completed, generates the second report i.e., 'Test readiness review report'. This report confirms if the test site can be setup or if not, then what are the remaining tasks to setup the test site.

C. DATABASE

Tables 3 (a) and (b) show a snapshot of the database including sample data. The data is related to the COTS test equipment which includes the test equipment name, make, model, and specifications. Each item is assigned a unique ID. The software application developed in LabVIEW provides

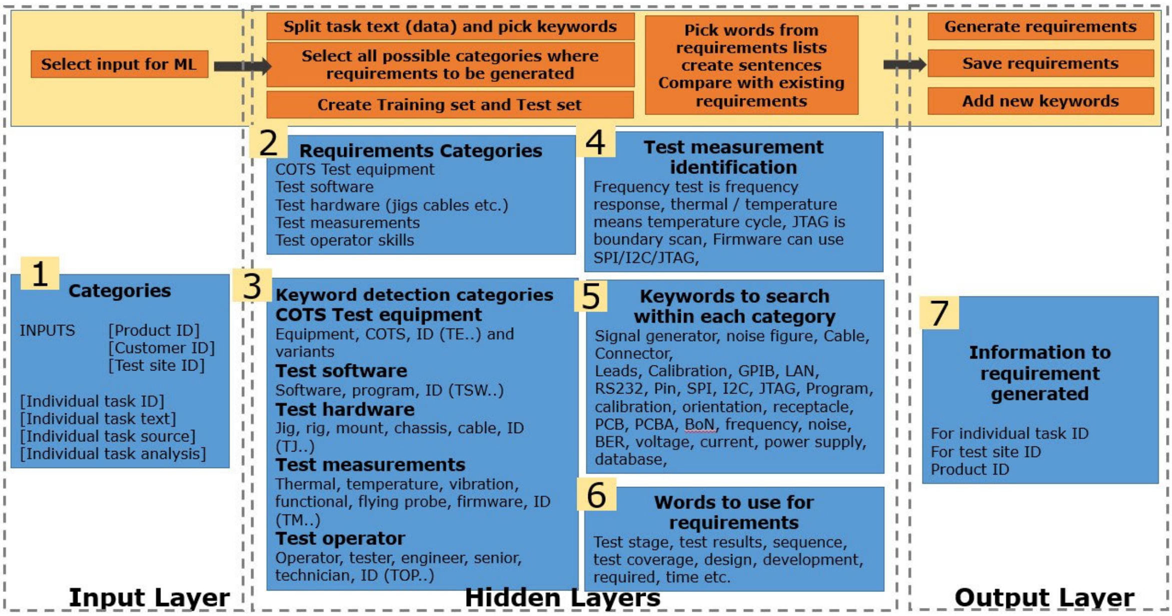

FIGURE 6. Machine learning algorithm.

TABLE 3A. (A) A snapshot of COTS test equipment data stored in the database. (B) A snapshot of test site data stored in the database.

(A)

ID	COTS Test Equipment	Make	Model	Specification
EQ-1	DMM	Company 1	Model 1	Han held DMM
EQ-2	Oscilloscope	Company 2	Model 2	4 Channel 1 GHz
EQ-3	Oscilloscope	Company 4	Model 4	2 Channel 300 MHz
EQ-4	Power Supply	Company 1	Model 3	Triple Output, 25V 5A

(B)

Test Site ID	Test Equipment	Test Software	Test hardware	Test Stages	Other
TST00 015	Signal generator, DMM, PSU	Visual Basic	Cables, Test jig	3 (Flying probe, program, function)	OS Win7

an interface for updating the database where details of new COTS test equipment and new test site data are added as shown in table 3. Other data such as fault and repair information, VoC information and requirements, FoM data are added automatically as discussed in section VI.

D. MACHINE LEARNING ALGORITHM

The structure of the machine learning algorithm is presented in figure 6. The figure shows the different layers and activities carried out. The input to this is the raw customer information collected through the VoC interface. Each customer information is assigned a unique ID and using the machine learning algorithm this is translated into customer requirement automatically. For the supervised machine learning algorithm to be accurate, lots of historical data is needed which is collected and stored in the database part of this research. A unique test set is also created for this algorithm to be effective. Details of this dataset are listed in the hidden layers.

In figure 6, the machine-learning algorithm is presented through seven activities. The first activity which is marked as '1' is to get the customer information at the input layer which is entered through the VoC interface. The customer information is taken as a block of data and assigned a 'Product ID', 'Customer ID', and a 'Test site ID. Once the ID is assigned, each task within the block is then processed. Four different features of individual tasks are considered as shown in the figure. Each task is then processed by placing it into a customer requirements category as marked by activity '2'. This categorization is achieved using the dataset presented based on the keywords, some of which are shown in the figure marked by activity '3'. The next step is to decode the individual task within customer information, one example is shown in the figure under activity '4'. Extracting information for each task once they are placed into a category is achieved using another dataset, some keywords are shown within activity '5'. Finally, a third dataset is used, some keywords are shown in activity '6' to create the requirements. All the activities from '2' till '6' are within hidden layers. Customer test requirements are presented to the user through the output payer marked by activity '7'.

VI. IMPLEMENTATION OF THE PROPOSED PROCESSES

A. SETTING UP TEST SITE FOR A NEW ELECTRONIC PRODUCT

In this section, the process of setting up a test site for a new electronic product is discussed and various activities carried out are mentioned.

1) PROPOSED PROCESS

Figure 7 shows the block diagram of the proposed method. The required inputs to setup a site for testing a new electronic

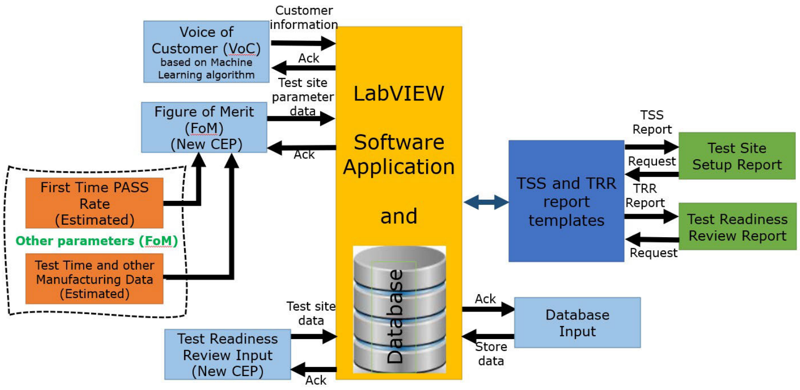

FIGURE 7. Block diagram of proposed test site setup for new CEPs.

product are listed on the left. The data is captured within the different categories as shown in the process flow. The main category is the VoC interface while all other inputs are dependent on this interface.

The next input is the FoM interface, which is used to enter certain specific details required to setup a test site that is not normally provided by the customer. Some inputs i.e., estimated first-time PASS rate and other manufacturing data which are part of the FoM interface are shown separately just to highlight the importance of these parameters. When setting up a test site for a new electronic product, the TSDA uses some estimated values due to the unavailability of actual data. These estimated values are reviewed and updated at a later stage when actual values are made available. These estimated values can either be selected by reviewing existing test sites for similar products or if a piece of test equipment was used previously and the data acquisition speed, performance, control port, etc. details are known then these can be used. Due to this, it is recommended that the TSDA should consider storing as much data as possible in the database when designing and setting up a test site. This helps at a later stage in determining estimated values for a new implementation. The estimated test times can also be determined based on the type of new product and how it will be deployed. Once the process is completed then the last interface i.e., the Test Readiness Review interface is used to make sure the test site is ready to be setup.

The VoC data entered is processed and this is then fed to the next stage. The FoM data entered through the interface combined with the VoC data is then used to calculate FoM. Each parameter within FoM is assigned a weightage and can vary and be reviewed by the authority. Details of each input parameter are discussed in detail in this section. The following inputs are required for setting up the test site for a new product.

2) THE VOC INTERFACE

Table 4 shows the VoC interface where the customer requirements are entered. Each test site is assigned a unique ID which will be used as a reference for all the tasks related to that test site. Each task is also assigned an ID within the main unique ID. All the details of the task including the source are also entered. These tasks are reviewed by the TSDA and after further discussion with the customer are then concluded as possible or not possible. It is important to use certain specific words because the test software takes decision based on these specific words. It is very important to understand the information provided by the customer so that these can be converted into proper test-related requirements. If the customer information is not captured early in the process, then this will add delays later.

TABLE 4. The VoC table for setting a new test site for CEP – experimental data.

Task ID	Task Details	Source	Analysis Category
S0001	Batch size 1000 and 250 per month	Meeting	Possible
S0002	Test Development budget £2000	Email	Possible
S0003	Test Results to be submitted electronically	Meeting	Possible

The product may not be tested completely or to the satisfaction if all the requirements are not captured. Templates are created to ensure the customer data is entered using standard-specific words normally used in this industry. As an example, one customer may request a temperature test for their product while another customer may request a thermal test for their product. Both the words here refer to the same test and every time a new word is used, it is then added to the database

Customer requirements can be captured both formally or informally through various stages and interactions. Some of the sources can be through customer meetings, emails, audio, and video calls, controlled and uncontrolled documents, and informal chat.

The step after collecting customer requirements is analysis. It is very important to both understand and then analyze these requirements and arrange them in terms of importance. After analysis, these requirements can be grouped into the categories which are "achievable" and "not achievable". Once each requirement is categorized then these are discussed with the customer again for confirmation. All the achievable requirements are then looked at in further detail to consider how these will be demonstrated to the customer.

3) THE FoM INTERFACE

Table 5 shows various parameters required and entered through the FoM interface. The main categories are in the first column with subcategories listed in the second column. The main categories include ''product information'', ''budget'', ''type of test required'' etc. Some of the inputs are translated from the customer information while others are entered by the TSDA after understanding customer requirements. Subcategories are also used within the main categories to have better coverage when implementing the test site. The table also includes experimental data which is listed in the last column under ''user data''.

The estimated value of the first-time PASS rate is selected as 95%. This is done because a 5% failure rate can be acceptable depending on the type of product and quantity tested. The actual first-time PASS rate information is updated later after testing a few batches.

The unit under test, test time, and other estimated parameters depend on the product type and tests to be conducted and reviewing similar products tested before. These parameters can include estimated test site setup time, estimated test time, estimated time to debug a faulty board, estimated time to train operator, etc.

A new test site to test electronic products depends on the product type and what test coverage is required. While calculating FoM, the TSDA considers the unit under test type and category which dictate what tests are required. As an example, if the product is deployed underwater then more tests will be added as compared to the product deployed on land. Expected quantity, estimated test time, and budget values are used to decide what sort of test jig, etc can be used. Depending on the customer requirements and expertise available, the test Software is selected, and some examples are LabVIEW, Python, C++, etc. The database provides the details of what test equipment is available and if the required equipment is not available then either this can be purchased or hired. Another parameter to consider is the hardware driver for test equipment. If the test equipment was used before then the hardware drivers are likely available. The test development team also considers the test equipment obsolescence.

The test jig design depends on the unit under test layout i.e., location of test pins. It is recommended that the test pins should all be on the same side if possible and desirable to have the connector and component numbering in a sequence. This will help in debugging later. Different types of jigs can be designed like a bed of nails jig, a programming jig, or a simple mount.

When setting up test site hardware it is important to consider different cables and sacrificial connectors. It is also important to find out from the customer about what interfaces are available on the unit under test which can include serial, SPI, I2C, JTAG, etc. If a boundary scan is required, then

TABLE 5. The FoM parameters for setting up a new test site and experimental data.

Main category	Subcategory	User data
Product Information	Type	Audio, RF, Power supply, Camera, Medical devices, etc.
	Batch size	Low is 50; Mid is 500; High is 10,000
	Where used	Underwater, Aerospace, Land, etc.
Budget	Test development	Budget for software development, making jigs, training, etc.
	Other	None
Type of Test required	PCB level (UUT is OFF)	Boundary Scan, JTAG, Flying Probe test
	PCB level (UUT is ON)	Programming (download firmware), bed of nails jig, functional test
	Cable Testing	Test cables or connectors on the unit under test
	Complete Unit Test	Go / No-go test, functional test, temperature test, vibration test
Operator	Skill level	Assign numbers from 1 to 5. Where 1 is starter level and 5 is expert level
	User Interface	Type of user interface i.e., GUI etc.
	Training	What training is required and how long will it take
Documentation	Test procedures	What level of documentation is required
	Test Results	What format is required to save test results i.e., MS Excel, MS Word, electronic, or a paper copy?

check the tools available. In terms of programming, it can onboard or off-board programming. The option to select depends on the batch quantity, cost, etc.

Test software should have a good GUI and self-explanatory so that the test procedure is not required. The operator can only concentrate on the test software and complete tasks as displayed. When writing test software, it is important to check the test software itself for all the features and that the test software is doing what it is supposed to do. Finally, version control should also be implemented. The sequence of tests is important and can help in reducing overall test time. Some customers request that the test application be controlled and monitored over the web while others want an email notification at the end of the batch. A good test software means limited test operator training required.

Another feature is to log the fault data so that this can be used at a later stage for diagnosis and future development. Having a fault database means the test software can suggest, based on a machine-learning algorithm, which component is faulty or if a component value needs changing. This will help speed up the debug process as well as reduce debug costs. Test software should also be modular and the operator, depending on the access level, can run any individual test without running the full test sequence. If one test has failed,

TABLE 6. The TRR parameters for CEP test sites.

Main Category	Sub-Category	Selection	Comments
Capture Test development Cost		Cost agreed	
Schematics		Available	
PCB Layouts		Available	
Bill of Material		Available	
Datasheets		Available	
Cable / Wiring Diagram		No	Not required
Firmware Programming	Pre-programmed (External)	N/A	
	Pre-programmed (Internal)	Yes	
	Device programmer available	Yes	
	Firmware file available	Yes	
	Programming cable available	Yes	
	Programmed part of functional test	No	
	In-circuit programmer available	N/A	Not required
Flying probe Test	CAD file available		
	GERBER files available	No	
	Panel size information	Yes	
	PCB mount available	Yes	
Cable Test	Make cables	Yes	
	Netlist	Yes	
	Any Customer cable required	No	No cables provided
Boundary Scan	JTAG Files available	N/A	No JTAG port
	JTAG programmer / cable available	N/A	
	JTAG Jig required	N/A	
Functional Test	Customer test procedure available	Yes	
	Any other customer document referenced in the main test procedure	No	Not applicable
	Internal test procedure required	N/A	Not required
Functional Test Software	Customer Test software available	Yes	
	Test Software required	No	
	Cables etc. required	No	
Equipment	Customer provided	No	
	Available	Yes	Available in-house
	Hire Equipment	N/A	

then there is no need to run the whole sequence again. Each stage should be executed independently, and this can be done by having an initialization sequence for each test stage.

The test procedure, if required, should be focused on manufacturing test, and meant for the skill level of the operator. The test procedure should not contain information that may be irrelevant to the operator. Having more information than needed can increase test time hence an optimized test procedure with more pictures and less text should be used.

The TSDA should also consider how test results should be stored. Some customer prefers results stored in MS Office Word, Excel, etc. and others recommend MS Access or XML, etc. Before selecting different tests, some critical components and parts of the circuit are also considered. All of this will provide test coverage for the unit under test.

4) TEST SITE SETUP REPORT

This is the first report generated by the process when the FoM process is completed. This report act as a baseline for setting up the test site. This report considers all customer requirements and FoM parameters and provides details like what test equipment to use, details of test jig, test software, test sequence, operator skills required, etc. The TSDA can procure all the items as per the report and once everything is available then the test site can be setup.

5) TRR INTERFACE

Table 6 shows the TRR template. This is a checklist to make sure if all the tasks are completed. Each item in the list can have one of the three options which are "Yes" meaning the task is completed, "No" means the task is pending and "N/A" means this task is not applicable for this product. All the tasks with N/A will not be shown in the TRR report and only the tasks with Yes and No will be listed. To setup the test site all the applicable items should have Yes in the last column. The TSDA can still setup the test site if any task is No but is a low-risk task.

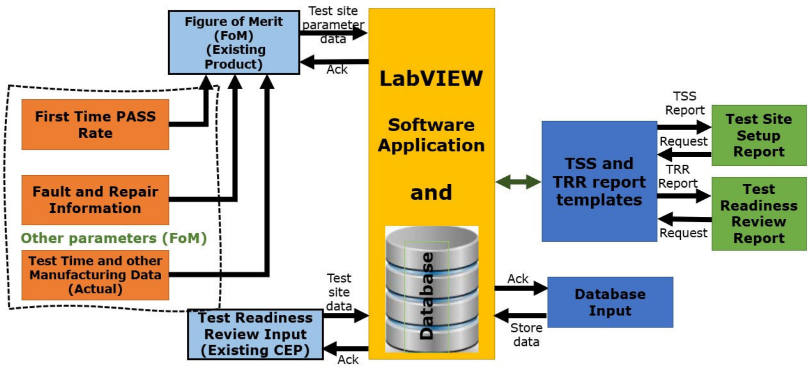

FIGURE 8. Block diagram of proposed optimization of existing test site of CEPs.

B. OPTIMIZATION OF AN EXISTING TEST SITE FOR AN ELECTRONIC PRODUCT

1) PROPOSED METHOD

Figure 8 shows the block diagram for optimizing an existing test site for an electronic product. The proposed inputs are on the left side of the block diagram. The process is initiated through the FoM input interface. As the test site had already gone through the initial setup hence there is no customer input interface required. Any potential changes required for modification of the test site are still discussed with the customer, but the resulting information is entered using the FoM input interface.

The entered data is then processed, and a test site setup report is generated. The TSDA or other members of the test team then purchase new items which can include test jigs, test equipment, cables, etc. As with the new test site design, once the items are made available then the last input i.e., test readiness review input is used as a failsafe step for confirmation.

The level of optimization can vary and depends on the amount and quality of data collected. The optimization includes removing certain tests where there is no failure or a few failures. Sometimes due to low test coverage, a part of the circuit is not tested, and the test operator can see failures. During optimization, more tests can be added to increase test coverage. The test team can also suggest replacing a certain cable with a different type to improve reliability. Obsolesce can also drive the change which is a forced change. Updating test software to make it more robust and optimized to reduce test time. All or any other changes required are based on the data collected which includes the fault date. The optimization can also be due to a change in the product. Depending on the change this can be considered as a new product but if the change is minor then optimization can be used. The test operator may not belong to the test team, so it is also important to interview the test operator and understand if there are any problems. Finally, training is provided to the test operators in line with the changes.

As shown in the process diagram, the actual parameter values are used instead of estimated values. The main input is the fault details and what was done to fix the fault i.e., repair information. A complete review is carried out once a new test is added or an existing test is modified. During the review process test, jig maintenance schedules and calibration in some cases are also considered.

FoM for existing test sites depends on the first-time PASS rate, fault, and repair information, test times, and other manufacturing data, etc. If the test had been set up using this process, then the initial reports generated at the time of setting up the test site for the first time are also reviewed.

2) FOM INTERFACE (OPTIMIZATION OF EXISTING TEST SITES

Table 7 lists different categories for FoM for existing test site optimization. The FoM for existing test sites is different from that of new test sites. The main category and sub-categories are listed in the first two columns. The last column includes typical experimental data that is collected and entered by the TSDA. It is important to consider if the electronic product itself is modified or if there is a plan to modify it. The next is the budget that defines the scope of what can be achieved. It is also seen that the test operator at a time does not follow the test procedures and hence makes mistakes which results in reduced yield. As part of data collection, the test operator is also monitored. The location of the test jig in reference to the test computer or operator position is also an important factor to consider. The optimization process is focused on the review of what is available and what new techniques etc. are available which can be used. The overall target to reduce unit under test's test time by either maintaining or increasing test coverage.

Depending on how the test site is setup, a separate fault and repair database can also be maintained, and in such a situation an interface may be required to pull the data from this separate database and then load it into the Test site optimization system database.

The first-time PASS rate is a very important parameter. It is expected that this value should be high. A low first-time PASS rate and a high second-time PASS rate is also a valid scenario where it is likely that either the operator is not careful and not enabling something on the unit under test like a switch

TABLE 7. The FoM parameters for optimization of existing test sites of CEP with experimental data.

Main category	Subcategory	Examples
Product Information	Review if anything is changed	Is the product modified?
Budget	Test Development	What budget is available for test development
	Other	None
Type of Test required	Review existing test stages	Can any test stage be removed, or a new stage be added, or can stages be merged?
Operator	Review Data collected	Is the operator making mistakes, is the test interface user-friendly?
Documentation	Test procedures	Review test procedures
	Test Results	Review test results
Yield / Fault Data	Analyze collected data	Analysis can be done

or a pot etc. The test operator is then setting the switch of the pot the second time around after the unit under test failed. The TSDA needs to take this scenario into account and consider a default position of the switch or the pot on the unit under test to increase the first-time yield.

The fault and repair details are collected every time a unit under test fails the test. A food test site allows to user to enter the repair information for the fault so when the same fault occurs next time then the solution is available. When optimizing a test site, this fault and repair information is reviewed and analyzed, and more frequently occurring faults are picked up and the root cause analysis is performed.

Table 8 shows a fault and repair database with experimental data. Normally fault and repair details are logged twice for each unit under test in case of failure. If the unit under test failed twice then this can be sent for debugging. All the faults for the second time onwards are logged under retest failure. Once a few units under test batches are tested, there will be a reasonable amount of fault, and repair information can be collected.

TABLE 8. Fault and repair template for existing CEPs.

Purchase Order	Purchase Order Qty	Unit under test Serial Number	PASS	Date	Operator ID	Fault	Repair
PO 012	50	SNS002	×	D1	TO3	Conn broken	Fixed
PO0 045	225	SNS003	×	D3	TO2	U1 faulty	replace U1

When optimizing an existing test site some information like frequency of a specific fault, specific component failure, operator-related errors, electrical and mechanical failures, manufacturing failures like dry joint, open, short circuit faults are also considered. After the test site is modified or optimized then it is recommended to run a small batch of the unit under test to make sure everything is in place.

3) TEST SITE SETUP REPORT

Test site setup report is generated at the end of the FoM process. This report provides all the necessary details for the Teat site to modify the existing test site. As mentioned previously for new test sites, this report provides details of test jig modification, replacement or up-gradation of test equipment and test software, etc. if required.

4) TRR INTERFACE

This template is identical to the one used for new test sites and details are provided in table 6 in section VI-A-5.

To complete the process, customer retunes are also considered. Increasing test coverage and improving overall testing will result in a reduced number of customer returns. The rest of the parameter's details like test equipment changes, test hardware, and jig redesign, test software, and test procedure are the same as explained in the new test site design section.

VII. VALIDATION OF THE PROPOSED PROCESS THROUGH EXPERIMENTAL SETUPS

A. EXPERIMENTAL SETUP OF AN RF RECEIVER - NEW TEST SITE SETUP PROCESS VALIDATION

Table 9 shows the list of customer requirements captured for setting up a test site for a new electronic product. The information is entered through the VoC input interface. The block of data is assigned a unique ID M00213. Individual items on the list are also assigned unique IDs. As per the customer information, the product is an RF device that will be used on land. The customer provided details of the batch quantity and power supply requirements. The customer also provided top-level details of certain tests that are required.

The table is a snapshot of information received from the customer initially. All the customer requirements are concluded as achievable apart from one. The pre-programming of a programmable chip was not possible due to a faulty in-house programmer. This programmer was not available to buy hence this was concluded as not achievable.

Table 10 shows how customer information is translated into requirements. The system picks up the customer information and then picks up test requirements that fit an item or a group of items. In the table, the system concluded that the isolation test on PCB is not required because the product will be deployed on land, so this specific test is not necessary. Due to product complexity, the possible operator skill set is also determined. It was concluded that the type of connectors on the unit under test normally gets broken and since there is enough budget so it is recommended that sacrificial connectors can be used.

The customer requested a test jig to pick up test signals and since all the test points are on the same side of the PCB, so a bed of nails test jig is recommended. Finally, based

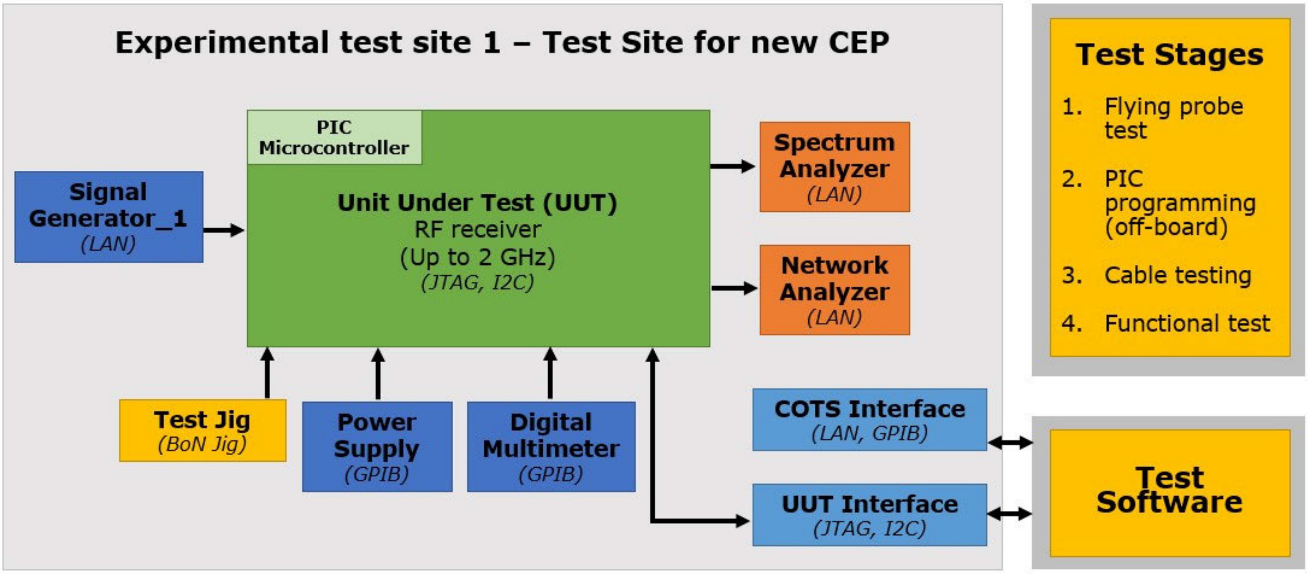

FIGURE 9. Experimental new test site setup for an RF receiver.

TABLE 9. The VoC information captured for setting up a test site for the new CEP - RF receiver.

Product	Product 368	Customer	Customer 21
Test site ID	M00213		
Sub Task ID	Details	Source	Analysis
S001	The product type is RF	Meeting	Achievable
S002	Product to be deployed on Land	Meeting	Achievable
S003	Total batch size 3000 units	Meeting	Achievable
S004	Production quantity per month is 250 units	Meeting	Achievable
S005	Test development budget is £1000	Email	Achievable
S006	Test jig required	Email	Achievable
S007	All test points on one side of the PCB	Telephone	Achievable
S008	Firmware to be downloaded via JTAG	Email	Achievable
S009	Test software required	Meeting	Achievable
S010	Estimated power supply ratings are 12V DC and 1A	Email	Achievable
S011	Voltage and current measurements	Telephone	Achievable
S012	I2C interface test	Meeting	Achievable
S013	Frequency range up to 2GHz	Email	Achievable
S014	Gain test	Meeting	Achievable
S015	Noise figure test	Meeting	Achievable
S016	RF cable testing	Meeting	Achievable
S017	Pre-programmed PIC microcontroller	Email	Not achievable

on the frequency range and type of tests requested, the test equipment required are listed. LabVIEW is selected to write test software because of the availability of test equipment drivers and in-house software expertise.

Once the customer information is translated into actual test requirements then the rest of the FoM process is completed and the test site setup report is generated. In the test site setup report the requirements are then listed for each main and subcategory in the template. The TSDA then initiates the procurement using this report. After purchasing or designing everything, the second report i.e., the TRR report is generated.

Figure 9 shows the block diagram of the new test site designed for the RF receiver. The figure shows the 4 test stages and COTS test equipment interconnection. The first test is a flying probe test where the component orientation and values are checked while the unit under test remains OFF. At this test stage, all passive components are checked. In the next test stage, the PIC microcontroller is programmed using a standalone PIC programmer. The programming is carried out off-board. The third test stage is cable testing and finally, the functional test is carried out at the last test stage. The product is extensively tested at the functional test stage for both performance and manufacturing defects. The test measurements are picked up from test points on the unit under test using a bed of nails test jig.

B. EXPERIMENTAL SETUP OF AN RF ANTENNA – EXISTING TEST SITE OPTIMIZATION PROCESS VALIDATION

Table 11 lists the reasons for upgrading an existing test site for an antenna product. It is important to understand and capture the reasons for upgrading or modifying an existing test site. Here the main reason is that the test site overall is very old and unreliable. Some test equipment is also obsolete hence in case of a breakdown, there is no backup. Due to the current state of the test site, the test operator is taking longer to test a unit under test as the first time the PASS rate is low.

TABLE 10. Translation of customer information into customer requirements for RF receiver.

Product	Product 368	Customer Customer 21
Test site ID	M00213	
Sub Task ID	Customer information	Customer requirements
S001	The product type is RF	
S002	Product to be deployed on Land	Isolation testing not required
S003	Total batch size 3000 units	Operator skill level - Engineer is sufficient
S004	Production quantity per month is 250 units	
S005	Test development budget is £1000	Sacrificial connectors will be used
S006	Test jig required	Bed of Nails jig can be used
S007	All test points on one side of the PCB	
S008	Firmware to be downloaded via JTAG	JTAG software and interface required
S009	Test software required	LabVIEW will be used for the development
S010	Estimated power supply ratings 12V DC, 1A	Single output PSU with GPIB interface
S011	Voltage and current measurements	DMM with GPIB interface
S012	I2C interface test	USB to I2C adapter required
S013	Frequency range up to 2GHz	
S014	Gain test	Spectrum Analyzer required
S015	Noise figure test	Signal Generator required
S016	RF cable testing	Network Analyzer required

TABLE 11. Information collected for optimization of an existing antenna test site.

Product:	Product 012	Customer:	Customer 04
Test site ID:		M00008	
Reasons for upgrade			
The Existing system is very old.			
The test has repeatability issues.			
The operating system is Win 7			
The equipment is old and now obsolete.			
ATE software developer left the company			
Test time is 8 min per unit under test			
Test results are stored as a text file			
The test jig is broken and high maintenance			

TABLE 12. Requirements for optimization of an existing antenna test site.

Product:	Product 012	Customer:	Customer 04
New test site ID:	M00287	Old test site ID:	M00008
New requirements			
Operating system Win 10			
New Test software to be developed			
Three options are required 1. Calibration mode, 2. Production mode and 3. Diagnostic mode			
The estimated test time is 4 min per unit under test			
New Network Analyser to be installed			
Test jig to be redesigned with sacrificial connectors			
Barcode scanner to be used			
The test site should be accessible via LAN			
Test software to display fault code and repair information based on existing fault and repair data			

Table 12 is the outcome of what needs to be done based on the reasons mentioned in the previous table. This process is the translation of information into requirements and after that rest of the FoM process can be completed. The test site is assigned a new main ID after modification and the old main ID is also kept as a reference.

Figure 10 shows the block diagram of an RF antenna that is optimized using the proposed process. The reasons for optimizations are listed in table 11. The test time is reduced to half mainly because a new COTS network analyzer is used, and new and optimized test software is developed. The test time includes the one-off network analyzer calibration time which is distributed among the unit under test batch.

VIII. DISCUSSION

CEM companies face the daunting task of manufacturing CEPs which includes testing, normally the last stage before the product is shipped to the customer. The challenge is due to several reasons, some are mentioned in this section.

The main problem is that there are no agreed standards or a universal approach for electronic product testing during manufacturing. The available standards or regulations are for product manufacturing which does not cover product testing. In the absence of any standard, the CEM companies come up with their standards which both advantages and disadvantages. The approach presented here provides a solution to this problem through the FoM which will provide consistency to the CEP testing.

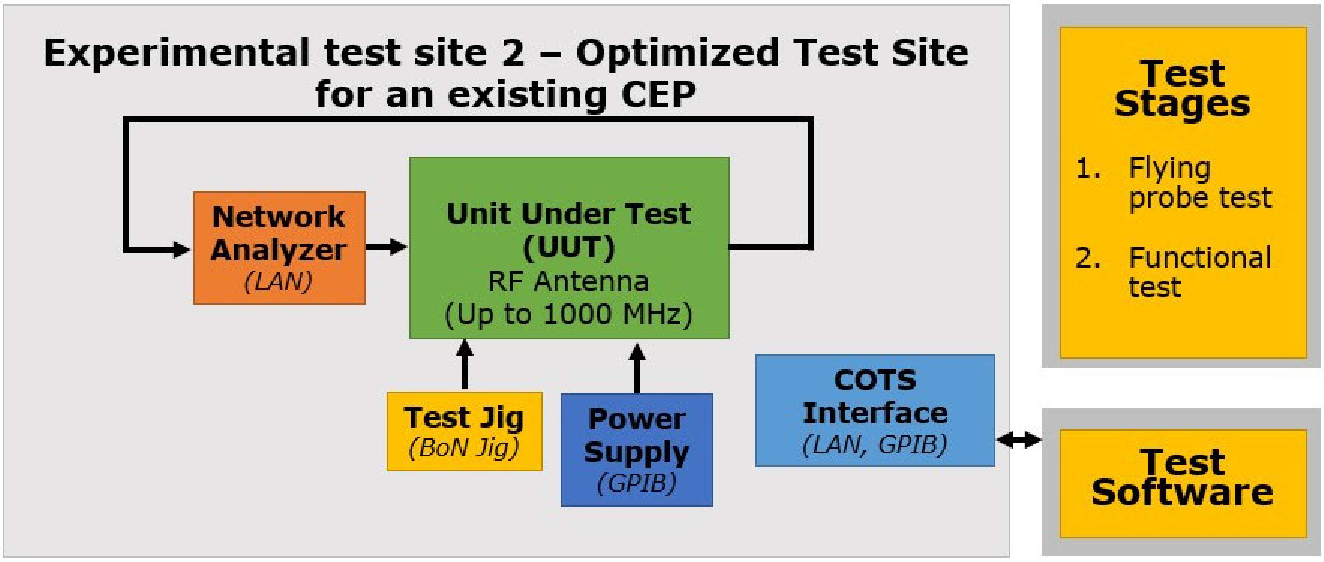

FIGURE 10. Experimental test site optimized for an RF antenna.

Translating customer information into proper test requirements is also a challenge because of the lack of a standard method and different terminologies used. The customers usually do not provide the required information at the start of the process, adding delays to the test site setup. This issue is often overlooked and creates a bottleneck at a later stage. The proposed process provides a solution for this based on a machine learning algorithm and a uniquely created dataset.

With the variety of CEPs and their variants, CEM companies are expected to maintain a good technical knowledge of electronic products and how these products can be tested. This is due to the different requirements and techniques used when designing a test site for different CEP types and their variants. The proposed system provides a knowledge base currently containing details of 400 CEPs. The interface is provided to add more test sites and CEP data to improve the knowledge base.

Often the test system design engineers use the same approach for testing different CEP types which can result in over or under testing. Less testing can result in a faulty CEP being shipped to the customer while over-testing means higher cost to the CEM company. Using the proposed system, the TSDA can benefit from the knowledge base and can use specific techniques that are effective for different CEP types.

The TSDA is required to make several decisions such as the number of test stages, test coverage, type of test jig to be used, test software options, test time, etc. The proposed process will provide the required information and thus saving time and cost.

This research focuses on the issues mentioned in this section and is a step towards defining a standard approach. The key factor behind this research is to collect and use existing knowledge and through an intelligent system generate all details required to design a test site quickly and reliably for CEP. A VoC and FoM interface is developed for this purpose.

In this article, around 400 electronic products and their variants and, 42 test sites of different electronic products are reviewed. The details of the test sites reviewed are summarized in table 1 while details of some of the electronic products are presented in table 2. The FoM presented here is proposed after a thorough review of these electronic products and test sites. The process is validated using two experimental test sites and results are presented. The process can also be applied to proof of design test sites for electronic products. Test sites are required for both PCB level testing and electronic product assemblies.

IX. CONCLUSION

This article presents a process and its implementation through a software application for designing new test sites and optimization of existing test sites for electronic products CEPs. In this research two unique VoC and FoM interfaces are presented. Setting up a new test site for CEPs is dependent on customer input which is captured through the proposed VoC interface and then translated into customer requirements using a machine-learning-based algorithm. A dataset is also created for the machine-learning-based application. The other unique feature of the proposed process is the FoM which takes into consideration customer requirements and other parameters that are discussed in this article. The standard approach presented here not only speeds up the process of setting up a test site but also brings consistency. The research focuses on different parameters and their importance in setting up a test site.

The process of modification and optimization of existing test sites is also discussed, and it is shown how this can be achieved by using certain parameters. Optimizing an existing test site for CEPs depends on how far we want to go in terms of reducing test time within the budget while improving test coverage. This process will also help in reducing the number of customer returns thus improving overall profitability for CEM companies while also achieving customer satisfaction. The two processes i.e., setting up a new test site and optimization of existing CEP test sites are slightly different which are highlighted in this article. The process can be extended to setup test sites for any electronic product proof of design test as well as manufacturing test stages.

Having a standard approach means it is easy to train staff and improve consistency and reduce human error. The process is implemented using the machine-learning-based software application developed in LabVIEW. The process is validated by setting up a new test site for an RF product and optimizing an existing test site and results are presented.

In the future, more parameters can be used when calculating FoM. The database can be expanded, and more fields can be added. TSS and TRR reports can be improved, and more templates can be added to the database. The process of translating customer information into actual test requirements can also be improved by conducting more customer surveys.

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