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An Automated Process for Designing Test Sites for Electronic Products Based on Figure of Merit and Machine Learning

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- Siddiqui, A.; Zia, M.Y.I.; Otero, P. "A Universal Machine-Learning-Based Automated Testing System for Consumer Electronic Products". *Electronics* **2021**, *10*, 136, https://doi.org/10.3390/electronics10020136
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Estas publicaciones avalan su tesis doctoral y ninguna otra tesis.

Además, el Sr. Siddiqui es co-autor de otros artículos publicados en revistas también indexadas en los Journal Citation Reports del Web of Science.

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Abstract

The manufacturing industry plays an important role in the development of a country by employing its skilled and semi-skilled workforce. Electronic manufacturing companies launch new products frequently and spend a lot of time verifying their designs. These designs are verified through rigorous validation carried out using several pre-manufacturing tests. The products are ready for manufacturing after passing these tests. These companies focus on maintaining a good standard of their products which can be achieved through the manufacturing test. At this stage, companies setup test sites for testing these products, which are different from validation tests. To compete with similar companies, the manufacturing companies need to have an optimized electronic product testing system. Products are tested for manufacturing faults and functionality to maintain quality control which is a continuous process. Both consumer electronics and other products go through a similar process.

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. CEM companies face a constant challenge to maintain quality standards during frequent product launches. A manufacturing test verifies product functionality and identifies manufacturing defects. Failure to complete testing can even result in product recalls.

This research is divided into two parts. The first part of the research is focused on designing test sites for new electronic products and optimization of existing electronic products test sites. The second part of the research is related to interfacing with existing test sites and then collecting, processing, and visualizing test sites data and generating a recommendation for continuous improvement.

In the first part of the research, a process is presented for the automated design of electronic product test sites. Currently, there is no standard approach for setting up a test site for electronic products. Normally the parameters used for taking this decision include the type of testing required, test partial or complete batch, type of equipment to be used, etc. The existing techniques rely on few parameters and the selection of these parameters also varies due to the lack of a standard method. 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 translates 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.

In this research, a software application is developed to implement standard way of setting up a test site. The software prompts test site design authority to enter parameters required to setup a test site using VoC, FoM, database, and test readiness review (TRR) interfaces. This application is linked to a database containing test equipment details and previous test sites data like test jigs, interface adapters, estimated and actual test times, first-time yield, etc. Based on the user input data the software performs analysis

and generates reports to setup a test site and also evaluate test readiness of the test site. This approach incorporates most of the techniques required to setup for most 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.

In the second part of the research, a universal automated testing system has been proposed for CEM companies to streamline their test process in reduced test cost and time. A universal hardware interface is designed for connecting commercial off-the-shelf (COTS) test equipment and unit under test (UUT). A software application, based on machine-learning, is developed in LabVIEW. This software application is used for the collection and analysis of manufacturing test site data The implementation is achieved through a process where manufacturing test data is collected and analyzed. The test site data for around 100 test sites have been collected. The application automatically selects COTS test equipment drivers and interfaces on UUT and test measurements for test sites through a universal hardware interface. Further, it collects real-time test measurement data, performs analysis, generates reports and key performance indicators (KPIs), and provides recommendations using machine-learning. It also maintains a database for historical data to improve manufacturing processes.

The data collected is for low and mid-volume batch-size for a month, where a weekly analysis is normally done. The application provides a standard approach based on graphical analysis to review data trends and provide recommendations to the manufacturing organizations for cost reduction, increased first-time yield, training requirements for the operators, etc. Initial results obtained using the application show that the proposed approach is efficient and reliable for test site data collection and analysis of a variety of products.

The proposed system can be deployed standalone as well as a replacement for the test department module of enterprise resource planning (ERP) systems providing direct access to test site hardware. Finally, the system is validated through an experimental setup in a CEM company.

Resumen

R1. Antecedentes

La industria manufacturera desempeña un papel importante en el desarrollo de un país al proporcionar empleo a su mano de obra cualificada y semicualificada. Las empresas de fabricación de productos electrónicos de consumo se enfrentan a un reto constante para mantener los estándares de calidad durante los frecuentes lanzamientos de productos. Las empresas buscan mantener un buen nivel de calidad de sus productos, lo que puede lograrse mediante pruebas de fabricación. Para poder competir con empresas similares, las empresas de fabricación necesitan tener un sistema optimizado de pruebas de productos electrónicos. Estas pruebas son la última fase de la fabricación y están consideradas parte de ella. Los productos se someten a pruebas de fabricación y funcionalidad para mantener el control de calidad, que es un proceso continuo. Para poder llevar a cabo las pruebas, es necesaria la creación de un centro de ensayos apropiado para el producto que se está probando. Para ello es imprescindible la comprensión previa de cómo deben configurarse estos centros y tener un profundo conocimiento del producto que se desea probar.

Las pruebas de fabricación verifican la funcionalidad del producto e identifican los defectos de fabricación. Si no se completan satisfactoriamente las pruebas, se puede llegar a retirar el producto y renunciar a su venta.

Las empresas fabricantes de circuitos y sistemas electrónicos de consumo (*Consumer Electronic Manufacturing*, CEM) tienen en su oferta los servicios de diseño y realización de pruebas de funcionamiento conforme a las especificaciones de los productos que establecen sus clientes y acorde a los requisitos de los usuarios finales. Estos productos electrónicos se someten primero a una prueba de validación y verificación para comprobar el diseño y, posteriormente, a pruebas de fabricación para comprobar la fiabilidad, la calidad y los defectos de fabricación. Las empresas de electrónica crean continuamente nuevos productos y dedican muchos recursos, humanos y materiales, a verificar sus diseños, lo que además implica un incremento del tiempo necesario para lanzar un nuevo producto. La verificación consiste en una rigurosa validación múltiple, llevada a cabo mediante varias pruebas previas a la fabricación. Una vez superadas estas pruebas, los productos están listos para su fabricación. Las pruebas de fabricación son diferentes de las pruebas de validación y se llevan a cabo en centros de ensayo, que son diseñados en función del tipo de producto electrónico. En la fase de fabricación, las empresas instalan centros de ensayos para probar los productos. En la actualidad, no existe un enfoque estándar para la creación de un centro de ensayos para productos electrónicos.

Dentro de la industria CEM hay un tipo particular de empresa que se denomina fabricante de equipo original, OEM (*Original Equipment Manufacturer*). Son empresas que diseñan y fabrican productos que venden a terceras empresas y el producto se comercializa bajo la marca de estas terceras empresas para los usuarios finales. Normalmente, la empresa OEM se ocupa de todo el proceso post-venta del producto de su cliente. En general, si de una empresa se dice que es CEM quiere decir que no es OEM.

Los productos electrónicos de consumo, CEPs (*Consumer Electronic Products*), son fabricados en su mayoría por empresas OEM y CEM. Estas empresas llevan a cabo diversas actividades. Una de ellas es la realización de las pruebas de sus productos, que es de lo que trata esta tesis. Tanto la fabricación como su última etapa, las pruebas, de los PEC se basan en herramientas y técnicas específicas. Esta tesis se ocupa de las técnicas y herramienta específicas de las pruebas.

R2. Partes de la investigación

En esta investigación se ha propuesto un sistema universal de pruebas automatizadas para que las empresas de fabricación de productos electrónicos de consumo agilicen su proceso de pruebas con un coste reducido en un tiempo breve. La investigación que se ha llevado a cabo en esta tesis doctoral se divide en dos partes. La primera parte se centra en el diseño de centros de ensayos para nuevos productos electrónicos y la optimización de los centros de ensayos ya existentes. La segunda parte de la investigación está relacionada con la comunicación con los centros de ensayo existentes y la ulterior recopilación, procesamiento y visualización de los datos de los sitios de prueba y la generación de recomendaciones para la mejora continua.

R3. Primera parte: diseño automatizado de centros de ensayo

En la primera parte de la investigación se presenta un proceso para el diseño automatizado de centro de ensayos de productos electrónicos y otro para la optimización de los existentes. En la actualidad, no existe un procedimiento estándar para decidir cómo configurar un centro de ensayos. Normalmente, los criterios utilizados para tomar esta decisión tienen en cuenta el tipo de ensayo requerido, si el lote a probar es parcial o completo, el tipo de instrumentación que se va a utilizar, etc. Las técnicas existentes se basan en pocos parámetros y la selección de estos parámetros también varía debido a la falta de un procedimiento estándar. Esta tesis persigue la definición de un enfoque común para el diseño y la configuración de los centros de ensayos de productos electrónicos. Se puede lograr a través de un proceso en el que se recogen y analizan los datos de las pruebas de fabricación.

Los procesos propuestos incluyen una interfaz que interpreta la opinión del cliente (*voice-of-customer*, VoC), que se basa en un conjunto de datos único y que, mediante una técnica de aprendizaje automático, traduce la información del cliente en requisitos del mismo, y proporciona una cifra de mérito (*figure-of-merit*, FoM), obtenida como resultado de esta investigación utilizando varios parámetros clave relacionados con las pruebas.

Estos procesos propuestos son un paso importante hacia la definición de un enfoque estándar definir los centros de ensayo de los productos de consumo y otros productos electrónicos. Los procesos se implementan utilizando una aplicación de software desarrollada en LabVIEW, que está vinculada a una base de datos que contiene datos de pruebas para alrededor de 400 productos recogidos como parte de esta investigación y forman una base de conocimiento para los procesos propuestos. En esta investigación se ha desarrollado una aplicación de software utilizando LabVIEW que implementa una forma estándar de configurar un centro de ensayos. El software pide a la “autoridad” (el ingeniero responsable) del diseño del centro de ensayos que introduzca los parámetros necesarios para configurar un centro de ensayos utilizando las interfaces de VoC, de FoM, de la base de datos y de la comprobación de prueba preparada, TRR (*Test Readiness Review*). Esta aplicación está vinculada a una base de datos que contiene los detalles del conjunto de los instrumentos de medida y equipos de prueba y los datos de los centros de ensayos anteriores, como son las plantillas de pruebas, los adaptadores entre instrumentos y equipos, los tiempos de prueba estimados y reales, el rendimiento del primer intento (*First Time Yield*, FTY), etc. A partir de los datos introducidos por el usuario, el software realiza un análisis y genera informes para configurar el centro de ensayos y también para evaluar la preparación de las pruebas. Este enfoque incorpora la mayoría de las técnicas necesarias para la configuración del centro de ensayos de la inmensa mayoría de los productos electrónicos que se fabrican hoy en día.

Por último, los procesos que se han desarrollado y obtenido en la investigación se validan mediante dos casos: la creación de un nuevo centro de ensayos experimental para un receptor de RF y la optimización de un centro de ensayos existente de un sistema de antenas.

R3.1. Limitaciones a resolver

Tras completar la revisión del estado del arte, se identificaron algunas limitaciones. La principal limitación de los procesos de configuración de los centros de ensayos de productos electrónicos existentes es la falta de normas o la ausencia de un enfoque común. Las normas utilizadas en la industria CEM lo son para la fabricación y no específicamente para las pruebas de los productos electrónicos de consumo. Un ejemplo es el marcado CE de los CEPs fabricados para el mercado europeo. Esta norma es simplemente una confirmación de que los CEPs que se fabrican fuera de la Unión Europea están construidos según sus normas. Al igual que otras normas similares, no incluye cómo ni a qué nivel deben someterse a prueba los productos que se fabrican.

El siguiente problema está relacionado con los requisitos de los clientes. En la actualidad, no existe un procedimiento estándar para recoger los requisitos de los clientes. Los clientes utilizan diferentes terminologías y proporcionan información en diferentes etapas de la fabricación de productos electrónicos y, a menudo, se observa que se pasa por alto alguna información importante. Estas cuestiones pueden tener un impacto directo en la calidad del producto. Por ejemplo, un cliente puede querer una prueba térmica pero no estar seguro del rango de temperatura. Seleccionar un rango de temperatura más alto puede reducir la vida útil del producto, mientras que el producto puede no funcionar correctamente a temperaturas extremas si el rango de temperatura es inferior al óptimo. Este ejemplo pone de manifiesto la importancia de generar correctamente los requisitos del cliente.

Se fabrica una gran variedad de productos electrónicos y se lanzan continuamente nuevas variantes, por lo que es muy difícil para las empresas de fabricación adquirir y mantener los conocimientos necesarios para trabajar con ellos. Tener un buen conocimiento del producto es esencial para establecer un buen centro de ensayos. Estos tipos de productos y sus variantes incluyen dispositivos médicos, sensores, productos basados en RF, productos digitales complejos basados en *Field Programmable Gate Array* (FPGA), radares, productos desplegados bajo el agua, sistemas aeroespaciales, productos de fibra óptica, etc. El problema es que un ingeniero de diseño de sistemas de prueba puede ser un experto en la comprensión y prueba de productos de RF, pero no necesariamente tener los mismos conocimientos cuando se trata de un dispositivo de procesamiento de imágenes. Del mismo modo, un experto en productos basados en FPGA puede no ser capaz de configurar un centro de pruebas para un sistema de comunicación submarino.

Por último, en lo relativo a la descripción del problema cuyo análisis y solución se aborda en esta tesis, no hay ninguna base de datos que contenga datos técnicos de los centros de ensayo existentes, ni información sobre las diferentes técnicas que pueden utilizarse para diseñar nuevos centros de ensayo.

No existe una base de conocimientos sobre cómo se pueden probar los diferentes circuitos y sistemas electrónicos.

R3.2. Contribuciones de la primera parte de la investigación

Para proporcionar una solución que supere las limitaciones arriba mencionadas, en esta tesis se presentan dos procesos automatizados basados en el aprendizaje automático (*Machine-Learning*). El primer proceso es para la creación de un nuevo centro de ensayos y el segundo proceso es para la optimización de un centro de ensayos ya existente, tanto para las pruebas de productos electrónicos en los conjuntos de placas de circuitos impresos como para los productos acabados, siempre en el ámbito de los procesos propios de la industria de fabricación de productos electrónicos. Los dos procesos comprenden tres bloques principales que incluyen los interfaces de una única VoC, de la FoM y de la base de datos que contiene los datos de fabricación y prueba de los centros de ensayo existentes.

El primer proceso para la creación de un nuevo centro de ensayos para productos electrónicos se basa en las interfaces de VoC y de FoM. El segundo proceso es la optimización de un centro de ensayos existente para productos de consumo y otros productos electrónicos, basado en la FoM y en los datos históricos de fabricación y de los centros de ensayos ya existentes.

Los procesos propuestos se implementan mediante una aplicación de software desarrollada en LabVIEW que proporciona interfaces gráficas de usuario para ambos procesos. La interfaz para la creación de nuevos centros de ensayo incluye las interfaces propuestas de VoC y de FoM. La aplicación de software propuesta genera informes que se utilizan para la creación de nuevos centros de ensayo y para la optimización de los ya existentes. La aplicación también está vinculada a una base de datos que incluye los datos de los centros de ensayo de unos 400 productos que se han recogido en el marco de esta investigación. La base de datos también incluye los datos de los centros de ensayo existentes, los detalles de la instrumentación disponible en el mercado y los detalles de las averías y reparaciones. La aplicación incorpora una interfaz gracias a la cual pueden añadirse nuevos registros de datos dentro de las categorías mencionadas.

La interfaz de VoC toma la información del cliente y la convierte automáticamente en requisitos de cliente, utilizando el aprendizaje automático supervisado. A continuación, la interfaz FoM propuesta toma los requisitos del cliente y otros datos de las pruebas para generar automáticamente informes que se utilizan para configurar los centros de ensayos. Los informes incluyen detalles de los requisitos de software de prueba, instrumentos de medida comerciales, fases de las pruebas, tiempos de prueba estimados, etc.

Con el proceso propuesto, se puede configurar u optimizar rápidamente un centro de ensayos para cualquier producto electrónico, utilizando las interfaces de VoC única y de cifra de mérito. Las empresas de fabricación de productos electrónicos de consumo ahorrarán tiempo y recursos y podrán crear centros de ensayos con conocimientos técnicos limitados.

Por último, se crea un conjunto de datos de pruebas (*test dataset*) único, con los datos recogidos y este conjunto de datos pruebas constituye la base de la aplicación de aprendizaje automático. Se pueden añadir más datos para mejorar el conjunto de datos cuando sea necesario. El proceso que aquí se presenta puede aplicarse a cualquier producto electrónico que requiera pruebas durante la fabricación o también durante la fase de prueba de diseño.

R3.3. Implementación de la primera parte de la investigación

Los procesos propuestos en esta primera parte se han implementado bajo la forma de una aplicación de software desarrollada en LabVIEW, que está vinculada a una base de datos que contiene datos de prueba de unos 400 productos recopilados en el marco de esta investigación y que constituyen una base de conocimientos para los procesos propuestos. Por último, los procesos se han validado mediante la creación de un nuevo sitio de prueba experimental para un receptor de RF y la optimización de un sitio de prueba existente de un sistema de antena.

R3.4. Discusión

Las empresas de fabricación de productos electrónicos de consumo se enfrentan a la ardua tarea de fabricar productos electrónicos. Está generalmente aceptado que la fabricación incluye las pruebas, que normalmente son la última etapa antes del embalado para que el producto se envíe al cliente o al usuario final, según sea el caso. Las pruebas en sí mismas constituyen un problema con frecuencia de mayor envergadura que la fabricación, propiamente dicha, es decir, entendida como acopio de componentes, montaje, ensamblaje, conexionado, etc. El reto se debe a varias razones, algunas de las cuales se mencionan a continuación.

El principal problema es que no hay normas comunes ni un enfoque universal para las pruebas de productos electrónicos durante la fabricación. Las normas o reglamentos disponibles se refieren a la fabricación de productos, lo que no incluye los ensayos de los productos finales. A falta de una norma común, las empresas de fabricación de productos electrónicos de consumo elaboran sus propias normas, lo cual presenta ventajas pero también grandes inconvenientes. El enfoque que se presenta en esta tesis ofrece una solución a este problema a través de la FoM, solución que proporcionará consistencia a las pruebas de productos electrónicos.

Traducir la información del cliente a requisitos de prueba adecuados también es un reto debido a la falta de un método estándar y a las diferentes terminologías utilizadas. Los clientes no suelen proporcionar la información necesaria al principio del proceso, lo que añade retrasos a la configuración del centro de ensayos. Esta cuestión suele pasarse por alto y da lugar a un embudo para la transición a la siguiente fase en el proceso de fabricación. El proceso propuesto ofrece una solución para ello basada en un algoritmo de aprendizaje automático y un conjunto de datos. La creación de esta base de datos es una de las contribuciones de esta tesis.

Con la gran variedad de CEPs, a lo que hay que añadir las distintas versiones de un producto genérico, se espera que las empresas de fabricación de productos electrónicos de consumo adquieran un profundo conocimiento técnico de los productos electrónicos y de cómo se pueden probar estos productos. Y que ese conocimiento se mantenga en el tiempo y se extienda, no sólo por la evolución de los productos, también por el aumento de la experiencia (*know how*) en la creación de centros de ensayo y de realización de las pruebas. Todo ello causado por los diferentes requisitos y técnicas que se emplean a la hora de diseñar un centro de ensayos para los distintos tipos de productos de electrónica de consumo y sus variantes. El sistema que se propone en esta tesis proporciona una base de conocimientos que, en el instante de la conclusión de esta Memoria, contiene detalles de 400 productos electrónicos de consumo, lo que la hace única en el sector. La interfaz de operación del sistema permite añadir más centros de ensayo y más datos de productos electrónicos de consumo para aumentar el conocimiento almacenado en esa base de datos.

A menudo, los ingenieros de diseño de centros de ensayo utilizan el mismo enfoque para probar diferentes tipos de CEPs, lo que en ocasiones da lugar bien a un exceso, bien a una falta de pruebas. Un número menor de pruebas puede hacer que se envíe al cliente un producto defectuoso, mientras que un exceso de pruebas supone un innecesariamente mayor coste para la empresa fabricante de productos electrónicos. Con el sistema propuesto, los responsables del diseño del centro de ensayos puede beneficiarse de los contenidos de la base de conocimientos y utilizar técnicas específicas que sean las más eficaces para los distintos tipos de productos electrónicos.

El ingeniero responsable del diseño del centro de ensayos debe tomar varias decisiones, como el número de etapas de prueba, la cobertura de la prueba, el tipo de plantilla de prueba que se utilizará, las opciones de software de prueba, el tiempo de prueba, etc. El proceso que se propone en esta tesis proporcionará la información necesaria y permitirá ahorrar tiempo y costes.

La investigación recogida en esta Memoria se centra en las cuestiones mencionadas en los párrafos anteriores y es un paso hacia la definición de un enfoque estándar. El factor clave de esta investigación es recopilar y utilizar los conocimientos existentes y, a través de un sistema inteligente, generar todos los detalles necesarios para diseñar un centro de ensayos para un determinado CEP de forma rápida y fiable. Para ello se ha desarrollado una interfaz de VoC y FoM.

En esta investigación se han revisado exhaustivamente la información de prueba de alrededor de 400 productos electrónicos y sus variantes y de 42 centros de ensayos de diferentes productos electrónicos. Los detalles de los centros de ensayos analizados y los detalles de algunos (incluir los de los 400 productos analizados no era operativo ni útil) de los productos electrónicos se han incluido en la presente Memoria. La cifra de mérito que se presenta aquí se propone tras una revisión exhaustiva de estos productos electrónicos y centros de ensayos. El proceso se ha validado mediante la experimentación con dos centros de ensayos y se presentan los resultados obtenidos. El proceso también puede aplicarse a los centros de ensayos de diseño de productos electrónicos. Los centros de ensayos son necesarios tanto para las pruebas a nivel de placa de circuito impreso como para productos electrónicos ensamblados.

R3.5. Conclusiones

En esta primera parte de la investigación se presentan procesos y sus implementaciones a través de una aplicación de software para el diseño de nuevos centros de ensayo de CEPs y la optimización de los ya existentes. Se han propuesto dos interfaces únicas de VoC y de FoM. La creación de un nuevo centro de ensayos depende de la información proporcionada por el cliente, que se recoge a través de la interfaz de VoC propuesta y luego se traduce a requisitos de cliente mediante un algoritmo basado en el aprendizaje automático. También se crea un conjunto de datos para la aplicación basada en el aprendizaje automático. La otra característica única del proceso propuesto es la FoM, que tiene en cuenta los requisitos del cliente y otros parámetros que se analizan en detalle en la Memoria de la tesis. El enfoque estándar que se presenta no sólo acelera el proceso de creación de un centro de ensayos, sino que también aporta coherencia a todo el proceso de prueba y medida. La investigación se centra en diferentes parámetros y en la importancia de cada parámetro en el proceso.

También se ha abordado el proceso de modificación y optimización de los centros de ensayo existentes y se muestra cómo puede lograrse utilizando ciertos parámetros. La optimización de un centro de ensayos existente para CEPs depende de hasta dónde se desee llegar en cuanto a la reducción de la duración de las pruebas, mejorando de paso la cobertura de las mismas, dentro del presupuesto económico de la fabricación del producto. Este proceso también ayudará a reducir el número de devoluciones de los clientes (productos finales defectuosos), mejorando así la rentabilidad global de las empresas de la industria CEM, al tiempo que se consigue la satisfacción de los clientes. Los dos procesos, es decir, la creación de un nuevo centro de ensayos y la optimización de los ya existentes, son ligeramente diferentes y ambos se han tratado en la Memoria. El proceso puede extenderse a la creación de centros de ensayo para cualquier prueba de diseño de productos electrónicos, así como a las fases de prueba de la fabricación.

Disponer de un enfoque estándar significa que es más fácil formar al personal, mejorar la coherencia y la consistencia de las pruebas y reducir los errores humanos. Los procesos propuestos se han implementado bajo la forma de una aplicación de *software* basada en el aprendizaje automático, aplicación desarrollada en LabVIEW. Los procesos se han validado mediante la creación de un nuevo centro de ensayos para un producto de RF y la optimización de un centro de existente y en la Memoria se presentan ambos resultados.

R3.6. Primera parte: recomendaciones futuras

La primera parte de la investigación se ha llevado a cabo sin dejar de contemplar futuras mejoras. Entre ellas cabe citar lo que sigue: Se puede ampliar la base de datos de conocimiento, no sólo incorporando los resultados de nuevos CEPs, también se pueden añadir más campos; podrán utilizarse más parámetros para calcular la FoM; podrán mejorarse los informes de la configuración del centro de pruebas (*Test Site Setup*, TSS) y de comprobación de prueba preparada (TRR); podrán añadirse más plantillas a la base de datos; podrá mejorarse el proceso de traducción de la información del cliente a requisitos de prueba reales realizando más encuestas a los clientes.

Aunque los resultados de la investigación constituyen un avance notable hacia la definición de un enfoque estándar para la configuración de los centros de ensayo, la FoM tiene sus limitaciones. Por ello, quizá en el futuro deberán añadirse más parámetros en el cálculo de la FoM. Asimismo, la ampliación de la base de datos de conocimiento y la actualización de la plantilla de TRR servirán para la creación de centros de ensayo para CEPs más complejos.

R4. Segunda parte: sistema universal de pruebas

En la segunda parte de la investigación se ha propuesto un sistema universal de pruebas automatizadas para que las empresas de la industria CEM agilicen sus procedimientos de pruebas en un tiempo y con un coste reducidos. Se ha diseñado una interfaz universal de *hardware* para conectar los equipos de instrumentación electrónica de medida y la unidad bajo prueba (*Unit Under Test*, UUT). El sistema propuesto, basado en aprendizaje automático, se ha llevado a la práctico en la forma de una aplicación *software* en LabVIEW. Esta aplicación de software se utiliza para la recopilación y el análisis de los datos del centro de ensayos de fabricación. El sistema incorpora un proceso en el que se recopilan y analizan los datos de pruebas de fabricación. Se han recogido los datos y los resultados de las pruebas de alrededor de 100 centros de ensayo. La aplicación selecciona automáticamente los controladores e interfaces entre la instrumentación electrónica de medida y el UUT, así como las medidas de prueba de los centros de ensayo por medio de una interfaz *hardware* universal. Además, recoge los datos de las medidas en tiempo real, realiza análisis, genera informes e indicadores clave de rendimiento (*Key Performance Indicator*, KPI) y proporciona recomendaciones. Los algoritmos que realizan todo lo anterior están basados en técnicas de aprendizaje automático. Por último, el sistema también mantiene y actualiza una base de datos históricos de conocimiento que se usará para mejorar los procesos de fabricación.

En la configuración del sistema ha sido preciso tomar algunas decisiones relacionadas con volúmenes de datos. Se ha elegido la unidad de tiempo mes para que los archivos *batch* recogidos sean de volumen medio o bajo (con criterios de 2021 para esta denominación). El análisis de los datos, sin embargo, se realiza semanalmente, para que la actualización de la base de conocimiento no sufra retrasos. La aplicación proporciona un enfoque estándar basado en el análisis gráfico para revisar las tendencias de los datos y proporcionar recomendaciones a los distintos departamentos de la empresa CEM para la reducción de costes, el aumento del rendimiento del primer intento (FTY), el establecimiento de requisitos de formación de los operadores, etc. Los primeros resultados obtenidos con el uso de la aplicación muestran que el enfoque propuesto es eficaz y fiable para la recogida de datos en el centro de ensayos y para el análisis de los procesos de medida de muy diversos productos electrónicos.

R4.1. Limitaciones

Cuando se lanza un nuevo CEP, el equipo de desarrollo de pruebas tiene que seguir todos los pasos y diseñar un centro de ensayos independiente, que sólo puede utilizarse para probar ese CEP específico. Un centro de pruebas típico incluye equipos de instrumentación electrónica de medida, interfaces, plantillas de pruebas, *software* de prueba, etc. A falta de un marco universal de centros de ensayos, la reutilización de los centros de ensayos disponibles es muy limitada.

Para las pruebas automatizadas, en la actualidad se desarrolla una aplicación *software* para cada CEP, que también requiere su propia validación. El tiempo de comercialización de un CEP es importante, por lo que cualquier retraso añadido a un calendario ya apretado supone una pérdida de ingresos y la posibilidad de que se embalen y se despachen productos defectuosos.

En una empresa CEM típica, se prueban miles de UUTs mensualmente y no hay un sistema central que coteje los datos, revise los fallos, recomiende la reparación o rectificación de los mismos y los presente en diferentes categorías. Por ejemplo, un UUT podría fallar debido a un exceso de soldadura en un borne de un componente y que la solución a ese fallo fuese reducir la pasta de soldadura. Esto es un problema para el departamento de soldadura convencional, por lo que, a menos que se informe a este departamento, el fallo puede no ser rectificado. La búsqueda manual de fallos y su clasificación es una tarea tediosa y puede ocupar varias horas incluso a personal muy especializado.

El diseño de cualquier sistema universal requiere una base de conocimiento y de datos históricos, lo cual es una tarea difícil de completar. Para recopilar esos datos, es necesario seguir las pautas de un proceso que pueda centrarse en la información que está disponible y que sea capaz de recopilar y, sobre todo, clasificar y etiquetar esa información.

R4.2. Contribuciones

La implementación del sistema propuesto es de bajo coste, eficiente, fácil de usar y proporciona una solución a todas las tareas realizadas en un departamento de pruebas típico de una empresa CEM. El sistema propuesto presenta seis características novedosas. Estas características incluyen:

- una interfaz *hardware* universal para equipos de instrumentos electrónicos de medida y sus interfaces con los posibles UUT,
- una aplicación *software* universal para automatizar las pruebas CEP,
- el control de los instrumentos electrónicos y la recopilación de datos de prueba,
- informes automatizados y gráficos,
- KPIs y
- generación de recomendaciones para la mejora continua basada en el aprendizaje automático supervisado.

A diferencia de los módulos existentes utilizados en los departamentos de pruebas de las empresas CEM, el sistema puede conectarse a los sistemas de planificación de recursos empresariales (*Enterprise Resource Planning*, ERP) para proporcionar acceso directo al hardware de pruebas, incluidos los equipos de pruebas y los productos electrónicos que se prueban. Alternativamente, también puede desplegarse como sistema independiente en sustitución del sistema ERP específicamente en el departamento de pruebas de una empresa CEM.

Además del proceso propuesto y del sistema que lo implementa, el correspondiente capítulo de la Memoria ofrece una visión detallada de todas las actividades relacionadas con las pruebas CEP dentro de la industria CEM. De este modo, se abren nuevas vías para que los investigadores exploren este ámbito poco estudiado. Se destacan algunos problemas y se aportan soluciones. Por primera vez se aplica un algoritmo de aprendizaje automático a las pruebas CEP a esta escala. Se crea y presenta el proceso de detección y categorización de fallos, así como un conjunto de datos de aprendizaje.

R4.3. Implementación

El sistema propuesto puede desplegarse de forma autónoma, así como sustituir al módulo del departamento de pruebas de los sistemas ERP, proporcionando acceso directo al *hardware* del centro de ensayos. Por último, el sistema se valida mediante un montaje experimental en una empresa de CEM.

R4.4. Discusión

La recopilación de datos sobre la calidad de las pruebas puede ayudar a las empresas de la industria CEM a comprender las áreas en las que es necesario mejorar o las áreas que están creando un embudo en los procesos de pruebas. Estas empresas pueden tomar medidas correctoras como rediseñar sus plantillas de pruebas, modificar la secuencia de pruebas, añadir o eliminar determinadas pruebas, procurar formación específica y enfocada para el personal y tener una idea clara sobre la contratación, la inversión en instrumentación y otros equipos de pruebas, etc. Sobre la base de la revisión, se identifican varias limitaciones en los sistemas existentes utilizados en el ámbito de las pruebas CEP de la industria CEM.

Normalmente se requiere que un nuevo CEP sea probado como parte del proceso de fabricación. Para ello es necesario un centro de ensayos, que incluye equipos de instrumentación electrónica, interfaces *hardware*, plantillas de prueba, *software* de prueba, etc. Debido a la falta de un sistema universal, las empresas CEM deben llevar a cabo todas las actividades para establecer sus propios centros de ensayos, lo que requiere mucho tiempo y esfuerzo. El sistema universal propuesto ofrece una solución a este problema y ahorra tiempo y costes a las empresas CEM, al tiempo que mantiene la coherencia y mejora la calidad. Para automatizar las pruebas también es necesario desarrollar un *software* de pruebas, lo que puede llevar mucho tiempo en función de la complejidad de la UUT. La siguiente cuestión es la validación de esta aplicación de *software*; a menudo se observa que, debido a la falta de tiempo y a la urgencia por comercializar el producto, se ignora la validación adecuada del *software*, lo que significa que puede despacharse un producto defectuoso. Con el sistema universal propuesto, las empresas CEM no tienen que desarrollar la aplicación de pruebas para cada nuevo producto y sólo tienen que integrar su centro de ensayos. Disponer de una aplicación de software universal para probar varias UUT es un paso importante, pero esto nos lleva al siguiente problema, que es identificar y mantener una biblioteca de subrutinas de *software* para las medidas de prueba. Debido a la variedad de UUTs, el tipo de medidas de prueba también varía en función de los equipos de instrumentación comerciales o propietarios.

La siguiente etapa es disponer de un proceso o enfoque que pueda decidir automáticamente, basándose en la información del operador de la prueba, qué medidas en las que consiste la prueba son necesarias y cómo deben tomarse estas medidas en función de la UUT. Un enfoque de aprendizaje automático puede resolver este problema, pero para que una técnica de aprendizaje automático supervisado funcione eficazmente se necesita una gran cantidad de datos históricos que incluyan el código de prueba para tomar las medidas de prueba. Para resolver este problema, se revisan alrededor de 100 sitios de prueba para una variedad de CEPs. Esto ayudó a crear una base de conocimientos para los equipos de instrumentación electrónica comerciales, las interfaces de hardware UUT y las medidas de prueba. El sistema está diseñado de forma que se puedan añadir fácilmente nuevos controladores de dispositivos y códigos de medida. El *software* de pruebas recibe la información del operador de pruebas, selecciona el código necesario de la base de datos, finaliza la secuencia de pruebas y el *software* de pruebas se genera rápidamente. Por último, para que el concepto anterior funcione, se necesita una interfaz *hardware* universal. Esta interfaz *hardware* debe tener todas las interfaces comunes para conectarse a cualquier centro de ensayos de productos electrónicos. Para que el sistema propuesto funcione, también se necesita una biblioteca de controladores de equipos de instrumentación electrónica comerciales y de otro tipo. También se tienen en cuenta las limitaciones y características de estas interfaces, como la velocidad de transmisión de datos, el número de dispositivos que se pueden conectar y los requisitos de alimentación. La gran mayoría de los equipos de instrumentación electrónica comerciales tiene uno de los puertos de control utilizados en la interfaz *hardware* universal.

Hay que tener en cuenta que mensualmente se prueban cientos y miles de unidades, y no es posible hacer un seguimiento y resolver los fallos mediante un proceso manual de análisis de fallos. La otra cuestión es categorizar los fallos para que el departamento correspondiente reciba detalles que le permitan encontrar una solución a esos fallos. El proceso automatizado que se presenta en la Memoria se apoya en una base de datos de conocimiento y la información sobre averías y reparaciones se recoge y se coloca en la categoría adecuada de la base de datos. Este proceso hará posible el proceso de análisis de fallos con un esfuerzo mínimo. Un aspecto importante de esta investigación es asegurarse de que el sistema propuesto pueda integrarse con los sistemas existentes utilizados en la industria CEM. Algunas empresas CEM utilizan los sistemas ERP; por lo tanto, se propone una interfaz entre el sistema propuesto y los actuales sistemas ERP. Se trata de una tarea difícil, ya que los sistemas ERP se desarrollan utilizando diferentes tecnologías y una interfaz universal requiere el estudio de diferentes sistemas ERP, sus interfaces y sus *plugins*. Como parte de esta investigación, se han revisado varios sistemas ERP de uso común en la industria CEM y se ha creado una interfaz entre el sistema propuesto y esos sistemas ERP. Otras empresas de la industria CEM utilizan sistemas autónomos, es decir, no integrados en los ERP, en sus departamentos de pruebas, lo que también se ha tenido en cuenta, de manera que el sistema propuesto también puede desplegarse para funcionar como un sistema autónomo.

El sistema propuesto también puede utilizarse fuera de la industria CEM para validar otras configuraciones experimentales para probar circuitos y sistemas electrónicos. Los investigadores pueden usar equipos comerciales de instrumentación y el *hardware* UUT para conectarse a sus circuitos o sistemas. A continuación, el *software* de prueba universal puede utilizarse para controlar y evaluar automáticamente sus diseños.

El sistema propuesto se valida en dos etapas. En primer lugar, la validación de la interfaz *hardware* universal y de los subsistemas de recogida de datos de prueba se realiza utilizando dos centros de ensayo experimentales; con la palabra experimental quiere decirse que se usan como ejemplos de centro de ensayo para validar los resultados de la investigación. Estos centros de ensayo se utilizan para probar dos tipos de productos diferentes. Esto demuestra que el sistema propuesto puede utilizarse para probar una variedad de CEPs. En segundo lugar, el subsistema de análisis de datos se valida desplegando el sistema propuesto en un entorno CEM en el que se recogen y analizan los datos y los resultados se presentan en forma de gráficos, KPIs y recomendaciones basadas en el aprendizaje automático.

R4.5. Conclusiones

Fruto de esta segunda parte de la investigación es una solución completa para las pruebas de CEP que incluye una interfaz *hardware* universal y una aplicación *software* basada en aprendizaje automático. El sistema propuesto proporciona el control de los equipos comerciales de instrumentación, la recogida de datos de prueba, el almacenamiento, el análisis, obtiene los KPIs y genera automáticamente recomendaciones. El sistema automatizado puede desplegarse como un sistema independiente, así como una alternativa a los sistemas ERP en los departamentos de pruebas de la industria CEM. Además, el sistema propuesto puede utilizarse para conectar cualquier centro de ensayos de productos electrónicos mediante una combinación de *hardware* universal y subsistemas de *software* basados en el aprendizaje automático. Este enfoque ahorra costes y tiempo, ya que no es necesario diseñar una interfaz de hardware adicional ni desarrollar un software de pruebas para cada producto. Además, el sistema es fácil de usar, flexible y requiere menos formación antes de su aplicación. El sistema propuesto se valida mediante pruebas experimentales de dos productos, un amplificador de RF multicanal y una grabadora de voz analógica. Sin embargo, el subsistema de procesamiento de datos se valida desplegándolo en un entorno CEM de volumen medio, y los resultados se presentan en forma de gráfico. Por último, se crea un conjunto de datos y se categorizan los fallos para las recomendaciones basadas en el aprendizaje automático y se presentan los resultados a través de ejemplos para agilizar los procesos, mejorar el mecanismo de pruebas y superar los fallos para obtener productos de buena calidad. El sistema de recopilación y análisis de datos propuesto puede ser utilizado tanto por empresas OEM como por empresas CEM.

R4.6. Segunda parte: recomendaciones futuras

En el futuro, el tamaño del conjunto de datos en la base de datos puede aumentarse añadiendo más detalles del sitio de prueba que serán útiles para el algoritmo de aprendizaje automático para mejorar aún más la decisión. Del mismo modo, en función de las necesidades del cliente, el enfoque puede aplicarse a las industrias de fabricación de gran volumen con más opciones.

También a futuro, un enfoque similar de recogida y análisis de datos de fabricación puede aplicarse a la fabricación de grandes volúmenes de CEPs.

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ATE	Automated Test Equipment
CEM	Consumer Electronic Manufacturing
CEP	Consumer electronic products
COTS	Commercial off-the-shelf
DAQ	Data Acquisition
DFM	Design for Manufacturability
DFT	Design for Testability
ENG	Engineer
ERP	Enterprise Resource Planning
FoM	Figure-of-Merit
FPGA	Field Programmable Gate Array
GPIB	General-purpose Interface Bus
GUI	Graphical User Interface
I2C	Inter-integrated Circuit
JTAG	Joint Test Action Group
KPI	Key Performance Indicators
LabVIEW	laboratory virtual instrument engineering workbench
NI PXI	National Instrument PCI eXtensions for instrumentation
OEM	Original Electronic Manufacturing
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
SEN	Senior Engineer
SPI	Serial Peripheral Interface
SQL	Structured Query Language
TEC	Technician
TO	Test Operator

TRR	Test Readiness Review
TSDA	Test site design authority
UUT	Unit Under Test
VoC	Voice of Customer
VVT	Validation and Verification Testing

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Chapter 1: Introduction

1.1. Introduction and background

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 electronic manufacturing 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 chapter.

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 don't have their own product range and manufacture and test electronic products for their customers. Customers of CEM companies design their electronic products and perform design for manufacturing and design for testability while their products are manufactured by CEM companies. Some CEM companies also carry out design for manufacturing and design for testability activities for their customers.

Testing of electronic products is a challenging task due to the variation in product types that are launched frequently. Often it is seen that due to constraints like time limitation, tight budget, or lack of expertise, faulty products are delivered to the customer. This results in high customer returns cost for the manufacturing company. An optimized product test site design can increase revenue for manufacturing companies and maintain a base of satisfied customers. A standard approach addresses these issues in helping companies to achieve their targets. The companies namely the OEM and CEM, which are responsible for manufacturing and testing electronic products can benefit from this. Other companies that use OEM and CEM to get their products manufactured can also benefit from this approach.

Electronic product test sites can be setup as manual, semi-automated, or fully automated depending on the requirements. The important factor is to make sure the product is neither under-tested nor over-tested. If the product is under-tested, then there is a possibility of a higher number of customer returns or an unsatisfied customer. An over-tested product means a high cost to the manufacturing company. Future up-gradation should also be considered when designing a test site so that some or most of the test site modules, sub-sections, or parts can be reused. It is also important to design the test site within the budget hence adding some features may not be viable to implement. Other things to consider are designing test jigs and implementing a maintenance schedule, selecting test equipment based on cost, availability, and features, where the test site will be setup, and how test results will be stored. Companies select one or more of these applications based on budget, expertise, customer requirements, etc.

Electronic products and gadgets are an essential part of our daily life. Every day numerous new products are launched. Electronic manufacturing companies are spending a lot of time and effort to design and manufacture these products. There are various parameters that these companies focus on depending on the type and end-users of these products. For example, the products designed and manufactured for the medical industry or deployed underwater communication should be reliable and precise, which is the priority for the manufacturing companies. Some electronic products such as toys are usually low cost but require more features to attract children and for such products quick turnaround is a priority. Successful product launch mainly depends on complete and precise yet quick testing. Failure to do so results in failed products, defects identified after product launch, product recalls, and ultimately, loss of a satisfied customer.

Consumer electronic product (CEP) manufacturing is based on the product lifecycle where a product design team initiates and completes the product design [1], which is qualified through validation and verification testing (VVT) [2]. The next step is to perform the design for manufacturing (DFM) [3] process, which makes the product ready for manufacturing. The product is then manufactured. To validate that the product is manufactured according to the set standards and design, a manufacturing test is carried out. This manufacturing test is setup and validated through a design for testability (DFT) process [4]. The products that pass this manufacturing test are shipped to the customers.

We are surrounded by electronic products. Some of them have become necessities in our daily lives. End users want good quality and reliable products, which means the manufacturing companies at times end up in a situation where they compromise certain key factors like quality just to market the product in time. These companies have to keep up with the technology and skill levels so that they can maintain quality. There are various parameters that these companies focus on depending on the type of products and the end-user. Collecting manufacturing test data and analysis assists the companies to understand the areas where improvement is required. Using the manufacturing data, companies take actions like redesigning their test jigs, modifying the process sequence, changing the material they use or training the staff, etc. [5].

A solution is provided for electronic product manufacturing companies to be able to market their products in time with improved quality and test coverage. Using the process presented here, these companies can collect manufacturing test data for products tested within a duration. The data collected is then analyzed and recommendations are provided which the manufacturing companies can use to improve parameters like reduced test cost, high yield, improved test coverage, etc.

An electronic product goes through several qualification tests which are part of VVT. These tests can include drop test, accelerated life test, vibration test, etc. A qualified product then goes through several reviews and DFM [6]. After this stage a product is ready to be manufactured i.e., the company can source all components, parts, etc., and can build the product. To verify this, some companies build a small batch of prototypes to streamline DFM. A manufactured product is then tested for functionality or faults in the manufacturing process. To setup this, the product goes through DFT. At this stage parameters like (i) what test equipment is required, (ii) what test coverage is acceptable, (iii) how test signals can be picked, etc., are discussed, and implemented.

1.2. Scope of this research

The research is divided into two parts. Details and the scope of these parts are discussed in this section.

1.2.1. Designing test sites for electronic products

Figure 1.1 shows the roles of electronic product manufacturing companies within the CEM industry.

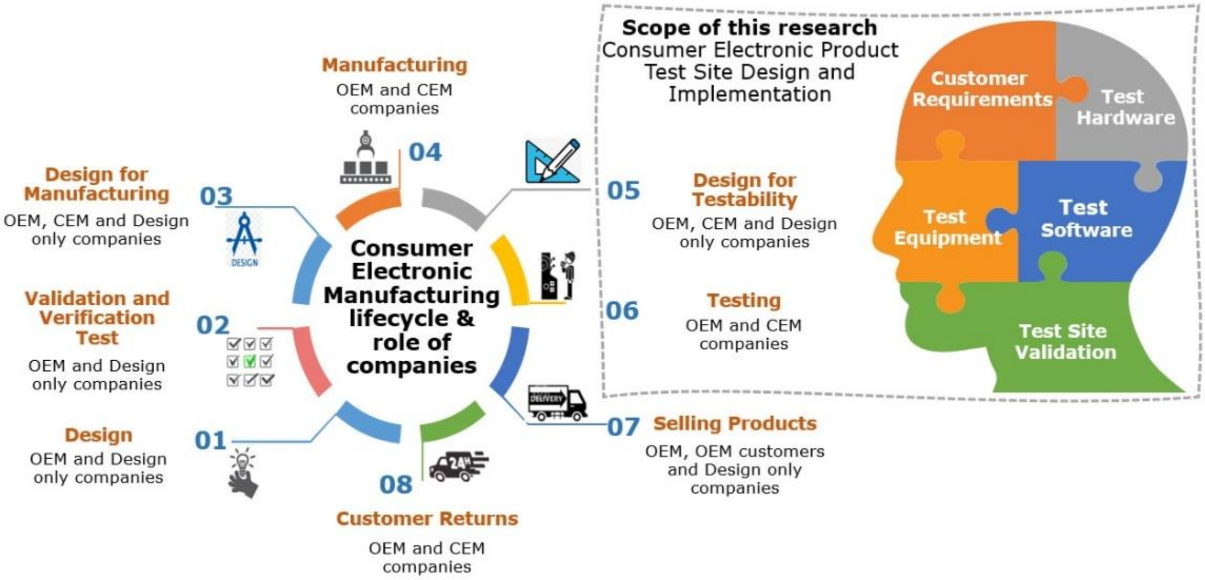

Figure 1.1. Scope of the test site design process within CEM lifecycle.

Consumer electronic products (CEPs) and non-consumer electronic products 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 and other electronic products rely on DFM and DFT tools and techniques.

1.2.2. Universal automated testing system for electronic products

Figure 1.2 illustrates the CEP lifecycle. The process starts with the product design team designing a product. The design is validated through a VVT process. This validation testing process can take weeks or months. Depending on the product, it can take a year before the first batch of prototypes is ready for the manufacturing test. The next step is to perform DFM so that the product can be manufactured. DFM process includes sourcing components, build printed circuit board (PCB) and manufacture printed circuit board assembly (PCBA), procure material and build product casing or housing, etc. Once the product is manufactured, DFT is carried out to capture requirements to test the product and identification of tools required for testing. The final stage is testing where the product is tested for functionality as well as manufacturing-related faults.

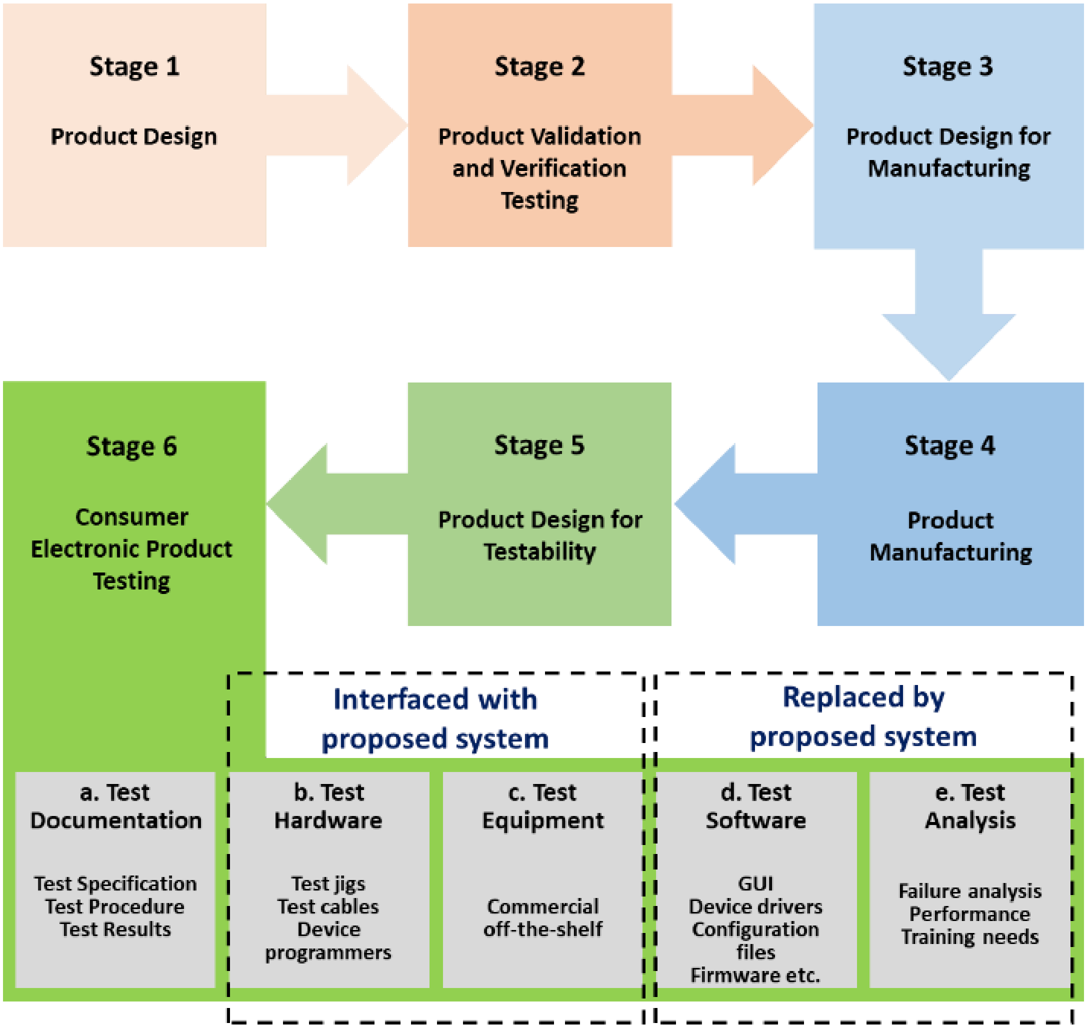

Figure 1.2. Scope of the universal automated testing system within CEM lifecycle.

During the CEP testing stage, a test site is setup and various activities are carried out, which are shown in Figure 1.2. The important point is that for every new product, a test site is required to be designed and implemented and the activities mentioned in stage 6 are repeated. Setting up a test site normally takes a few weeks to months to complete. Designing test sites is out of the scope of this research. The system proposed here is interfaced with two building blocks of the test site while replacing the other two as shown in Figure 1.2.

1.2.3. Machine-learning algorithm

Machine-learning has been rapidly replacing conventional processes, where certain tasks carried out by humans are being replaced by computers. Existing and new machine-learning algorithms are being applied for this purpose. The main element is a unique dataset that is created and defined for solving different problems, which is provided to the machine to learn and apply to the process. The overall performance and effectiveness of the machine-learning process depend on the quality and size of the dataset. A relationship is created between inputs and outputs where the new data is processed using the existing dataset.

Figure 1.3. shows the different machine-learning techniques and mapping of the scope of this research. Machine-learning techniques are either ‘Supervised’, ‘Unsupervised’, and ‘Reinforcement’ with further divisions. This research is based on a supervised machine-learning technique where data labels are used. The algorithm fits into the ‘Classified supervised machine-learning’ category. A unique dataset is created as part of the research work.

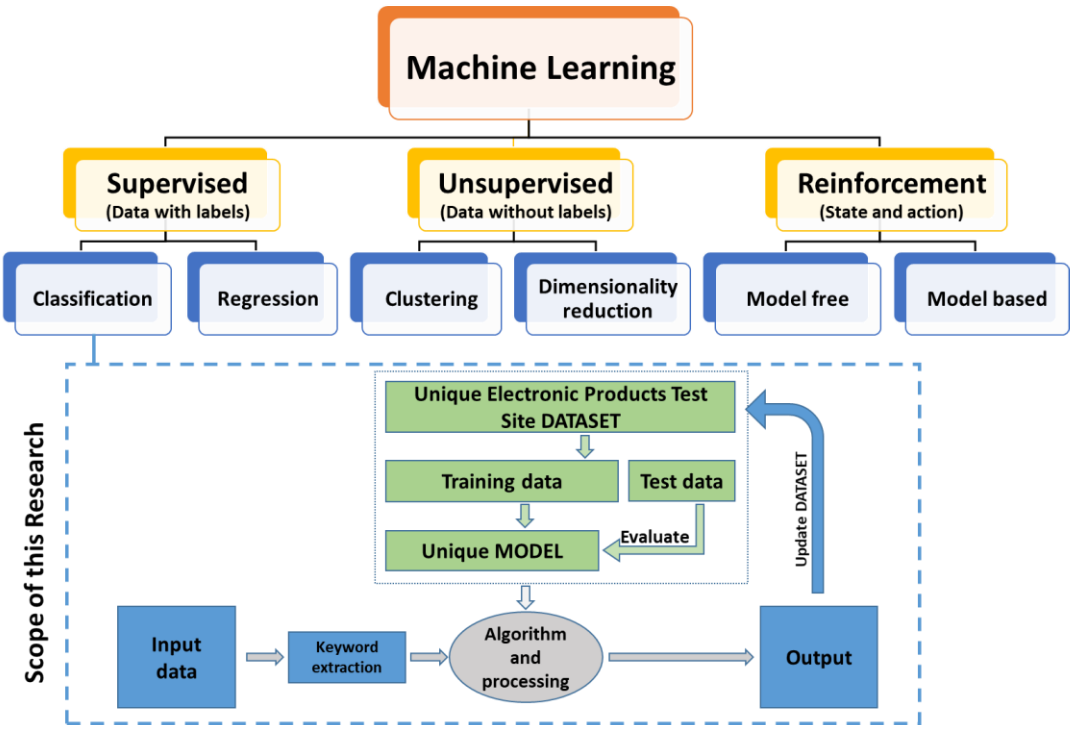

Figure 1.3. Scope of the machine-learning within this research.

1.3. Research objectives

The main objectives of this research are as follows:

1.3.1. Objective A

To define a process to design test sites for new electronic products based on a figure-of-merit.

1.3.2. Objective B

To define a process to optimize test sites for existing electronic products based on a figure-of-merit.

1.3.3. Objective C

To develop a machine-learning-based algorithm for the processes proposed in 1.3.1. and 1.3.2.

1.3.4. Objective D

Implementation of the proposed processes, mentioned in 1.3.1 and 1.3.2 using experimental test setup.

1.3.5. Objective E

To define a process for collection and analysis of manufacturing test sites data for electronic products.

1.3.6. Objective F

To develop a machine-learning-based algorithm for automated test sites data collection and analysis for electronic products proposed in 1.3.4.

1.3.7. Objective G

To design a universal hardware and software module for interfacing with electronic products test sites for manufacturing test sites data collection and analysis proposed in 1.3.4.

1.3.8. Objective H

Implementation of the proposed processes, mentioned in 1.3.5., using experimental test setup.

1.4. Significance of this research

The electronic product design and manufacturing industry play a key role in the country's economy. Manufacturing companies launch new products frequently and maintain manufacturing standards to keep a satisfied customer base. Companies also focus on quick product turnaround to reach the consumer market on time. The manufacturing test is an important stage where certain aspects of product design, functionality, and manufacturing defects are verified. To achieve this, manufacturing companies deploy expensive supply chain systems. The motivation behind this research is to help manufacturing companies reduce their cost which in turn reduces the cost to end-user.

There are lots of challenges that include thousands of electronic product types and variants, electronic products manufactured and tested in one country and shipped to other countries, lack of expertise, and complex process deployed. Electronic products range from medical devices, sensors, RF, complex digital, underwater, etc.

This research will provide a significant step towards standardizing the electronic products manufacturing process and improving the quality through effective testing. Overall, this research will benefit not only this industry but the community as large.

1.5. Related publications

Siddiqui, A.; Zia, M.Y.I.; Otero, P. A Universal Machine-Learning-Based Automated Testing System for Consumer Electronic Products. *Electronics* 2021, *10*, 136.

https://doi.org/10.3390/electronics10020136

Siddiqui, A.; Zia, M.Y.I.; Otero, P. A Novel Process to setup Electronic Products Test Sites based on Figure of Merit and Machine Learning. *IEEE Access* 2021,

https://doi.org/10.1109/ACCESS.2021.3084545

1.6. Dissertation organization

Chapter 1 provides an introduction, scope, and significance of this research and research objectives. The research is carried out in two parts which are defined in this chapter.

Chapter 2 presents the related work where details of the literature review are mentioned. As part of this research different electronic products, their test sites, and machine-learning techniques are reviewed. Data processing and collection techniques and review of ERP systems are also mentioned in this chapter.

Chapter 3 discusses the proposed process of designing test sites for new electronic products and optimization of test sites f existing electronic products. The proposed machine-learning-based algorithm for this process is also discussed in this chapter. The novelty of the process is also presented through a figure and finally, the implementation of the proposed process is discussed using experimental test sites. Details of research methodology is also mentioned here.

Chapter 4 presents the second part of the research where details of the proposed universal hardware and software module is provided. The proposed machine-learning algorithm is also discussed here. Test results and validation of the process through experimental test sites is also mentioned in this chapter. This chapter also includes the research methodology used for the proposed design implementation.

Chapter 5 provides the summary of the research, conclusions, and future research direction.

Chapter 2: Related Work

2.1. Scope of literature review

In this chapter, 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.

CEM companies require a system to support and control their processes. These companies deploy enterprise resource planning (ERP) systems to streamline their process and manage various aspects of manufacturing including data collection, storage, and analysis. These systems are essential to this industry. ERP systems, though, cover all aspects of the manufacturing industry, but they still do not provide a direct interface to test equipment and unit under test (UUT) sites. There is also no universal system, both software, and hardware, available for connecting to CEP test sites, so for every new product, a test site is required to be setup, which takes time and is also expensive.

In this research, a background study has been done within the categories mentioned in the following sections. The implementation of the proposed system is based on the outcome of this study.

2.1.1. 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 2.1. 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.

Table 2.1. 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.

2.1.2. Review of existing electronic product test sites

In this section different existing techniques and approaches are reviewed which are used for setting up electronic products test sites. In [7] 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 performed before the functional test and the unit under test is powered from the JTAG interface. The decision to use this test depends on the availability of integrated circuits with a JTAG port.

In [8] the authors highlighted the problems with the traditional test process for testing a satellite control system. To overcome this, they designed an automated test equipment (ATE) to improve efficiency and accuracy. The authors highlighted the problems with the traditional test process for a satellite control system in their manuscript. In [4] the author highlighted the importance of DFT techniques which can help in achieving an optimized test solution. Some of the points mentioned are to run boundary scan test, adding more test points on the PCB to increase test accessibility and help in improving test coverage. The author also discussed the use of ATE. In [9] the authors 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. They have used LabVIEW [10] for controlling the NI PXI system. The authors also provided details of the test jig, other cables and highlighted the importance of automated testing.

The 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 [11] 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 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. The hardware-software based testing automation of electronic components is also discussed by the authors. General purpose boards and adapters are designed for this purpose, which needs improvement for reliability in testing. A test site for an RF product is presented in [12] and [13]. They used a COTS vector network analyzer for taking measurements. A wireless system for temperature measurement is presented in [14]. The authors discussed how this setup can be deployed in different scenarios. This test site is setup for temperature measurements acquired through a wireless system and deployment scenarios are presented.

In [15] authors presented a framework for testing the internet of things based devices. 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 [16] for an aerospace product. The authors used simulation techniques for troubleshooting. This is a fully automated test site that includes fault-finding capability. In [17] 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 for image processing in [18] 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 [19]. Using this technique, a boundary scan can also be performed on the PCB assemblies. This product is a complex digital circuit where the JTAG port is considered the best option for downloading firmware at a high speed. In [20] 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 [21]. The unit under test is an optical device used for profiling depth. This application is used for acquiring data and instrument control. They used this software for controlling a LASER for imaging and depth profiling mass spectrometers and other instruments. An induction motor control test site is setup by authors in [22]. They used LabVIEW as a software platform to acquire data and hardware control. Finally, in [23] the authors used a general-purpose interface bus (GPIB) to control a bench power supply and a digital multimeter and acquired measurements. They used LabVIEW for instrument control. ATE performance, obsolescence, and compatibility issues are discussed in [24]. The authors discussed a systematic design approach that covers both software and hardware architecture.

In [25] 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 [26] using NI myRIO data acquisition system controlled using LabVIEW. A high-speed data acquisition system is developed by authors in [27]. They used the NI DAQ system controlled through LabVIEW. In [28] 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 [29] using LabVIEW and NI Elvis. The authors presented an automated system for electronic circuit testing in [30]. In [31] an RF circuit test method using a signal generator and PXI system is proposed by the authors. Low-frequency signal acquisition and analysis system is developed by the authors in [32] using an analog to digital, conversion. The authors used a LabVIEW toolkit for processing the acquired signal. In [33] the authors used LabVIEW to acquire signals from exiting interfaces used for spacecraft equipment. A data acquisition system is presented in [34] 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 [35] 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 [36]. In [37] 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 [38] where authors used the NI DAQ system for automated testing. In [39] authors presented an automated test system for an avionics system. Authors in [40] presented the architecture of GPIB and highlighted the pros and cons. A test site for remotely controlling and monitoring a motor is discussed in [41]. The setup presented in [42] is used for controlling a temperature chamber. This test site is very useful for doing environmental testing on different electronic products. In [43] 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 [44]. They also performed a comparison between manual and automated tests. The authors discussed PCB diagnostic and troubleshooting techniques in [45].

An automated test system for an RF device is presented by the author in [46] and carried out various RF tests including spurious test and automatic gain control. In [47] the authors presented a technique for automated testing for an electronic control unit using a CAN bus. The authors in [48] demonstrated the use of GPIB to automatically control and configure COTS test equipment.

A power supply output voltage calibration process is presented in [49] where the authors controlled a power supply using a GPIB interface and a digital multimeter to monitor power supply voltage. The authors in [50] 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 [51]. A summary of the above review is presented in Table 2.2. which includes both hardware and software information.

The important point is that for each of these test sites, the authors developed their test software or used a commercially available application. For taking measurements, the authors used different COTS test equipment.

Table 2.2. Summary of existing test sites reviewed

Product type	Software	Hardware
	Aerospace products	
Aerospace [16]	Visual basic	ATE, cables
Avionics system [39]	Details not provided	GPIB, PXI system
Satellite control system [8]	Java	ATE, CAN, and RS232 interfaces
Spacecraft interfaces [33]	LabVIEW	COTS hardware, MIL-1553, and SpaceWire
	Low frequency and biomedical electronics products	
Analog audio device [20]	Matlab	ADC, DAC
Wireless Audio product [30]	LabVIEW	NI PXI, bed of nails jig
ECG system [29]	LabVIEW	NI Elvis
EEG Headset [25]	LabVIEW	Transducer and Bluetooth
Low-frequency product [32]	LabVIEW	COTS ADC
Medical devices [44]	Python, LabVIEW	DAQ
	Digital electronic products	
Complex digital [7], [19]	COTS	JTAG, pods, cables
	Data acquisition products	
DAQ system [27], [34], [37]	LabVIEW	NI DAQ devices, GPIB interface, Oscilloscope, PIC microcontroller, transducer
	Motor control circuits	
DC motor driver [26]	LabVIEW	NI myRIO, DC motor driver
Induction motor [22]	LabVIEW	Data acquisition (DAQ) and control
Motor control [41]	LabVIEW	Camera, Arduino

Internet of things-based products		
Internet of things [15], [28]	LabVIEW / COTS	Network switch, Oscilloscope. waveform generator
Various circuits and products		
Printed circuit board (PCB) [9]	LabVIEW	PXI system, Bed of Nails fixture
Backplane [11]	COTS	COTS cable tester, connectors
Cable assembly [38]	LabVIEW	NI DAQ
The electronic control unit [47]	LabVIEW	CAN bus, Power supply
GPIB based system [40]	HP VEE Pro	GPIB interface
Microfluidic device [18]	LabVIEW	Camera and accessories
Optical device [21]	LabVIEW	DAQ
Power supply control [49]	LabVIEW	Power supply, digital multimeter, GPIB
Underwater modem [17]	LabVIEW	Sensors, cables
Thermal cycle for the unit under test [42]	LabVIEW	Environmental test chamber interface
Temperature probe [14]	COTS	Analyzer, antenna
Refrigerator [50]	LabVIEW	ATE, test jig, RS232, ADC, and sensors
RF circuits and products		
Antenna [35]	LabVIEW	Arduino, Stepper motors, and drivers
Antenna [12], [13]	COTS	Analyzer, cables
RF circuit [31]	LabVIEW	NI PXI, Signal generator,
RF current probe [43]	LabVIEW	Spectrum analyzer, Signal generator
RF device [46]	LabVIEW	SPI, I2C, HPIB
Software-defined radio [51]	LabVIEW	Signal generator, Spectrum analyzer, RS232, GPIB
Wireless sensor network [23]	LabVIEW	Digital multimeter, Power supply, and GPIB

2.1.3. Review of test sites data collection and analysis techniques

Data collection for any system is not an easy task. It is important to have a balance between what is important and useful. Collecting all data means there can be storage capacity issues. It is important to have a good understanding of what data are to be collected and useful for analysis at a later stage. In [52], the authors presented a process to measure the quality of manufacturing data. This approach helps to decide what data are to be collected and stored, resulting in efficient use of data storage space. Having an automated process also improves consistency. They have presented an automated process to analyze and improve data quality. Using the proposed approach, an information system's consistency can be evaluated, and the reliability of the results can be determined. This can help the management in taking appropriate decisions.

In [53], the authors presented a virtual factory concept to perform modeling and simulation. This approach clarifies the process before actual implementation and helps the companies to decide how and what data to collect. Modeling and simulation of vehicle manufacturing is considered as an example. The authors presented the concept of a virtual environment that can be used to perform analysis at various levels. The results are useful for the research community. The conclusion and recommendations from this paper can form the basis for further research. Authors in [54] discuss the defects in electronic products and how this approach can be used by companies to streamline their processes. The defects in electronic products are first considered based on the problems encountered during the design phase for new products. Once the first few batches of the products go through production then the process is updated, and actual faults or defects are considered. This is another approach that helps to determine what data are to be collected. The authors have presented two methods. To determine the defects in the products, two scenarios have been proposed in the research, (a) when the batch size is large, and (b) when the product is delivered for the first time.

The manufacturing data collection can be divided into two categories. First is the information related to performance, key indicators, etc., while the other one is specific to a product type. In [11], the authors presented an automated system to test backplanes. In this approach, the test data are collected automatically, which improves consistency, repeatability, and is time-saving. These data can also be used to efficiently design similar systems in the future without going through each and every step once again. Manufacturing companies at times focus on collecting data related to the product under test. This approach can help the companies in streamlining specific issues with testing software and hardware, only for the product that they are testing. Since limited data is collected, hence important issues like operator skill level, test times in comparison to similar products tested, training needs and other manufacturing problems, etc., will be missed.

In [55] the authors raised the issue of data storage capacity which can limit the manufacturing companies to collect selected data. Due to this, they will not be able to perform a complete analysis and only resolve limited manufacturing issues. Although this paper is focused on cloud data storage, the manufacturing companies with on-site data storage, face the same issue. The authors also discussed data management i.e., generating reports having different styles and content, which is difficult to have a consolidated approach, and staff in different departments require more effort to understand the reports. This is more relevant to large-scale manufacturing companies where data storage is an issue. However, small-scale manufacturing companies can also benefit from this approach. Cloud computing has gained popularity as more companies are looking at moving towards a cloud-based solution.

In [56], the authors discussed sensor data management. A data processing framework for data sourcing, analysis, and visualization is presented by the authors in [57].

An important aspect of this research is to make sure all the useful information related to the manufacturing test is collected which will then be used for continuous improvement in the process. It is also important to identify useful information from all data so that only the relevant information is stored. The approach also helps in reducing waste and cost reduction

In this research, an automated approach is presented which will replace the existing manual or semi-automatic process helping the manufacturing companies to quickly find the root cause of the problems and implement them before testing the next batch. This will have a direct impact on the consumer as they will get the product quality will improve next time.

2.1.4. Review of ERP systems used in the electronic manufacturing industry

In this research, the implementation and use of ERP systems within the test department of the CEM industry is considered. Various aspects of existing ERP systems including advantages, disadvantages, and limitations are reviewed within the scope of activities carried out during testing of electronic products. The proposed system is designed considering certain important parameters of existing ERP systems, which include cost, complexity, and limitation.

Manufacturing companies mostly use ERP systems in their factories. Some commonly used ERP systems used in the CEM industry are EPICOR [58], Syspro [59], Microsoft Dynamics [60], Sage Business Cloud X3 [61], SAP Business ByDesign [62], and Oracle ERP [63]. Details of these ERP systems are presented in Table 2.3. in alphabetical order.

Table 2.3. Some ERP systems in use in the consumer electronic manufacturing industry.

ERP Systems	**Deployment in the CEM Industry**			**Features**	**Limitations**	**Hardware Interface**
	Small	**Medium**	**Large**			
EPICOR [58]	✓	✓	✓	Production and material management, report generation	Limited financial analysis, user complexity	N/A
Microsoft Dynamics [60]	✓	✓	✓	Product visualization, financial forecasting	Complex front end, difficult to interface with 3rd party tools	N/A
Oracle ERP [63]	✓	✓	✓	Flexibility, easy integration of modules	Difficult training, low system performance	N/A
Sage Business Cloud X3 [61]	✓	✓	✓	Inventory management, production interface, shop floor, and quality control features	Difficulty in accessing interfaces quickly	N/A
SAP Business ByDesign [62]	✓	✓	×	Improved data analysis, data visualization, application grow with the business	Difficult customization, not user friendly	N/A
Syspro [59]	✓	✓	✓	Flexibility, cost tracking	Complex interface, difficult to integrate with 3rd party tools	N/A

The names of the ERP systems are presented in column 1, and the deployment in the CEM industry (small, medium, and large) scale is shown in column 2. The features are provided in column 3 followed by the limitations in column 4. Finally, the unavailability of the hardware interface is explicitly mentioned in column 5. It can be seen from the table that none of the ERP systems provide a direct interface to hardware or test equipment.

Further comparison of ERP systems is provided in [64]. The authors conducted a survey and studied various benefits provided by ERP systems and their impact on companies. In [65], the authors interfaced their system with ERP and extracted relevant data. The paper in [66] discusses factors affecting manufacturing cost and have used analytic resources to achieve manufacturing test cost reduction.

2.1.5. Review of 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 [67] 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 [68]. The use of historical data for detecting deviation from normal performance is mentioned in this paper which highlights limitations of existing machine-learning algorithms and tools. The authors used historical data to estimate the deviation from the required performance. Scikit Learn, a Python [69] module is used by authors in [70] for implementing a machine-learning algorithm. In [71] the authors reviewed some machine-learning algorithms and presented their findings which include some performance limitations. The authors reviewed machine-learning algorithms are reviewed in [72] with the focus on quality control and how production lines can be analyzed and benefited from machine-learning techniques.

The authors reviewed supervised and unsupervised machine-learning algorithms in [73]. They further explored the use of internet of things related applications. A review of some standard supervised machine-learning algorithms is presented in [74]. The authors also highlighted the main features of each algorithm reviewed. In [75] the author surveyed supervised machine-learning algorithms which included text classification. The authors reviewed security issues and limitations for machine-learning-based implementations in [76]. They also presented various trends where further research can be carried out. Finally, text data extraction and analysis are discussed by the authors in [77]. The focus of their research is data analysis and mining. They presented their work through three stages.

The use of machine-learning is increasing in various industries. In this section, different approaches and applications of machine-learning are reviewed.

2.2. 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.

When a new CEP is launched, the test development team has to go through all the steps and design a standalone test site, which can only be used for testing that specific CEP. A typical test site includes test equipment, interfaces, test jigs, test software, etc. In the absence of a universal test site framework, there is very limited reuse of available test sites.

For automated testing, a software application is developed for each CEP, which also requires validation. Time to market CEPs is important so any delay added to an already tight schedule means revenue lost and chances of faulty products being shipped.

In a typical CEM company, thousands of UUTs are tested monthly, and there is no central system that collates data, reviews faults, recommends repair or rectification of fault, and presents these in different categories. As an example, a UUT can fail due to more solder on a component pin, and the solution is to reduce the solder paste. This is an issue for the conventional soldering department, so unless this department is informed, the fault may not be rectified. Manual fault finding and putting them in categories is a tedious task and can take several hours.

Designing any universal system requires a knowledge base and historical data, which is a difficult task. To collect this data, a process is required, which can focus on what information is available, and how this information can be collected and categorized.

Chapter 3: Electronic Products Test Sites Design based on Figure of Merit and Machine-Learning

3.1. The novelty of the proposed test site design research

In this research, 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 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 3.3.3.

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 3.1. 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.

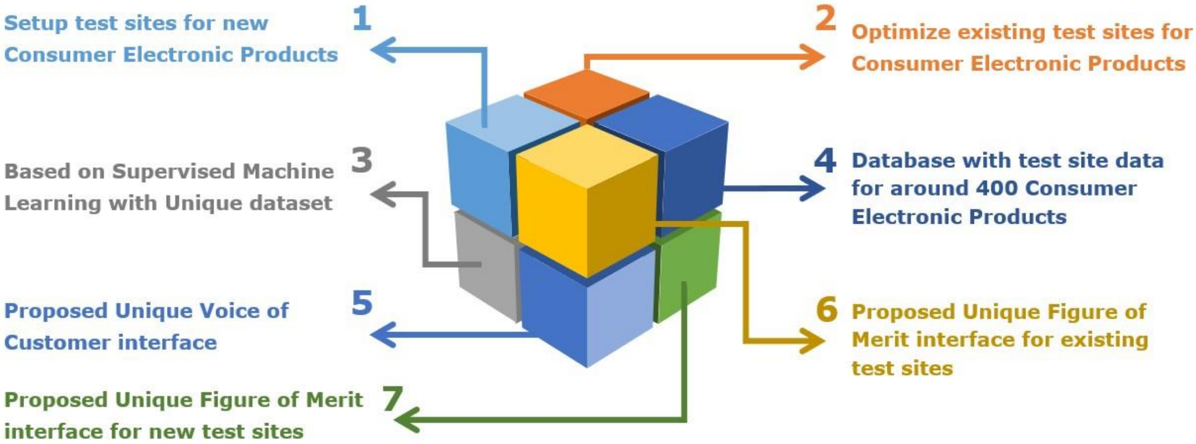

Figure 3.1. Novel features of the proposed test site design process.

3.2. 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 3.2. presents the research methodology through four steps.

3.2.1. 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.

3.2.2. 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 2.2.1.

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 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 2.1.2.

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 2.1.5.

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.

3.2.3. 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.

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 3.3. 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.

3.2.4. 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 sections 3.5.1 and 3.5.2. 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 3.5.3.

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.

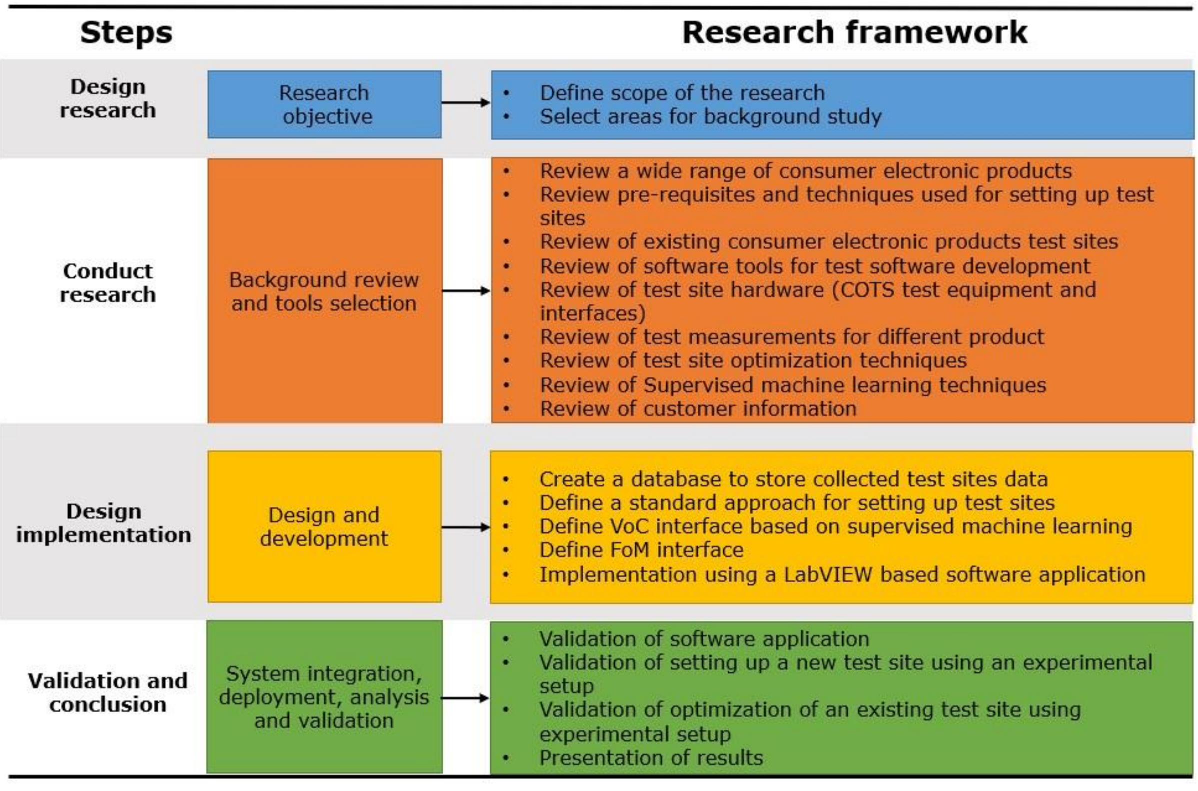

Figure 3.2. Research methodology for test site design process.

3.3. Proposed machine-learning-based automated process

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

3.3.1. Process block diagram

The proposed process to setup a test site for a new product is presented in figure 3.3. The block diagram shows the four inputs to the system which are 1) Database input interface, 2) VoC [78] [79] input interface, 3) FoM [80] [81] 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 [82]. 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 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.

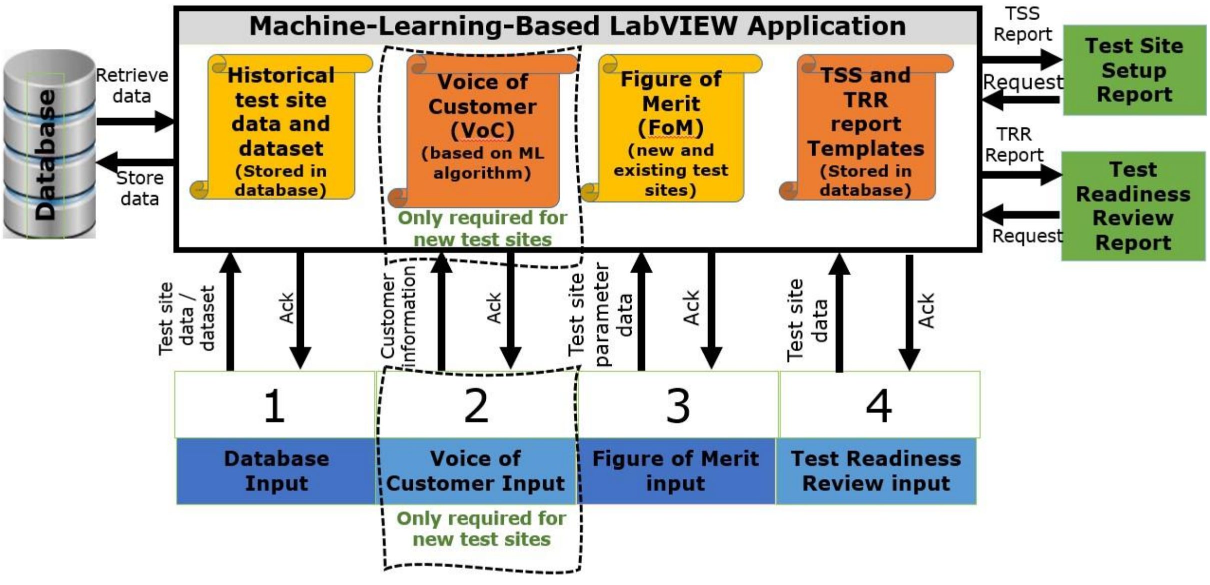

Figure 3.3. Block diagram of the proposed processes.

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.

3.3.2. Process flowchart

Figure 3.4. 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.

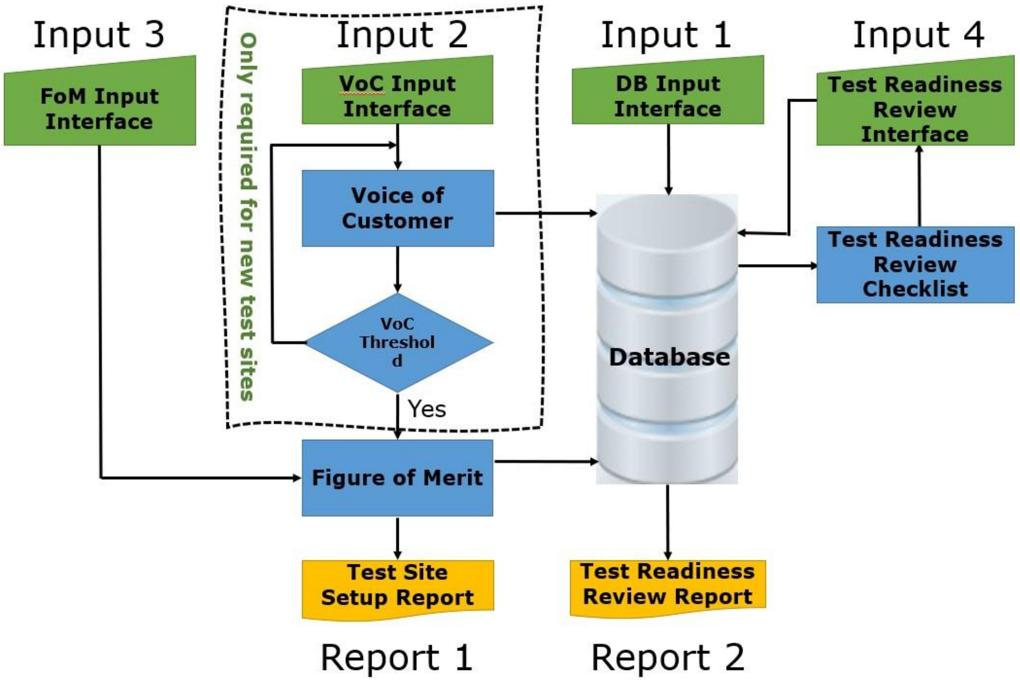

Figure 3.4. The flowchart of the proposed processes

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.

3.3.3. Database

Tables 3.1 (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 an interface for updating the database where details of new COTS test equipment and new test site data are added as shown in table 3.1. (A). Other data such as fault and repair information, VoC information and requirements, FoM data are added automatically as discussed in section 3.4.

Table 3.1. (A) A snapshot of COTS test equipment data stored in the database.

ID	COTS Test Equipment	Make	Model	Specification
EQ-1	DMM	Company 1	Model 1	Hand 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

Table 3.1. (B) A snapshot of test site data stored in the database.

Test Site ID	Test Equipment	Test Software	Test hardware	Test Stages	Other
TST00015	Signal generator, DMM, PSU	Visual Basic	Cables, Test jig	3 (Flying probe, program, function)	OS Win7

3.3.4. Machine-learning algorithm

The structure of the machine-learning algorithm is presented in figure 3.5. 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 3.5., 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'.

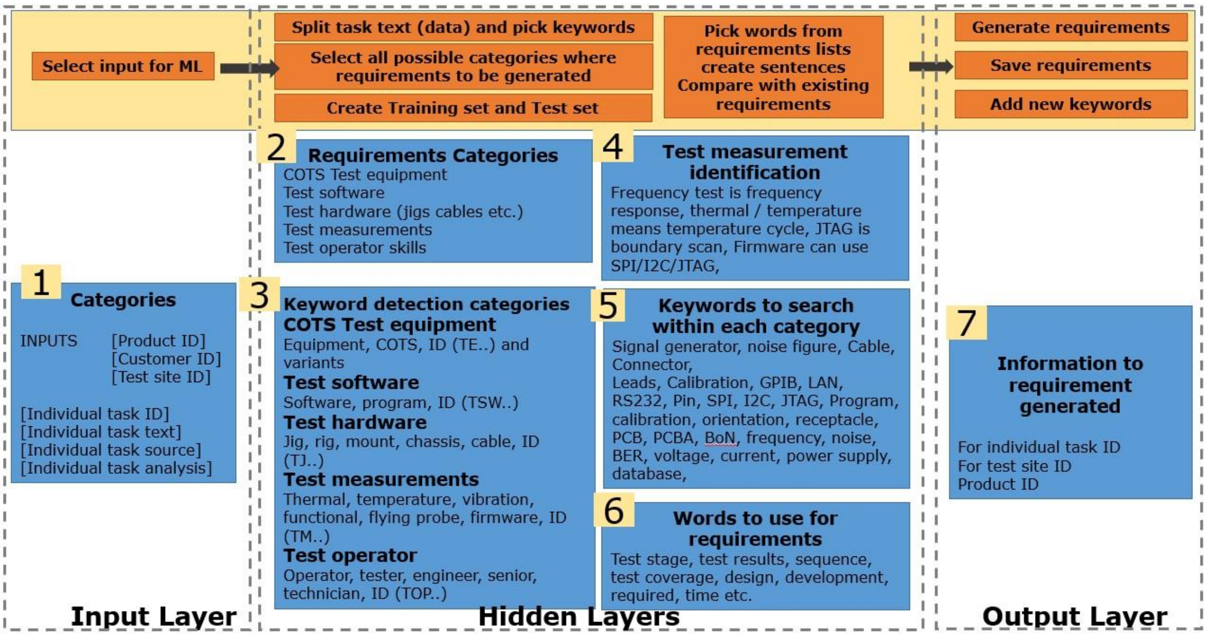

Figure 3.5. Machine-Learning algorithm for test site design process.

3.4. Implementation of the proposed process

3.4.1. Setting up a 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.

3.4.1.1. Proposed process

Figure 3.6. shows the block diagram of the proposed method. The required inputs to setup a site for testing a new electronic 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.

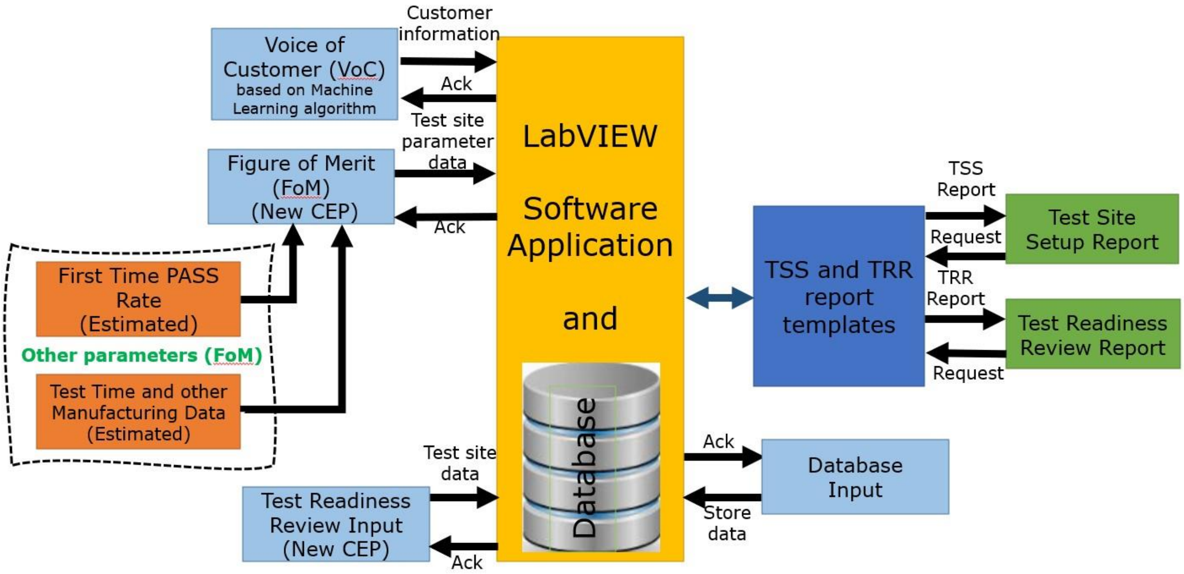

Figure 3.6. Block diagram of proposed test site setup for new CEPs.

3.4.1.2. The VoC interface

Table 3.2. 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 decisions 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 3.2. 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.

3.4.1.3. The FoM interface

Table 3.3. 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”.

Table 3.3. 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?

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 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, 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.

3.4.1.4. 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.

3.4.1.5. TRR interface

Table 3.4. 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.

Table 3.4. The TRR parameters for electronic product 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	

3.4.2. Optimization of an existing test site for an electronic product

3.4.2.1. Proposed method

Figure 3.7. 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.

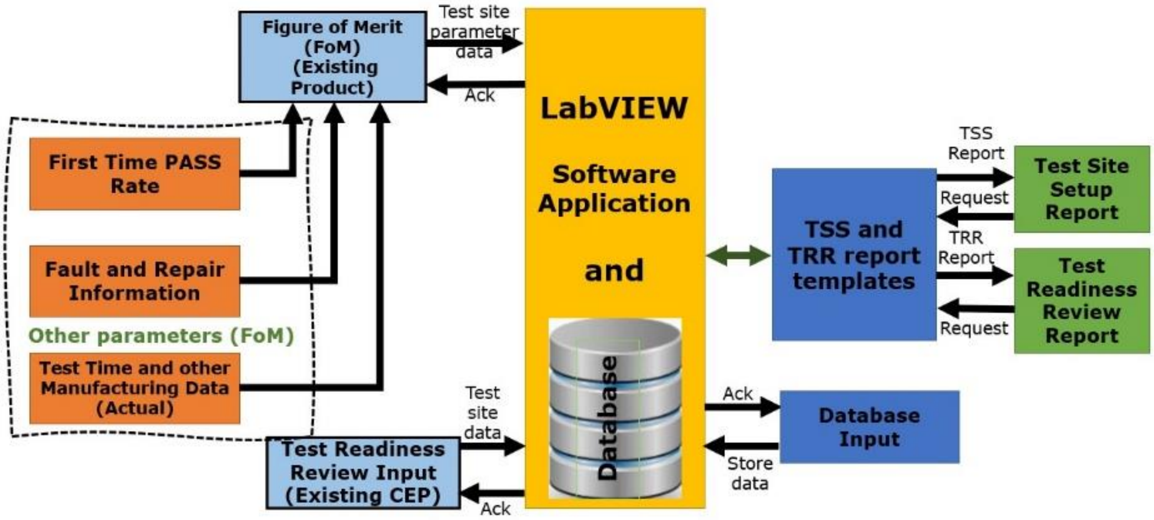

Figure 3.7. Block diagram of proposed optimization of existing test site of CEPs.

3.4.2.2. FoM interface (Optimization of existing test sites)

Table 3.5. 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.

Table 3.5. The FoM 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

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 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 3.6. 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 3.6. 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
PO0045	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.

3.4.2.3. 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 Test 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.

3.4.2.4. TRR interface

This template is identical to the one used for new test sites and details are provided in table 3.4. in section 3.4.1.5. 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.

3.5. Validation of the proposed process through experimental setups

3.5.1. Experimental setup of an RF receiver - New test site setup process validation

Table 3.7. shows the list of customer requirements captured for setting up a test site for a new electronic product.

Table 3.7. 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

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, power supply requirements, and 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 3.8. shows how customer information is translated into requirements.

Table 3.8. 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 and Noise figure tests	Spectrum Analyzer and Signal Generator required
S015	RF cable testing	Network Analyzer required

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 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 3.8. 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.

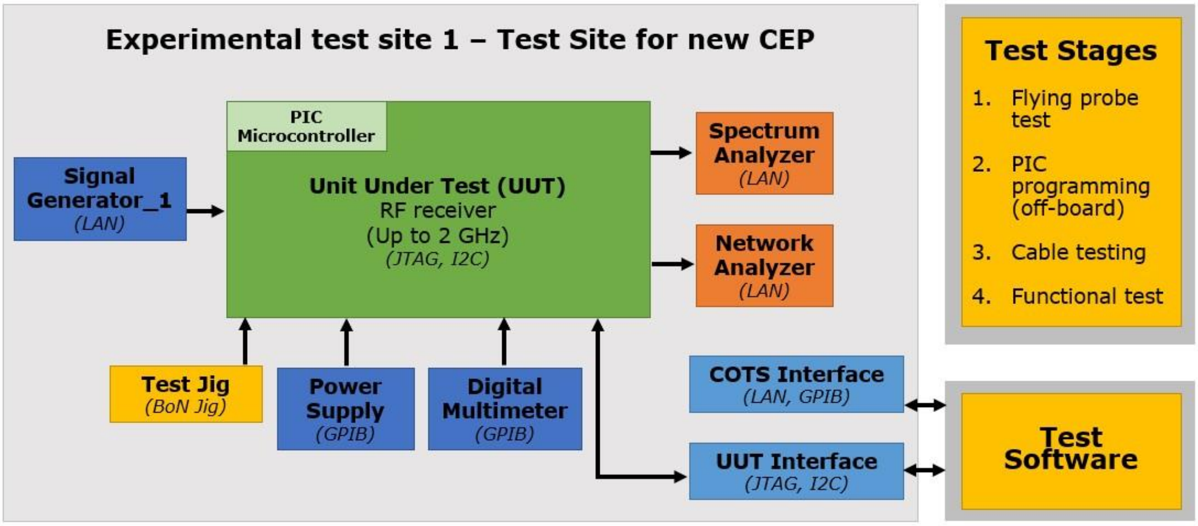

Figure 3.8. Experimental new test site setup for an RF receiver

3.5.2. Experimental setup of an audio product – New test site setup process validation

In this experimental setup, a test site is setup for audio electronic equipment. Based on the voice of customer, the frequency range is 20 Hz to 20 kHz. The customer allocated a limited budget for the development of test jig etc. The customer also allocated a budget for hiring any test equipment which is not available in-house. The manufacturing volume is low, so resource allocation is low risk. Due to on board JTAG port, it is agreed to use boundary scan to program firmware as well as initial continuity testing.

Test equipment is picked up from the database, based on the review of customer requirements. The total test time is low due to few test points and tests to be performed. Test equipment was available, so the test equipment was not hired. The test is divided into three stages: (a) Flying probe test, (b) Programming and continuity test using boundary scan, and (c) Functional test. Resources are also allocated for test software development. The estimated test times are 5 min/UUT for the flying probe test, 5 min/UUT for the boundary-scan test, and 7 min/UUT for the functional test. The results are presented in four tables 3.9. – 3.12.

Table 3.9 presents the data collected from the customer. Note that the information was collected at different stages and sources. The focus is to get the information from customers as early in the process as possible.

Table 3.9. VoC data for an audio electronic product

Task ID	Task Details	Source	Analysis category
A00001	Batch size is 100 for 6 months	Meeting	Possible
A00002	Budget include £500 plus equipment hire / purchase	Meeting	Possible
A00003	Power supply voltages for the UUT is +5V and +3.3V	Document	Possible
A00004	UUT will take 300mA	Email	Possible
A00005	JTAG port is required for programming	Telephone	Possible
A00006	Take measurements from around 10 test point on the UUT	Email	Possible
A00007	UUT requires an input signal of 20Hz to 20KHz	Document	Possible
A00008	Measure and plot frequency response from 300Hz to 20KHz	Document	Possible
A00009	Measure resistance of few resistors on the UUT	Document	Possible
A00010	Measure second and third harmonics frequency & amplitude	Document	Possible

Table 3.10. presents the test equipment details stored in the database used to select test equipment for the test site.

Table 3.10. Database – test equipment details

ID	COTS Test Equipment	Make	Model	Specifications
EQ-11	DMM	Comp 1	Model 1	General purpose DMM
EQ-12	Oscilloscope	Comp 2	Model 2	Max. 1 GHz
EQ-13	Oscilloscope	Comp 4	Model 4	Max. 300 MHz
EQ-14	Power supply	Comp 1	Model 3	Triple output up to 25 V, 5 A
EQ-15	Power supply	Comp 1	Model 3	Triple output up to 25 V, 5 A
EQ-16	Power supply	Comp 3	Model 5	Dual output up to 12 V, 5A
EQ-17	Spectrum analyzer	Comp 5	Model 6	Up to 3 GHz
EQ-18	Signal generator	Comp 3	Model 7	Up to 100 kHz
EQ-19	Signal generator	Comp 6	Model 8	Up to 1 MHz

Table 3.11. shows the FoM information for an audio product. The sources of this information are VoC, FoM, and DB input interfaces.

Table 3.11. FoM for an audio electronic product

Main category	Subcategory	User data
Product information	Type	Audio
	Batch size	100 per month
	Where used	Land
Budget	Test development	£500
Type of test required	PCB level (UUT is OFF)	Flying probe test
	PCB level (UUT is ON)	Programming and functional
	Cable testing	No information provided
	Complete unite test	Yes
Operator	Skill level	No information provided
	User interface	GUI required

Documentation	Training	No information provided
	Test procedures	No information provided
	Test results	No information provided
Estimated fault data	Analyzed collected data	No information provided
First-time pass rate	Test yield	No information provided
Other manufacturing data	Test equipment, estimated failure rate, etc.	No information provided

Table 3.12. is the TRRR generated by the systems based on operator inputs. All TRR entries not applicable to this product are deleted from the template. The test site is ready to be setup when there are ‘Yes’ entries in the last column. The operator can ignore some ‘No’ entries if these are not critical.

Table 3.12. TRR report

Customer: ABC Completed by: AS		Product: Audio
Main category	Sub category	Selection
Capture test development cost		Yes
Schematics		No
PCB layouts		No
Bill of material		No
Datasheets		No
Cable/wiring diagram		No
Firmware programming	Pre-programmed (External)	Yes
	Pre-programmed (Internal)	No
	Device programmer available	Yes
	Firmware file available	Yes
	Programming cable available	Yes
	Programmed part of functional test	Yes
	Firmware file available	No
	In-circuit programmer available	No
	Programming cable available	Yes

Flying probe test	CAD file available	Yes
	GERBER files available	Yes
	Panel size information	No
	PCBA mount available if required	Yes
Cable test	Netlist	Yes
	Any Customer cable required	No
	Make cables	No
Boundary-scan	JTAG files available	Yes
	JTAG cables available	Yes
	JTAG Jig Required	Yes
Functional test	Customer test procedure available	Yes
	Other customer document referenced in main test procedure	Yes
	Internal test procedure required	Yes
Functional test software	Customer Test software available	Yes
	Test Software required	Yes
	Cables etc. required	Yes
Equipment	Customer provided	Yes
	Available	Yes
	Hire Equipment	Yes
Test jig	Customer provided	No
	Available (Check if working)	Yes
	Make a new Jig	No
Test results	Test results template provided by the customer	Yes
	Test Results submission (Digital)	Yes
	Customer email address	No
	Test Results submission (Paper)	Yes

3.5.3. Experimental setup of an RF antenna – Existing test site optimization process validation

Table 3.13. 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 3.13. 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 3.14. is the outcome of what needs to be done based on the reasons mentioned in table 3.13. 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.

Table 3.14. 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			

Figure 3.9. shows the block diagram of an RF antenna that is optimized using the proposed process. The reasons for optimizations are listed in table 3.13. 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 test batch.

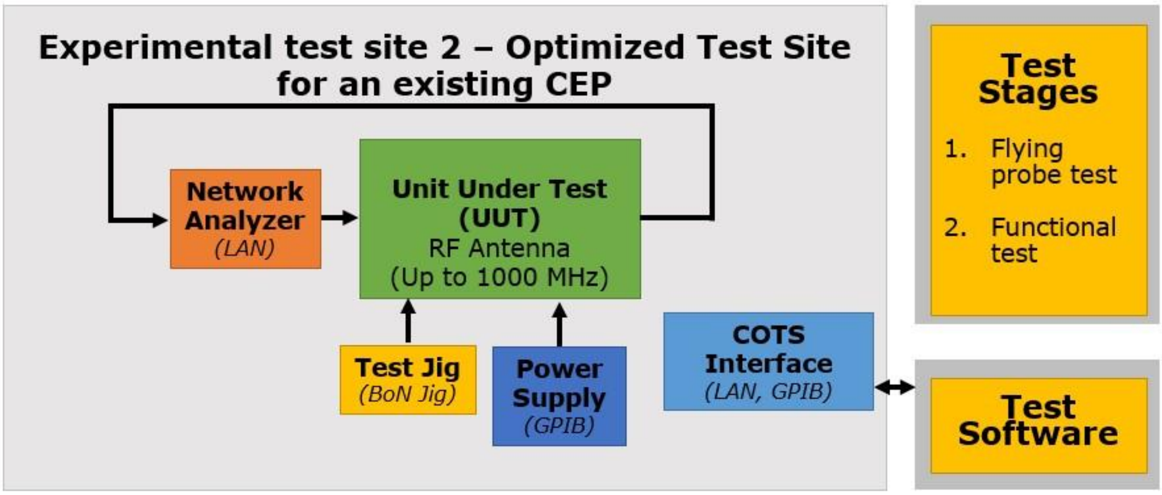

Figure 3.9. Experimental test site optimized for an RF antenna.

Chapter 4: Machine-Learning based Automated Testing System for Electronic Products

4.1. The novelty of the proposed automated test system

The proposed system is low-cost, efficient, and user-friendly and provides a solution to all tasks performed in a typical test department of a CEM company. Figure 4.1. presents six novel features of the proposed system.

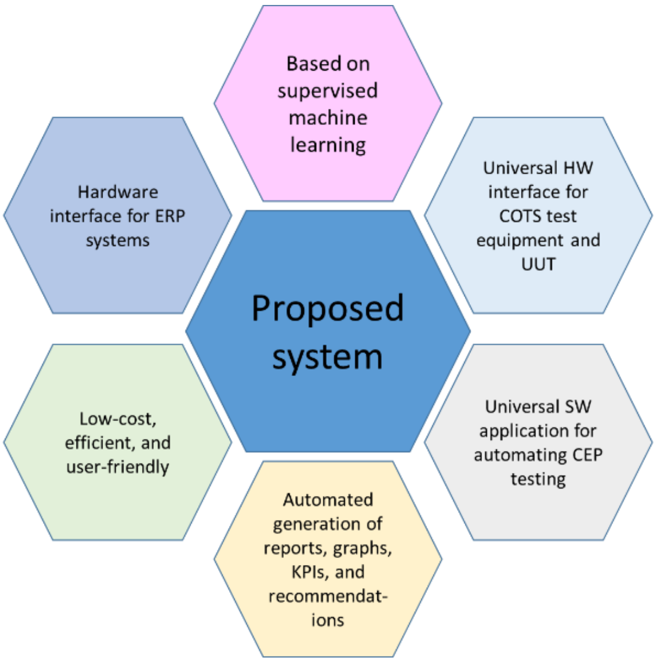

Figure 4.1. Novel features of the proposed automated test system.

These features include a universal hardware interface for COTS test equipment and UUT interfaces, a universal software application for automating CEP testing, test data collection and instrument control, automated reports, graphs, KPIs, and recommendation generation for continuous improvement based on supervised machine-learning. Unlike the existing modules used in test departments of CEM companies, the proposed system can be connected to ERP systems to provide direct access to test hardware, including test equipment and the electronic products being tested. Alternatively, it can also be deployed standalone system as a replacement for the ERP system specifically in the test department of a CEM company.

In addition to the proposed system, this research provides a detailed insight into all activities related to CEP testing within the CEM industry. This opens venues for researchers to explore this under-researched area. Some problems are highlighted, and their solutions are provided. A machine-learning algorithm is applied to CEP testing for the first time at this scale. The fault detection and categorization process, and a learning dataset is created and presented here.

4.2. Research methodology

The proposed system provides a universal and one-window solution for testing products within the CEM industry. This manuscript focuses on a universal system to control existing test sites, test data collection and analysis, and recommendations; however, designing test sites is outside the scope of this research. Figure 4.2. shows the various processes carried out within the research methodology. These processes are listed within design research, conduct research, design implementation, and validation and conclusion.

4.2.1. Design research

In this section, various techniques, applications, and processes used by CEM companies are studied. For this purpose, a review is carried out within the categories mentioned in Section 2.1. A thorough review is carried out before designing the proposed universal testing system.

4.2.2. Conduct research

The first step is to review the effectiveness of the proposed system. For the proposed system to be effective, lots of historical data are required. Therefore, manufacturing test data for around 100 test sites and 125 CEPs is collected for months where the products, i.e., UUTs range from simple digital, complex digital, camera, analog, high precision, RF, communication, and low-frequency products, etc. The review includes studying various aspects of these test sites, identification and collection of useful data, and trends analysis. The main categories of this review include test software, test equipment, and test measurements. This wide range of test data has helped in building a knowledge base related to these product types, which includes the test times, faults and repair, test operator (TO) skills needed, and other parameters. This information is also used in defining performance-related thresholds that are published using key performance indicators (KPIs). Some existing test sites are also reviewed, and details are presented in Section 2.1.2. Secondly, various data collection, analysis, and visualization techniques are reviewed in this research. The specific details of different techniques are discussed in Section 2.1.3.

The third step is to review test software for the test sites being evaluated so that a universal test application can be developed that takes into account the features reviewed in existing test sites software. To develop an application as an alternate for ERP systems and universal test site software, different available packages, or software platforms have been evaluated, two of which (LabVIEW and Python) are discussed here. LabVIEW is selected as the software application to implement the whole process primarily due to several useful built-in features. LabVIEW is fast becoming popular software used for developing test software. There are several reasons for selecting LabVIEW e.g., low deployment cost, availability of test equipment drivers, easy to create effective and user-friendly GUI, and quick test results analysis.

One of the features is a web-based control of the application, which is presented in [17]. In [83], the authors interfaced LabVIEW with Arduino, which is another important feature where LabVIEW can be used to control hardware. The image processing functions are used in [18] in LabVIEW. There are test sites for camera-related products and having these built-in functions helps in integrating with the proposed system. In [84], the GUI and data acquisition (DAQ) features of LabVIEW are used. The authors in [85] have used TCP/IP built-in functions of LabVIEW. In [86], authors used LabVIEW for interfacing with FPGA. In both the previous references, the authors used LabVIEW for hardware interfacing. The advantage of using LabVIEW is that this application can be used to implement every stage in the process including setting up test sites. If an existing test site software is already available in other applications, then LabVIEW also provides an interface to those applications. An advantage of using LabVIEW is that the existing test software or algorithms created in other applications can be easily and quickly integrated within LabVIEW. A closed-loop controller application is implemented in LabVIEW in [87]. The quality of LabVIEW GUI is far better than some other software applications with the added advantage of quick development. In [88], authors used LabVIEW's vision control module for image acquisition and interfaced their application with Lego Mindstorms EV3 controller. They have also highlighted the quick development feature of LabVIEW. There are other applications available such as Python. The authors in [89] used Python to create a suite to control laboratory experiments, which include hardware interface and GUI. Data visualization is also an important aspect of the research, and authors in [90] presented an interactive visualization system developed in Python.

The fourth step is the review of machine-learning techniques, which is already discussed in Section 2.1.5. and includes the areas where these techniques are applied.

The fifth step is to review a hardware interface required to connect the proposed system to the test site under consideration. Here, the details of the CEP test sites are reviewed, which include COTS test equipment, their interfaces, test measurements, and UUT hardware interfaces. The test sites' data show the complexity and variety of COTS test equipment, their interfaces, and test measurements, which the proposed system can handle. Some COTS test equipment is identified that include signal generators, arbitrary waveform generators, spectrum analyzers, power meters, network analyzers, digital multimeters, power supplies, etc. This COTS test equipment is controlled using different interfaces, which include GPIB, LAN, USB, RS232, etc., which are added to the proposed universal hardware sub-system. Details of test measurements are also collected. Some of these are audio, RF, amplitude modulation and phase shift keying signal generation using signal generators, frequency and spurious and adjacent channel power measurements using spectrum analyzers, cable impedance and S-parameter measurements using network analyzers, amplitude and frequency measurements using oscilloscopes, basic measurements using digital multimeters, etc. Many test sites reviewed also require connecting to the UUT directly without going through COTS test equipment. Some of the UUT interfaces reviewed include a serial peripheral interface (SPI), inter-integrated circuit (I2C), RS422, RS485, JTAG, etc. These interfaces are used for various test activities including firmware programming, UUT configuration, boundary scan, enabling/disabling of parts of the circuit, etc.

Finally, the last step is the review of the ERP systems. The ERP systems deployed by CEM companies are reviewed in Section 2.1.4.

4.2.3. Design implementation

Based on the findings, a universal hardware interface and software application is proposed, which stores the most common COTS test equipment drivers and several software subroutines for test measurements. Apart from that, device drivers and software subroutines for taking measurements from some common interfaces available on UUTs are also stored in the database. During the review several manufacturing test parameters are also identified and collected and based on the research findings, it is demonstrated that successful data analysis can be achieved by using the parameters identified after thorough research and presented in this manuscript.

LabVIEW is selected as the software application based on the review. LabVIEW files are called virtual instruments (VIs) and are saved with the ".vi" extension. LabVIEW provides a modular approach where sub-routines can be created and stored as subVIs. The outcome of this review is a top-level GUI application through which subVIs for test measurements and COTS test equipment drivers are selected from the database. The selected test measurement subVIs can be executed in a defined sequence.

The process mentioned above requires decision-making without human interaction. To cater to this problem, a supervised machine-learning technique is applied, so that the top-level VI can automatically select the required COTS test equipment drivers and test measurements subVIs. The details of COTS test equipment, UUT interfaces, and test measurements are entered by the TO for the test site under consideration and the test software automatically selects the subVIs from the database. The proposed machine-learning-based algorithm uses the COTS test equipment name, model number, interface type, measurement type, etc., to select the required subVI from the database.

The hardware interfaces discussed and reviewed in this section are selected, and a universal hardware interface is proposed, which includes two sub-systems for COTS test equipment and UUT interface, respectively. Details of these interfaces are discussed in Section 4.3.1. The proposed system also provides an interface for connecting to manual legacy test sites that do not have any integration capability. Through this interface, TO can manually enter test results, which are then stored in the database. The next step is to review information related to COTS test equipment. A list of COTS test equipment is created, and device drivers, written in LabVIEW, are stored in the database as subVIs. The system is developed and integrated in a way that it is easily expandable, i.e., more COTS test equipment drivers, test measurements, etc., can be added to improve coverage. The universal hardware interface is designed considering both the data rate and the number of devices on the UUT that can be connected.

At this stage, the proposed universal software and hardware sub-systems are integrated. The proposed system is connected to the test site through a universal hardware interface, and test data are acquired. The test data are then processed, and outputs are generated as customizable reports, graphs, and KPIs. Common customer requirements like logging of test times, staff performance analysis, logging of customer order details, test results, work in progress quantity, etc., are also considered. The software uses machine-learning to generate recommendations from the outputs. This is a unique feature of the proposed system, which can support CEM companies to implement continuous improvement.

The study of existing ERP systems deployed by companies in the CEM industry is carried out to understand various interfaces used, and based on the study, an interface is proposed for connecting to the ERP systems. Through the proposed ERP interface, all raw and analyzed data collected by the proposed system can be forwarded to the ERP system. This interface effectively provides ERP systems with direct access to the test site hardware. The proposed system can also be used as a standalone system in the test department.

4.2.4. Validation and conclusion

The final step is the validation stage. To validate the proposed data collection sub-system, experimental test site setups are connected to the universal hardware and software interface, which are discussed in detail in the next section. The data analysis, report generation, and recommendation sub-system are validated by deploying the proposed system in the test department of a CEM company. The proposed system has been successfully deployed in a mid-volume CEM company in their test department, and results are presented.

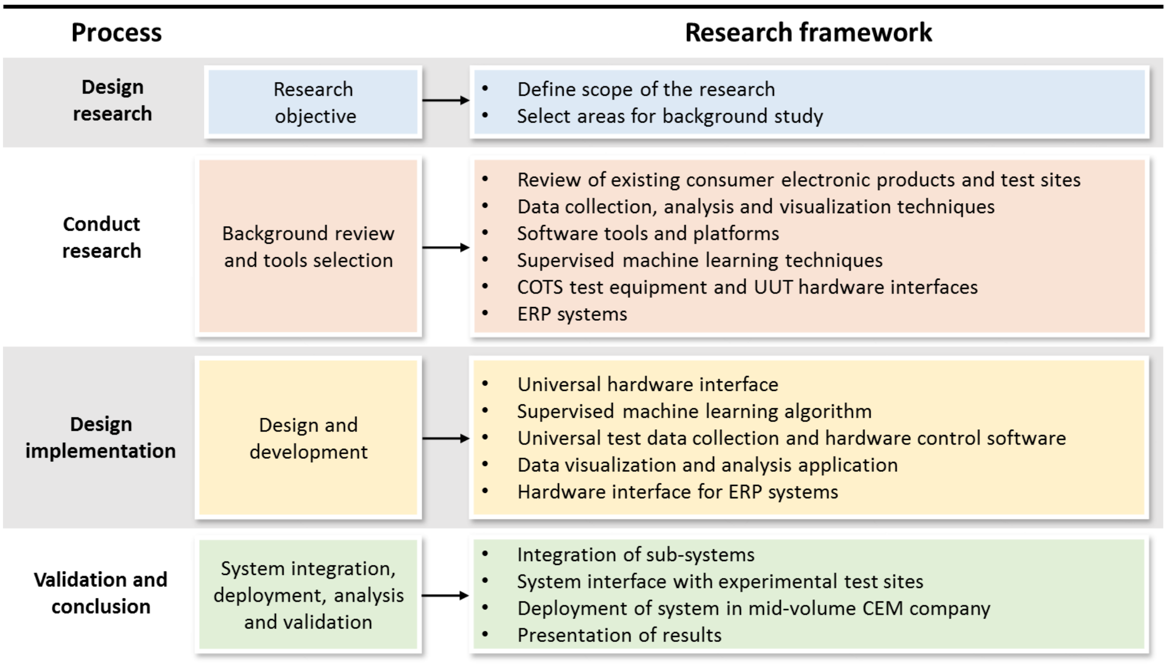

Figure 4.2. Research methodology for the automated test system.

4.3. The proposed automated testing system

The proposed system is divided into three subsystems namely (1) hardware interface, (2) software application, and (3) ERP interface are discussed here. Figure 4.2. shows the top-level block diagram of the proposed system. The figure illustrates the flow of data through a universal hardware interface and machine-learning-based software application.

4.3.1. Hardware interface

The first sub-system is a universal hardware interface for connecting to any CEP test site to control COTS test equipment and direct control of UUT as shown in figure 4.3. Due to the absence of any universal hardware interface currently in the industry, this proposed system can save development time, cost, and effort.

The hardware interface is further divided into two subsystems, the first is hardware interface 1 (HW_INT_1) for connecting the proposed system to COTS test equipment using GPIB, LAN, RS232, and USB interfaces. The second is hardware interface 2 (HW_INT_2), which connects to the UUT through I2C, SPI, JTAG, RS422, and RS485 interfaces. Almost all the new COTS test equipment can be connected via one of the interfaces proposed here.

4.3.2. Software application

The second sub-system is a supervised machine-learning-based software application developed in LabVIEW as shown in figure 4.3. This application uses supervised machine-learning to automatically select drivers for COTS and UUT and select the required measurement test code for any test site through a universal hardware interface. Further, this application collects real-time measurements and other test data, performs data analysis, generates reports, and KPIs. CEM companies and their clients spend months developing software for automated testing of almost every new product; using this universal software application, they can save development and validation time, which leads to a quicker product launch. Finally, it provides recommendations automatically using machine-learning techniques. This sub-system also includes a database that stores test sites' data, other raw manufacturing test data, analyzed data, COTS, and UUT interface drivers and test code for taking measurements.

This sub-system is further divided into three sub-systems: test data collection interface, database, and test data analysis interface. The test data collection interface connects, controls, and takes measurements from COTS test equipment and UUT. Test measurements code and device drivers are stored in the database. Device drivers and test measurements code are selected from the database automatically using machine-learning. The test data collection sub-system provides an interface for entering test data manually for manual legacy test sites. This is an important feature as well, which provides compatibility with the legacy sites, which cannot be automated. Further, a third interface is provided to enter other manufacturing data, which include purchase order, product, customer, and TO details.

Using the proposed system, the UUT test start time is logged automatically when the TO starts testing, and the test end time is logged when the testing is completed. This feature increases accuracy, and the TO is not required to use another system for time logging. Another advantage is that real-time analysis can be carried out while UUTs are tested. CEM companies can record details of each UUT including test time, faults if any, etc., automatically.

The test data analysis interface retrieves test data from the database, performs analysis, and generates output in the form of customizable reports, graphs, and KPIs. The management team can review the performance using these graphs and KPIs. Another unique feature is that this system provides recommendations automatically using machine-learning, based on the results generated. For machine-learning to be effective, a lot of data are collected and analyzed, and the management team is interviewed to understand how they make decisions.

The database stores all the test data, device drivers, and test measurement code. A continuous improvement interface is provided so that more data can be added to improve the overall performance of the system, increase coverage, and improve machine-learning-based decision-making. The database stores the data of around 100 test sites reviewed as part of this research. These data are the key to making machine-learning-based decision-making efficient and accurate.

4.3.3. ERP interface

The third sub-system is an interface for ERP systems to connect to COTS and UUT hardware interface and acquire all CEM test department related data directly as shown in figure 4.3. This is a unique feature that supports cost and time savings for CEM companies. The proposed interface for ERP systems is established using structured query language (SQL) commands to share both raw test data and analyzed test data. This proposed system is a replacement for the test department module of ERP systems in the CEM industry.

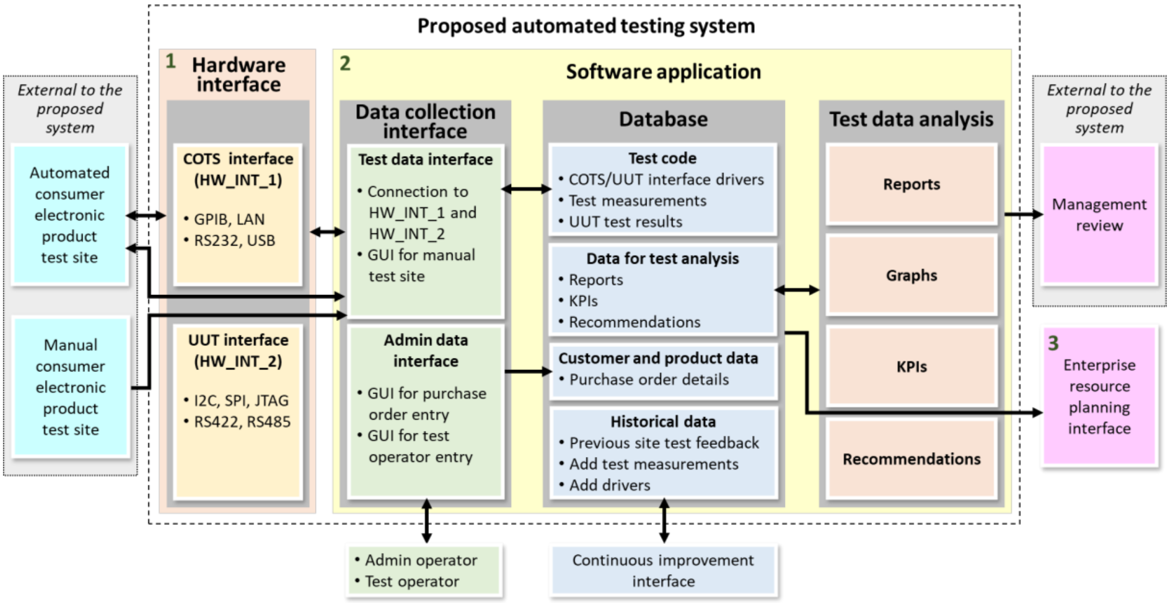

Figure 4.3. Proposed automated test system block diagram.

Figure 4.4. shows the proposed data collection building blocks of the proposed system through various interfaces and interconnections showing the direction of data flow and type of data.

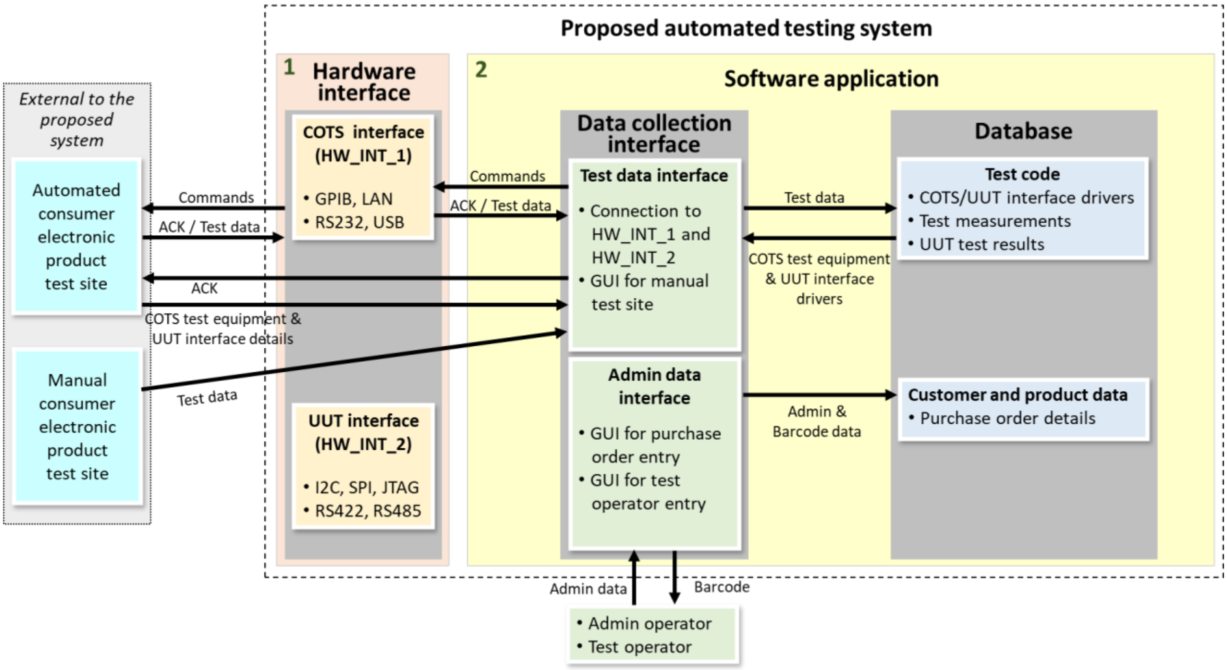

Figure 4.4. Proposed data collection sub-system data flow direction.

Similarly, Figure 4.5. presents the proposed data analysis building blocks of the proposed system, showing the data flow and connectivity.

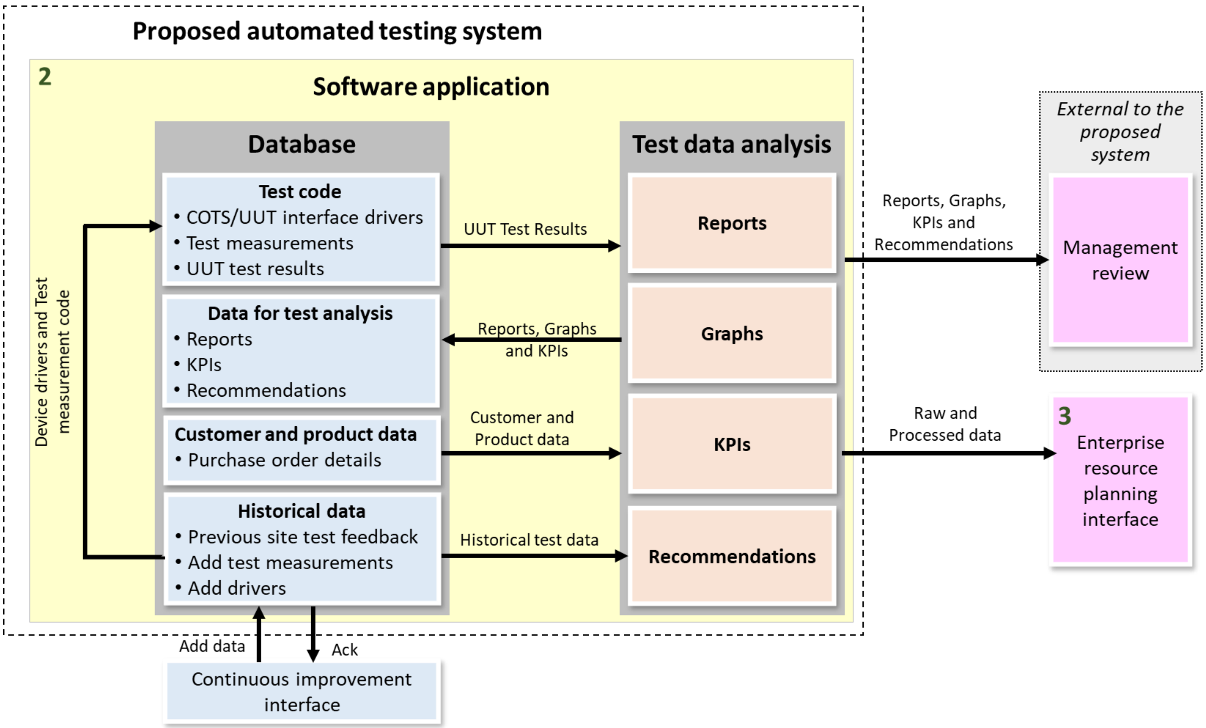

Figure 4.5. Proposed data analysis sub-system data flow direction.

In Figure 4.6., the structure of the machine-learning algorithm is presented. Four layers, i.e., input, two hidden, and the output layers are shown in the block diagram. The main inputs are the start and end dates during which recommendations are required. Once the dates are selected, all the CEPs tested in this duration are selected. Recommendations are generated in two main categories, which are product and the individual UUT within that product category. There are sub-categories of recommendations as well as shown within the hidden layers of the figure. The categories are selected based on certain keywords, some of these are listed in the figure. The machine-learning algorithm takes raw text, which is entered automatically by test software for FAIL UUTs, and the text entered by TO. Categories are identified by checking for keywords, and once the category is identified, then recommendations are generated using some more words to form sentences. These sentences are also compared with historical data, i.e., previously generated recommendations. In the end, these recommendations are stored in the database. The system also prompts the user to add new keywords picked up from the input text data.

Some examples of machine-learning-based recommendations for specific products are "Test operator 5 is takes more time", "Test operator 2 is expert in testing product 4", "Test operator 8 is suitable", "Product 4 estimated time is not correct", "Product 3 tests are insufficient", "Test jig 5 connector J9 is broken", "Test jig 1 needs maintenance", and "Test equipment 7 is going out of calibration". Similarly, some examples for individual UUT are "Component C1 wrong value", "Component D5 missing", "IC3 orientation wrong", "UUT 4 PCB quality is poor", UUT 5 solder paste is less", and "UUT 8 reflow required".

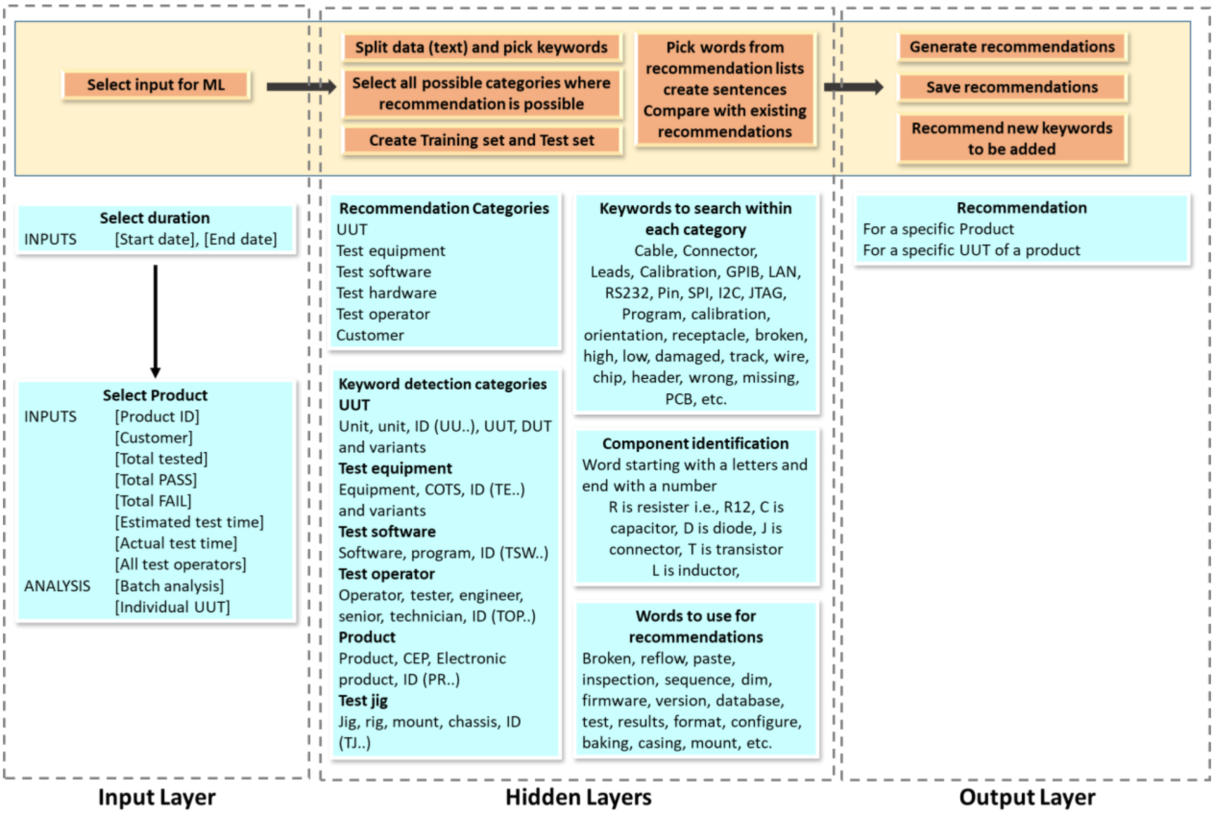

Figure 4.6. Machine-learning structure for automated recommendations.

4.4. Experimental setup

This section presents the experimental setup to validate the data collection sub-system. The validation of the test data collection sub-system, which includes a universal hardware interface, and a universal machine-learning-based software application is carried out using experimental test setups discussed in this section.

4.4.1. Experimental test site setup-1 for an RF amplifier

For validation of the universal hardware interface and machine-learning-based universal test data collection sub-systems, an experimental test site is selected, which is shown in Figure 4.7. The UUT is a multichannel RF amplifier with a frequency range of 950 MHz to 3 GHz. This frequency range is divided into four sub-channels, each having a different gain setting. The sub-channels are selected using the I2C interface on the device. The UUT has an SPI interface that is used for downloading firmware. At the input, two signal generators are connected. The signal generators generate different frequencies within the UUT frequency range. These signal generators are connected to the UUT via an RF switch. Four possibilities are considered, i.e., both signal generators are connected at the same time, either one is connected at a time, or both are disconnected. The UUT is switched ON using a bench power supply. At the output, a spectrum analyzer is connected to check frequency response. The two signal generators and a spectrum analyzer are fitted with a LAN interface, the power supply has a GPIB interface, and the RF switch is controlled via an RS232 port. The two interfaces on the UUT are SPI and I2C.

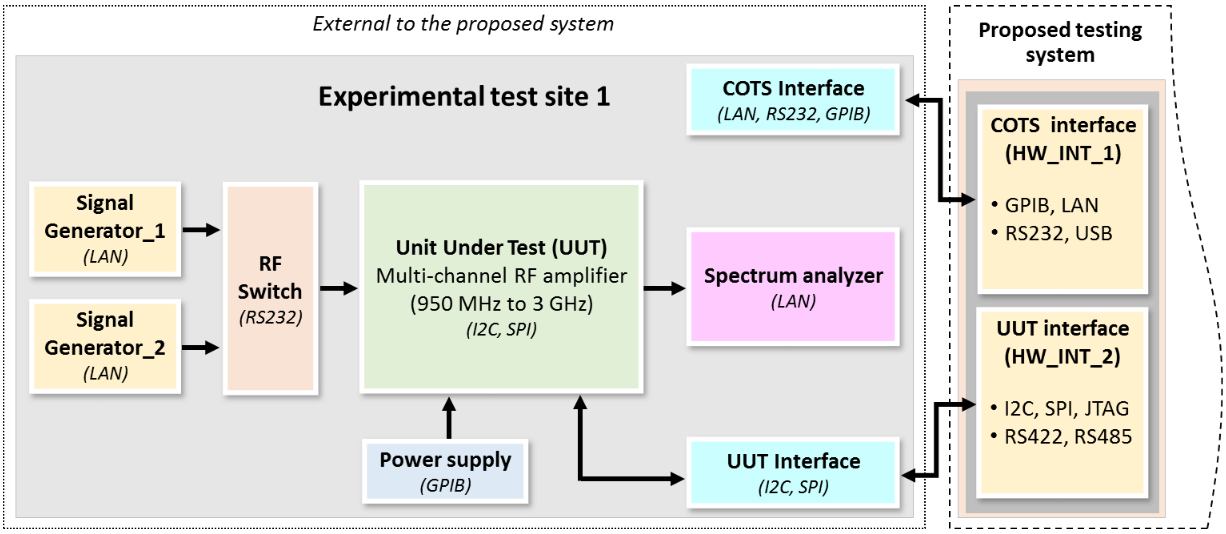

Figure 4.7. Experimental test site 1 setup.

The first step is the programming stage where a firmware file is downloaded via the SPI interface. The I2C interface on the UUT is used for selecting different frequency channels. For this experimental setup, two RF measurements are selected, namely, gain measurement and channel isolation.

The TO enters the details of the test site, which includes the make, model, and control port details of five COTS test equipment and two interfaces, i.e., SPI and I2C on the UUT. The TO also enters details of firmware file, which include file location, file size, checksum, etc., and I2C interface commands to enable or disable each channel on the UUT. TO then enters the details of two test measurements, i.e., gain and isolation measurements. The details include frequency range, amplitude scale, amplitude marker positions, etc., for gain measurement and combinations of different channels between isolation is required to be measured. Finally, the test sequence is defined, which is to download firmware, gain measurement, and isolation measurement.

The machine-learning application uses this information to select the required test code, i.e., subVIs from the database. The COTS test equipment device drivers, which are LabVIEW subVIs, are selected using the make, model number, and control port details. For downloading firmware and configuring UUT, SPI, and I2C device drivers are selected from the database. The test measurement code is selected from the database using the test measurement name and the COTS test equipment used. Test measurement details such as frequency range, marker position, test limits, etc., are saved in a text file external to the LabVIEW subVI, i.e., test measurement code. For firmware programming, machine-learning uses firmware file location, file size, checksum, etc., to download the code. This information is also saved in the external text file. Once all these tasks are completed then the complete information is saved in the database with a unique ID for the test site under consideration so that next time the TO does not need to repeat these steps. TO then initiates testing by entering TO identity, estimated UUT test times, and purchase order details, which include customer name, product part number, etc. The universal test software then performs a health check test on the COTS test equipment to make sure all hardware is connected. The health check test requests equipment to send identity and is a confirmation that COTS test equipment used on the test site can be controlled via the universal hardware interface. The next is to switch ON the power supply and check how much current the UUT is drawing. The test software then executes the tests in sequence and test results are acquired and saved in the database.

Using the proposed system, the test software development and test hardware interface is not required to be designed and built again. These tasks can normally take a few weeks or months to design and implement for a test site depending on the type. A new device driver or test measurement code can be added through the continuous improvement interface.

4.4.2. Experimental Test Site Setup-2 for an analog voice recorder

A test site for an analog voice recorder is integrated with the proposed system and automated using the universal interface. The test site includes a power supply, a signal generator, and an oscilloscope. The test site is shown in Figure 4.8., where the power supply and signal generator are controlled using the GPIB interface, while the oscilloscope is connected via the USB interface. Certain UUT parameters such as gain and filter settings are configured via the I2C interface. This was a manual test site, where TO was taking measurements by setting test equipment and configuring UUT. After connecting to the proposed system, the test site is now fully automated, and overall, 2 min per UUT time is saved. Similar to the previous section, the TO enters the details of COTS test equipment and UUT hardware interfaces. The software then creates the test sequence and executes the test.

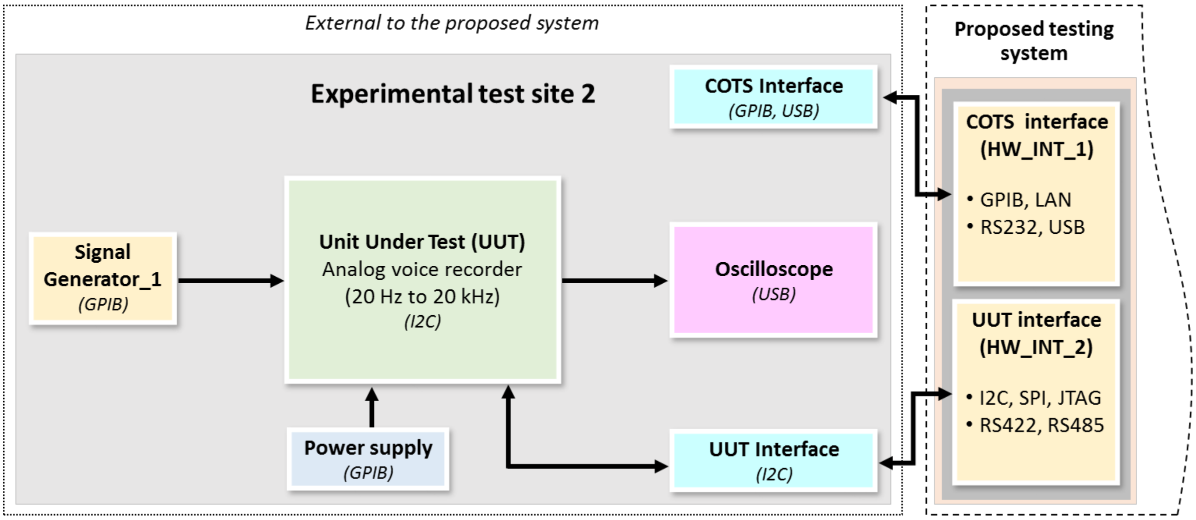

Figure 4.8. Experimental test site 2 setup.

4.5. Experimental results

The quality of test data collected is extremely important for any analysis. The analysis is performed using a test data analysis sub-system and various graphical results and KPIs are generated. More reports or results can be added as per requirements. Some of the graphical results are presented in this section.

The test data analysis sub-system of the proposed system is implemented and then validated in a mid-volume CEM environment for electronic product testing. The proposed system is deployed in the factory, and analysis is performed for the collected test data.

4.5.1. Test data analysis sub-system software interface

Test data analysis interface is implemented for supervisors or managers to perform analysis of the test data recorded/logged. An interface is created as a proof of concept and is installed, and results are presented. The analysis can be done based on two categories. The first category includes individual analysis for TOs, product, specific customer, POs, etc. In the second category, reports are generated for any duration by selecting the start and end dates for any of the parameters such as products, customers, POs, TOs, etc.

4.5.2. Manufacturing test data presented by product (UUT)

In this section, the data collected for different product types are presented graphically. The graphs present data collected for a month. Two product types, “Complex Digital” and “Camera”, are selected here for analysis. These products belong to different customers and are tested by TOs with different skills. The monthly testing is carried out and presented in this sub-section. The daily hours booked are shown on the *y*-axis, while three different parameters are shown on the *x*-axis. These *x*-axis parameters are test date, TO name and details, and customer details. The data are grouped based on the customers. The curved dotted line shown in the graphs is the data trend, i.e., hours booked by the TOs during the month. The straight line is the median value of the hours booked and the bar charts represent the actual hours booked daily.

Figure 4.9. shows results for product type “Complex Digital”. The products tested and presented here belong to four different customers, i.e., customer 15, customer 37, customer 40, and customer 5. There is a further division for each customer which is based on TO who worked on these products. Here 8 different TOs are utilized for testing these products.

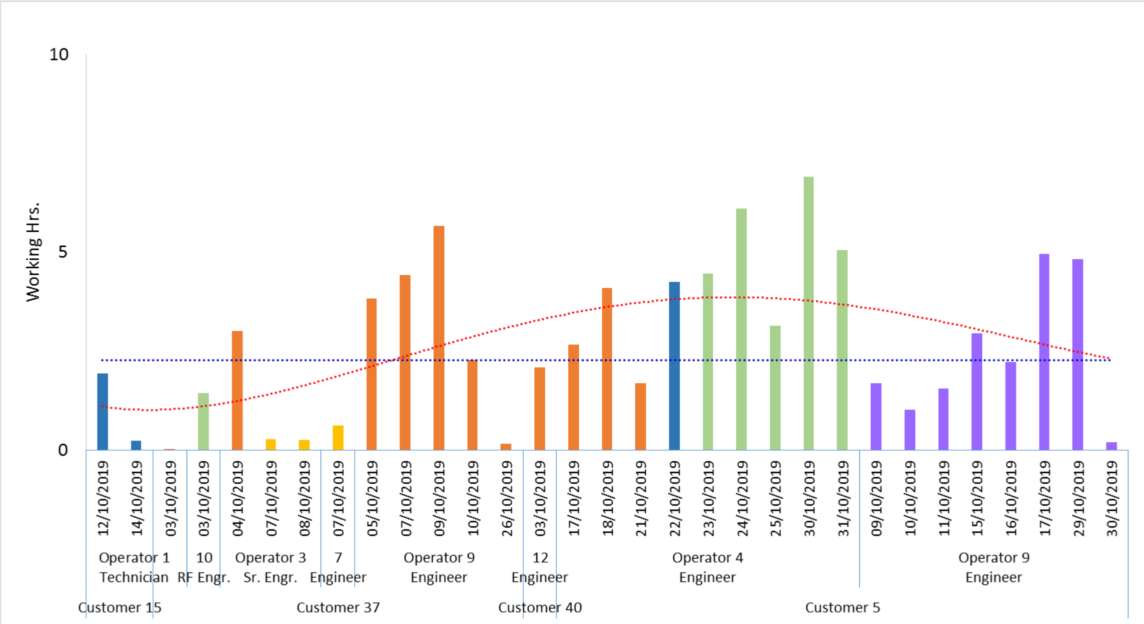

Figure 4.9. Product type Complex Digital—October 2019.

Figure 4.10. shows the results for the product type “Camera”. The cameras tested here belong to 2 different customers, and 6 different TOs, including a technician, 2 senior engineers, and 3 engineers, tested this product.

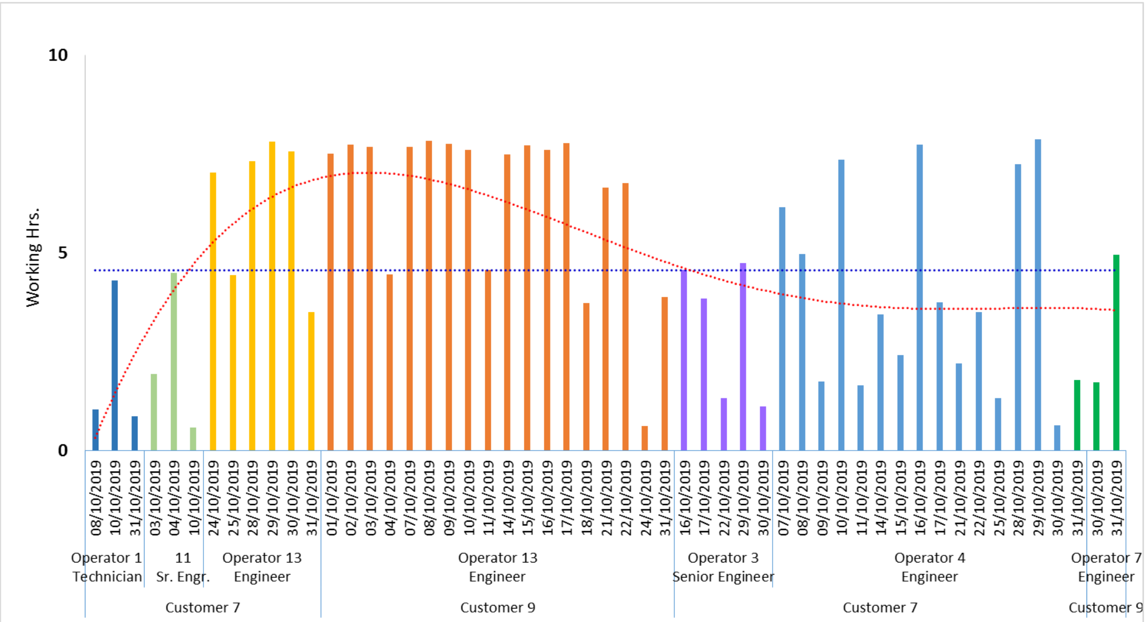

Figure 4.10. Product type Camera—October 2019.

4.5.3. Manufacturing data presented by the customer

In this section, the data collected, based on customer product, are presented graphically. The graphs present data collected for 2 customers for 3 months. Different TOs were utilized for testing customer products. The product types are based on customer orders. Figures in this section show the testing carried out for 2 different customers for 3 months. The daily time booking is shown on the *y*-axis, while details of TOs and dates are mentioned on the *x*-axis.

Figure 4.11. shows the test results for customer 15. The graph shows that the TOs spend more time testing this "Complex Digital" product for customer 15 around the middle of the 3 months duration. The increase in test time can vary and is dependent on the order intake and deadlines agreed with the customers. The data are grouped based on the 4 different TOs utilized.

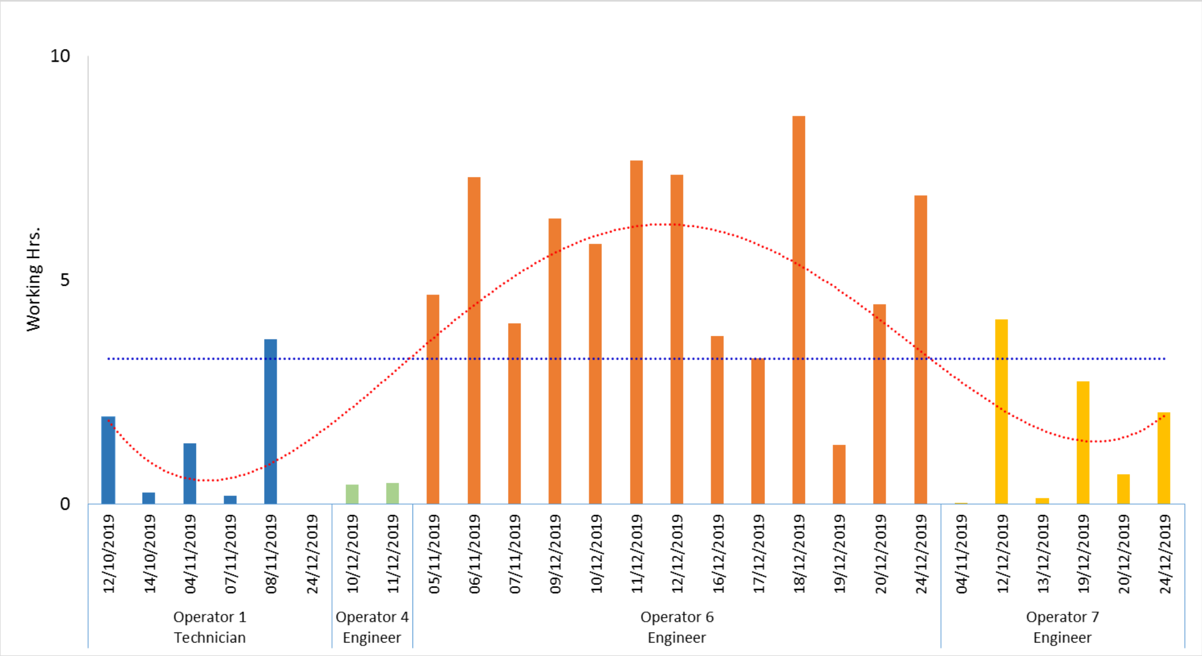

Figure 4.11. Customer 15, product type Complex Digital—Q4 2019.

Figure 4.12. shows test results for customer 20 and the product type is "Analog". The graph shows that 4 different TOs tested this product with the greatest number of hours booked by TO number 3.

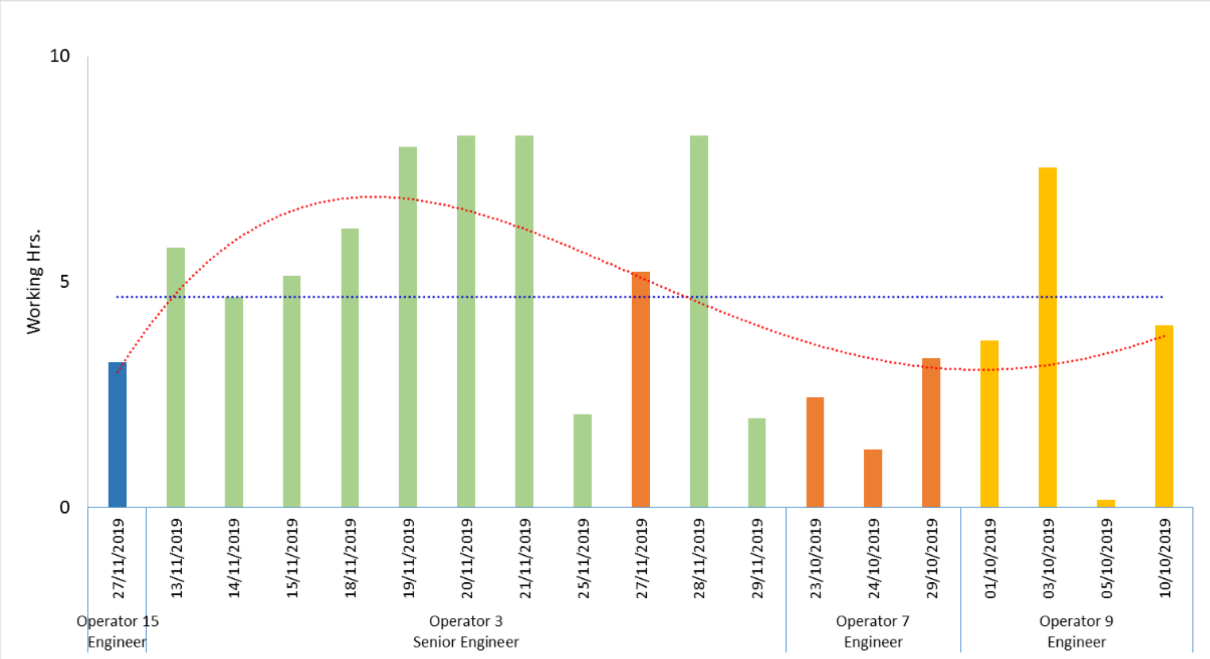

Figure 4.12. Customer 20, product type Analog—Q4 2019.

4.5.4. Manufacturing data presented by the test operator (TO)

In this section, the test data are collected and shown graphically for a month. The graphs are plotted for 2 different TOs. These graphs are useful in analyzing the performance of the TOs. The same analysis can also be performed for more than a month. Graphs shown in this section are for 2 different TOs. Data are collected and presented for a month.

Figure 4.13. shows the test hours booked by TO number 15. During this time, TO number 15 tested products for 5 different customers as shown on the *x*-axis. Here 4 different product types were tested, which are grouped as shown on the horizontal axis. The TO also booked some indirect hours, i.e., during this time the TO is not testing any customer products but spending time on a test jig maintenance.

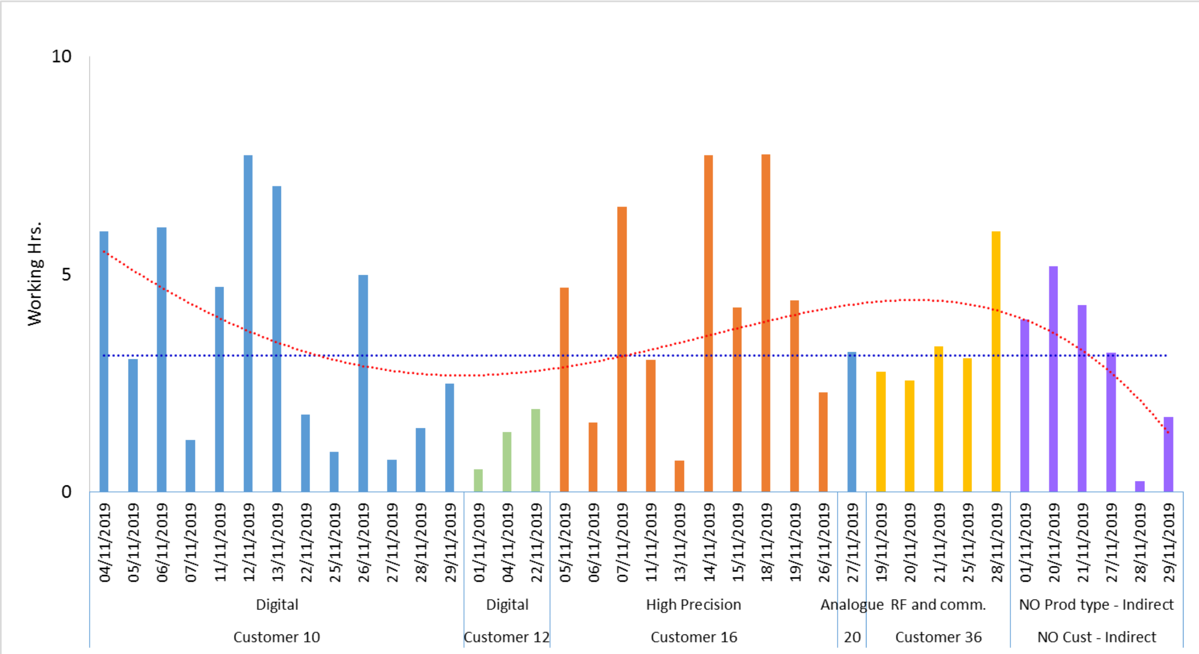

Figure 4.13. Test operator (TO) 15 (Engineer)—November 2019.

Figure 4.14. shows the test hours booked by one of the test technicians. TO number 16 tested 7 different product types for 9 different customers. TO number 16 also booked a fraction of the time as indirect booking. During this time, this operator attended a customer visit.

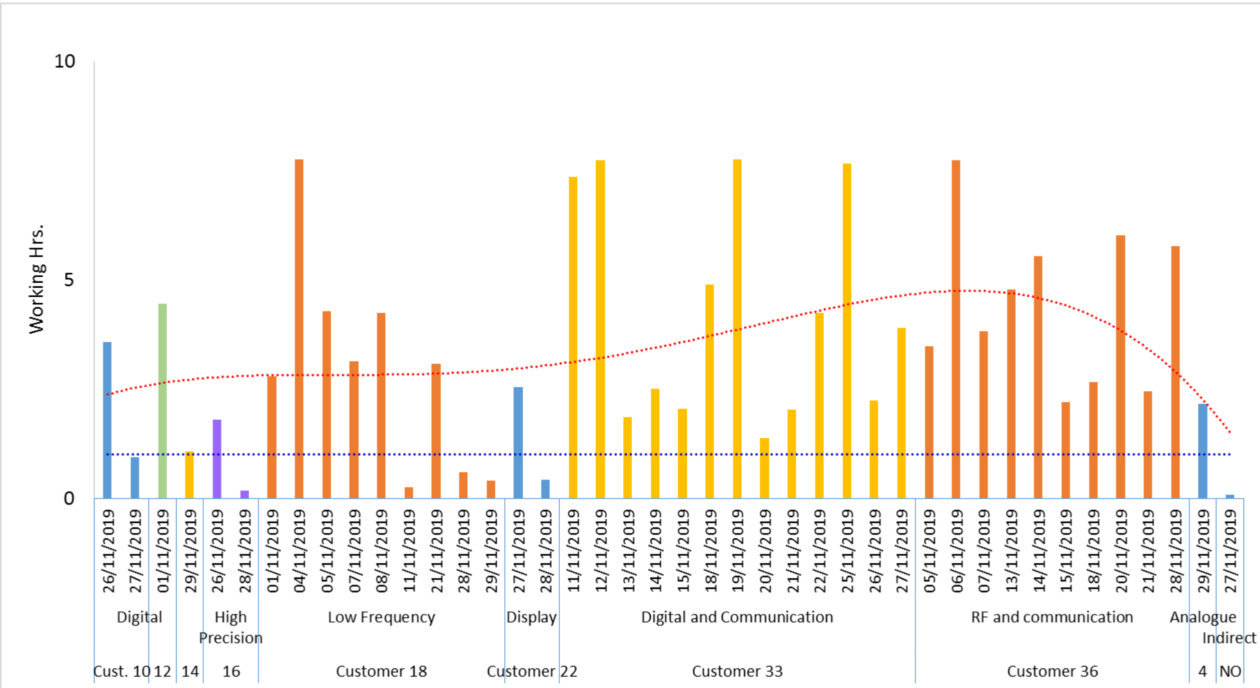

Figure 4.14. Test operator (TO) 16 (Technician)—November 2019.

4.5.5. Manufacturing operator performance—product wise

In this section, the test data collected are presented for the range of products tested during a quarter of the year. In Figure 4.15., testing carried out and hours booked by TOs within the categories technician, engineer, senior engineer, and RF engineer are shown on the vertical axis. The TOs and product range are listed on the other 2 axes. The total products tested were within the 14 product types. During this period, the TOs have also booked some indirect hours, i.e., time booked for non-products. Among the 4 different TOs, RF test engineers booked approximately 3% of the total hours booked due to the specialized RF testing carried out on a limited RF product range. Engineers and senior engineers booked approximately 75% of hours between them. The share of hours is not fixed and can vary depending on the number of staff employed within each category, order intake, quantity, and test times of the products tested, etc.

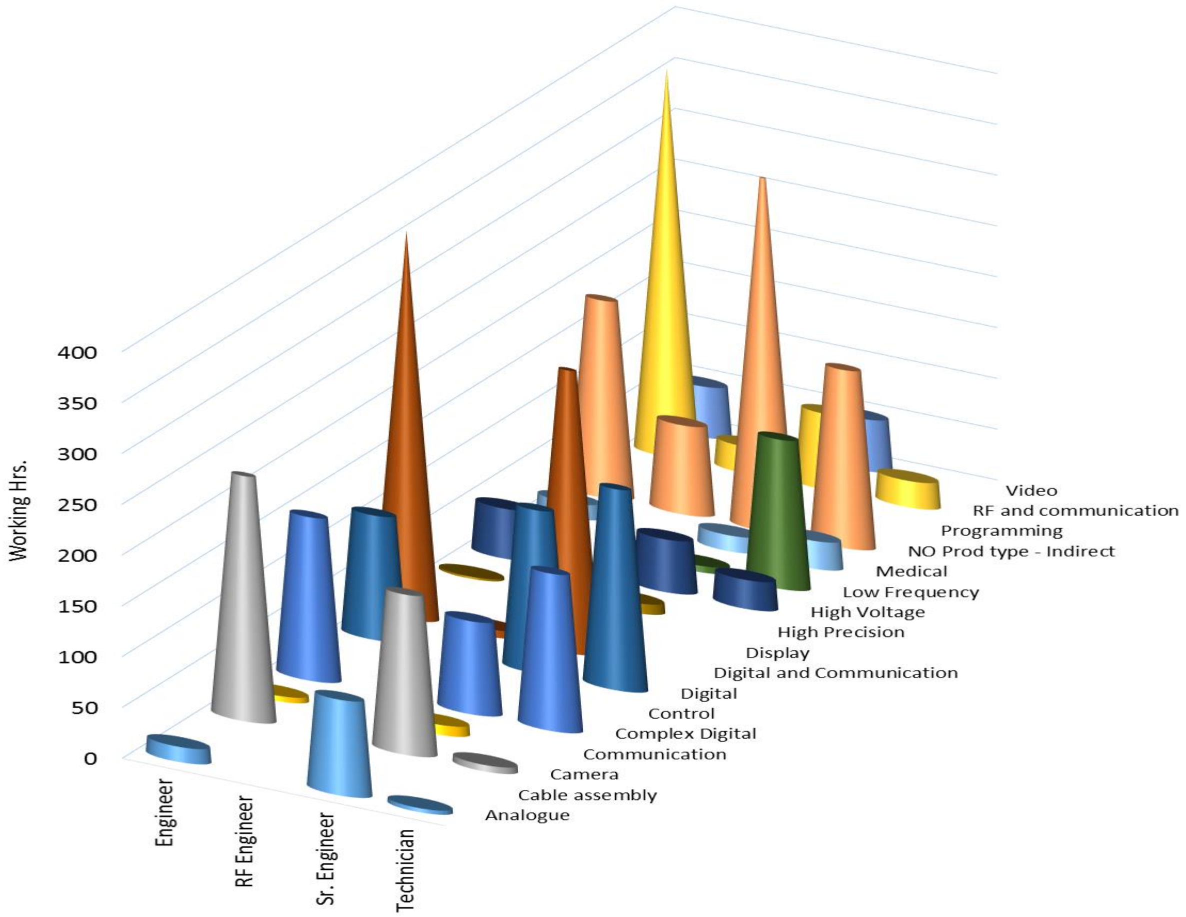

Figure 4.15. Product wise operator performance—Q1 2019.

4.5.6. Manufacturing operator performance—product wise

In this section, the test data collected are displayed for all the customers whose products were tested during a quarter of the year. In Figure 4.16., the test hours booked by TOs within the categories technician, engineer, senior engineer, and RF engineer are shown on the vertical axis. The TOs and customer names are listed on the other 2 axes. During this quarter, testing is carried out for 25 different customers.

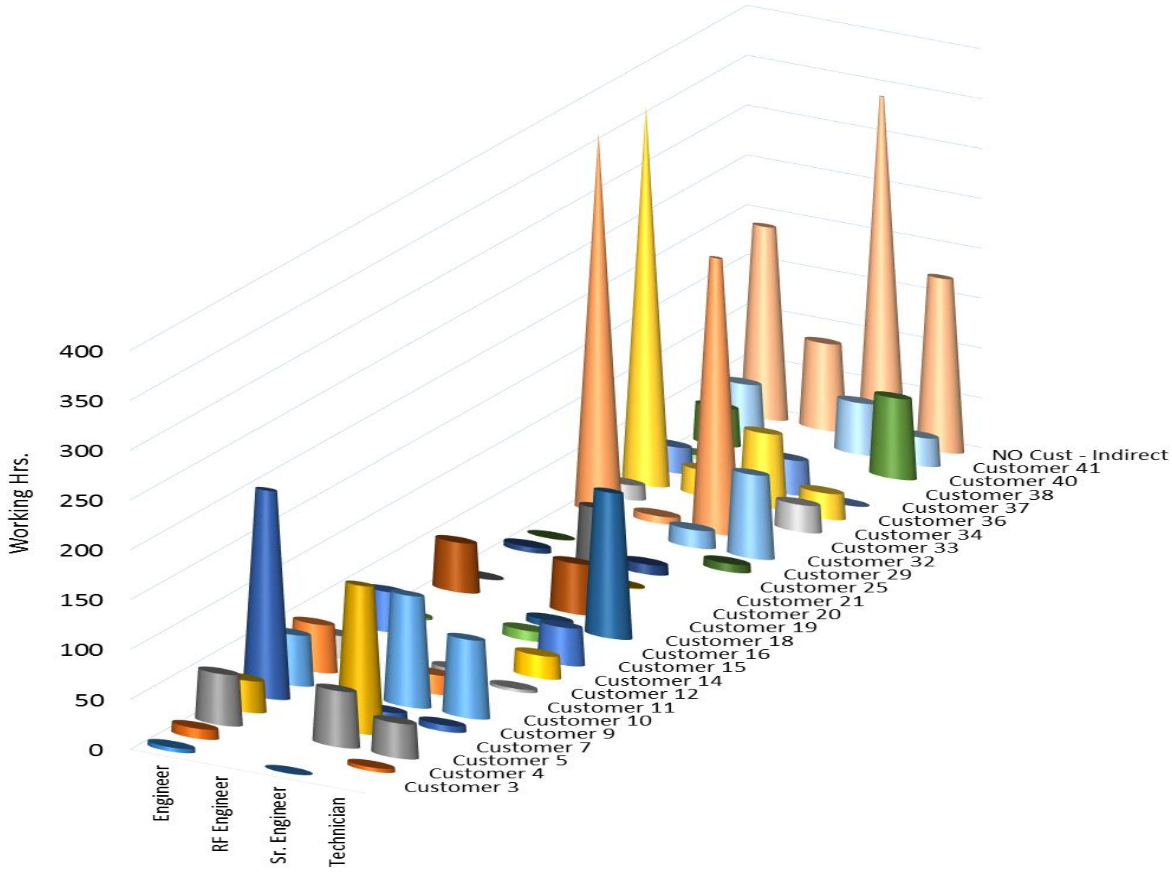

Figure 4.16. Customer wise operator performance—Q1 2019.

4.5.7. Manufacturing test data – rest of the categories

The manufacturing test data of four electronic product types namely analog, digital, complex digital, and high precision is collected during a month which is presented in Table 4.1. The test data includes customer PO listed in the first column, customer ID in the second column, and product type in the next column. Every product is also allocated a unique product number which is mentioned in the fourth column. The last two columns contain the operator ID and skill level. Three operator skill levels are used which are a senior engineer (SEN), engineer (ENG), and technician (TEC). To give more flexibility for analysis, everything i.e., customer, operator, product, etc., is allocated an exclusive ID. This also helps in maintaining historical data i.e., any new operator or customer, etc. will be allocated a new ID while if an operator leaves the company, then his or her ID will not be reallocated for correct record keeping.

Table 4.1. Monthly manufacturing test data

PO	Customer ID	Product Type	Product No.	Qty	Testing hrs.	Operator ID	Skill level
90	16	Analogue	112	1	14.04	7	ENG
92	16	Analogue	114	2	12.27	7	ENG
194	1	Analogue	108	8	20.54	8	ENG
225	19	Analogue	10	10	21.26	8	ENG
91	16	Analogue	113	11	65.18	7	ENG
89	16	Analogue	9	13	50.91	7	ENG
96	9	Digital	191	8	22.51	15	TEC
51	6	Digital	174	23	12.83	14	ENG
45	6	Digital	55	29	5.78	8	ENG
52	6	Digital	175	30	50.51	8	ENG
40	6	Digital	154	55	17.31	4	ENG
98	6	Digital	63	85	9.04	14	ENG
1	11	Complex Digital	88	9	15.79	2	SEN
205	25	Complex Digital	103	11	7.93	8	ENG
220	2	Complex Digital	149	23	17.9	4	ENG
13	2	Complex Digital	150	78	5.69	8	ENG
112	2	Complex Digital	17	89	14.83	4	ENG
35	11	Complex Digital	91	144	33.18	2	SEN
216	12	High Precision	250	1	14.58	10	SEN
183	12	High Precision	78	6	26.94	15	TEC
235	12	High Precision	82	6	8.72	15	TEC
231	12	High Precision	83	21	20.6	10	SEN
228	12	High Precision	76	36	6.31	15	TEC
184	12	High Precision	79	47	42.85	15	TEC

Finally, the remaining columns i.e., columns 5 and 6 contain the quantity tested for that product and the time booked to test that quantity. The test data table is kept simple which is an important feature of this test application. The manufacturing test data of four electronic products are presented in this research and similar data can also be analyzed for other product types. Analysis of the collected data is based on four parameters namely the product quantity tested, total test hours booked, test time per hour, and operator skills to test the product. These parameters directly affect the yield, test cost, and the product being delivered in time.

4.5.7.1. Product Quantity Tested

In Figure 4.17. the number of different products tested during a month is presented. The quantity of the products tested between product types and within a product type depends on the customer PO. Company performance can vary between months based on the operator skills, type, and quantity of product tested during that month which is dictated by the customer PO. From the graph, it can be seen that during that month digital and complex digital products are tested more than others.

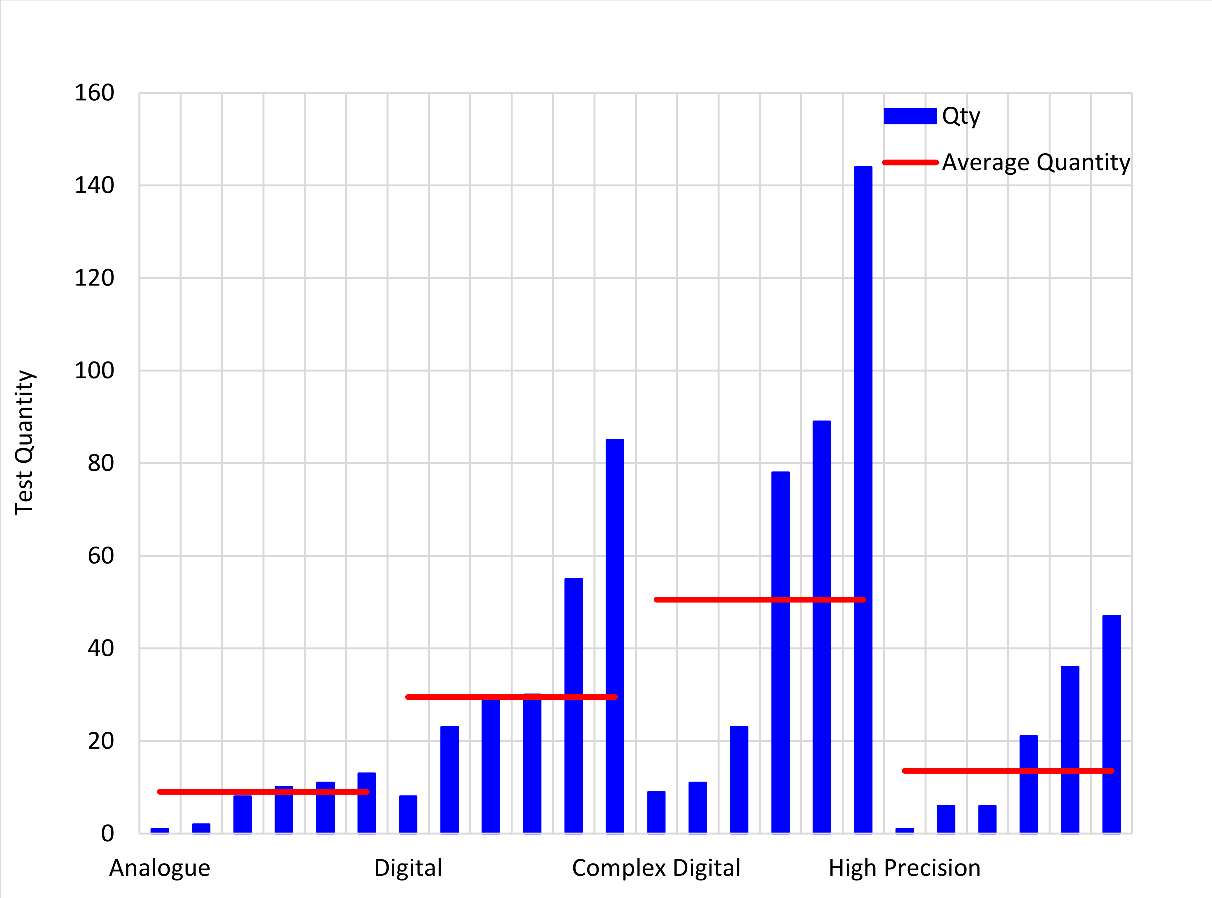

Figure 4.17. Manufacturing test data product quantity.

4.5.7.2. Total Test Hours Booked

In Figure 4.18., the total hours booked by test operators are presented. The test hours are grouped within the product type. The graph shows that the average test time booked to test all products within the category “analog” took longer. Comparing graphs 4 and 5 it can be concluded that although the quantity is less, yet the test hours booked are higher.

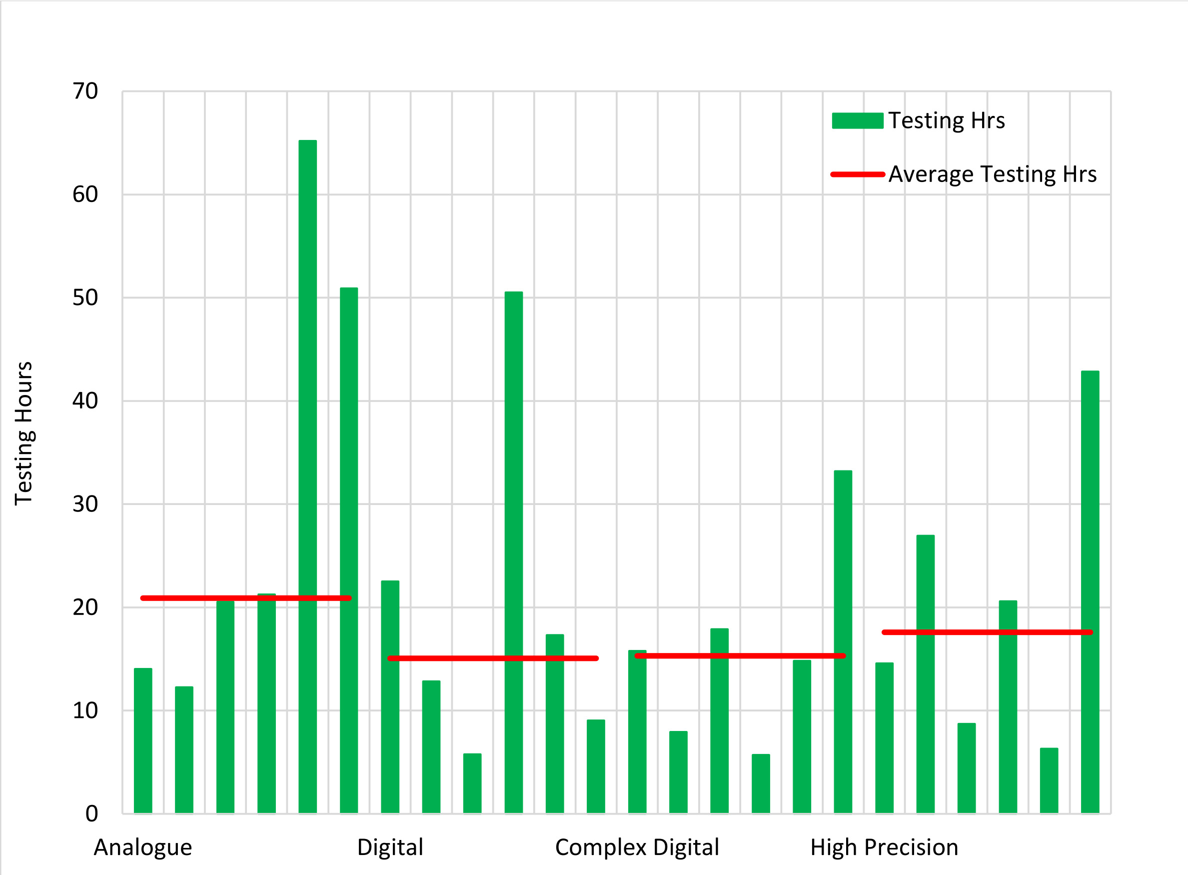

Figure 4.18. Manufacturing test data testing hours.

4.5.7.3. Testing Per Hour

In Figure 4.19. the test time per UUT is shown. The test times per UUT are higher for complex digital products due to the type of test, like boundary scan, on board device programming, checking protocols, etc. Test time for one high precision device is also high. The measurements for this type of device were very low signals and accuracy and focus is required to make sure the values are within the test limit. The test equipment variation is another parameter that elongated the testing.

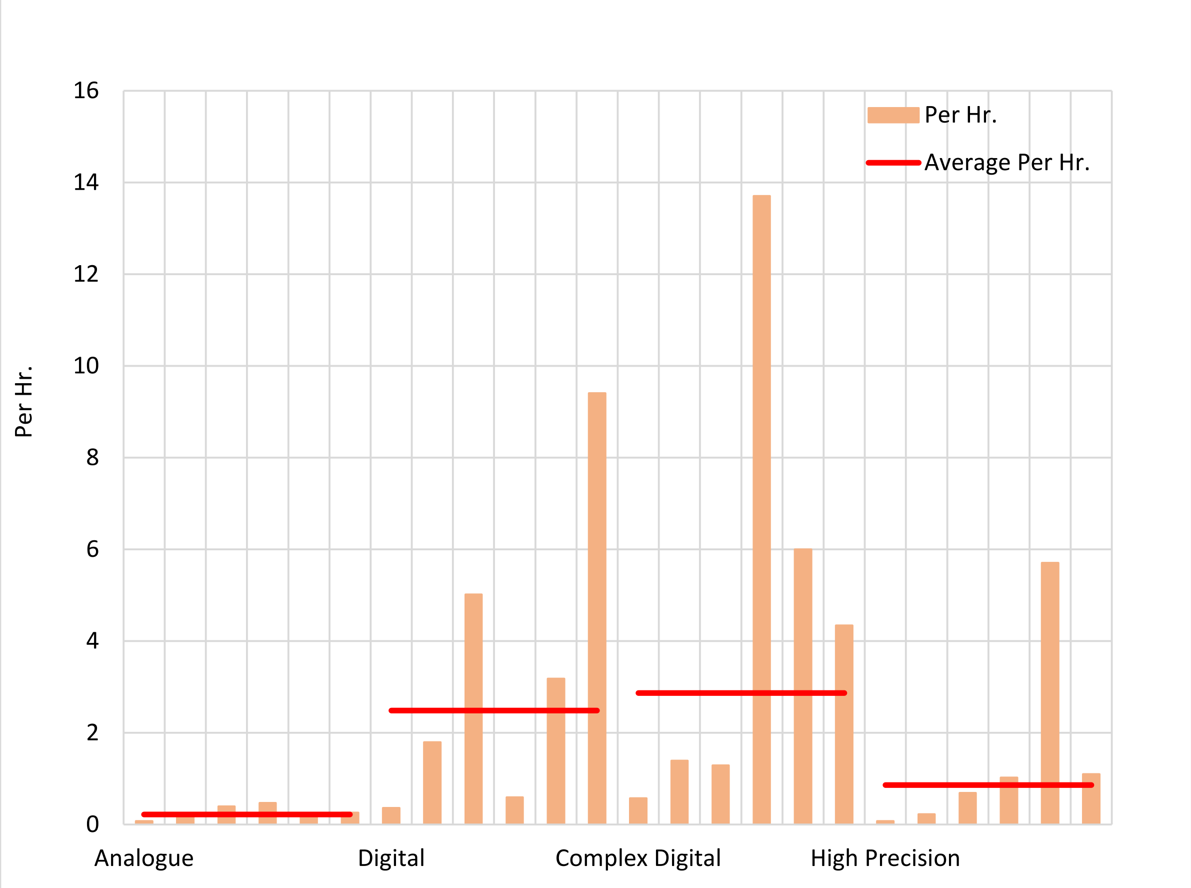

Figure 4.19. Manufacturing test data per hour.

4.5.7.4. Skills used in Manufacturing Test Data Collection

Figure 4.20. shows the skills levels of the operators used for testing different product types. SEN tested complex digital and high-precision products. TEC also tested high-precision products under the supervision of SEN.SEN was able to switch between products while TEC was testing that product full time. ENG performed testing for the rest of the product types. Based on the customer purchase orders, the company can also decide the numbers of TEC, ENG, and SEN they need to employ.

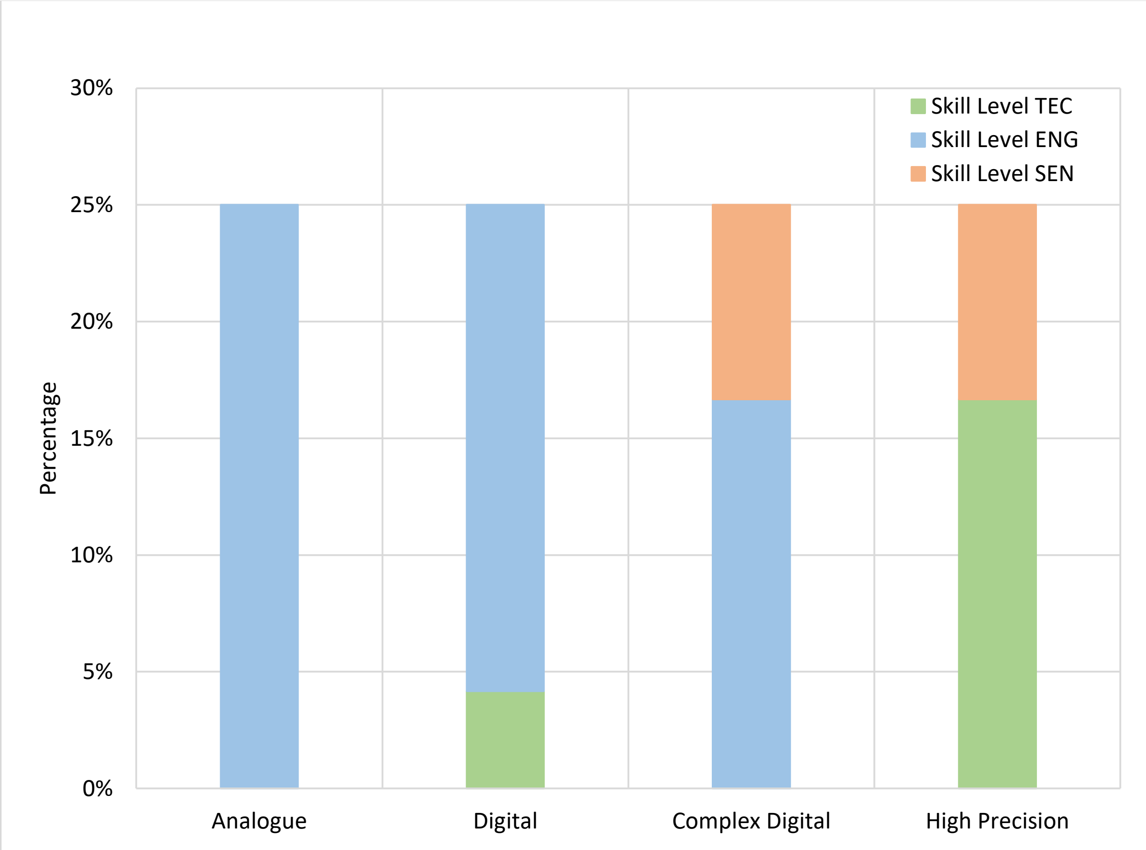

Figure 4.20. Manufacturing test operator skills.

A summary of manufacturing test data of four electronic products for one month is presented in Table 4.2. The parameters analyzed are quantity, testing hours, per hour testing, and operator skills used to test the products. It is concluded that almost half of the test products are complex digital, one-third are digital, a portion of high precision and very few are analog. Interestingly, analog products are few but they consume almost one-third of the total time, while the remaining time is almost equally distributed among the three types of products. In terms of per hour analysis, complex digital type of products took almost half of the total time, while digital products take almost one third, high precision takes less time, while the analog type of products takes the only fraction of time. In terms of skills, for the analog type of products team of engineers is required. Digital products require mostly engineering skills with the support of technicians. High precision products require a team of technicians under the supervision of senior engineers, and complex digital type of products require a team of engineers under the supervision of senior engineers.

Table 4.2. Summary of monthly manufacturing test data

Product type	Qty (%)	Testing hrs. (%)	Per hr. (%)	Skill level (%)		
				TEC	ENG	SEN
Analogue	6.0	35.6	2.6	-	25.0	-
Digital	30.8	22.8	35.1	4.2	20.8	-
Complex Digital	47.5	18.4	47.1	-	16.7	8.3
High Precision	15.7	23.2	15.2	16.7	-	8.3

4.5.8. Key performance indicators (KPIs)

Manufacturing companies present their performance via KPIs. These KPIs highlight the problems and shortcomings as well as show areas where improvements are made. In [91], the authors discussed and highlighted the importance of KPI. In [92], the authors defined KPIs to monitor performance. This is a standard method of presenting the performance of any system. Using the proposed system, the manufacturing companies can present their results via four KPIs, which are performance, capacity, distribution, and availability. In this research, 2 separate graphs for the KPI “Capacity” are presented for monthly electronic products tested and monthly test time booked. The results are for the first three quarters of the year, where months are listed on the *x*-axis.

In Figure 4.21., the number of monthly electronic products tested are shown via bar charts. The moving average is also shown in the graph. It can be seen from the graph that fewer products were tested during February, March, and April. The number of products tested depends on the customer orders booked and staff holidays. Using this KPI, companies can plan what resources are required in the future. Here, the results are presented monthly but can be changed as required.

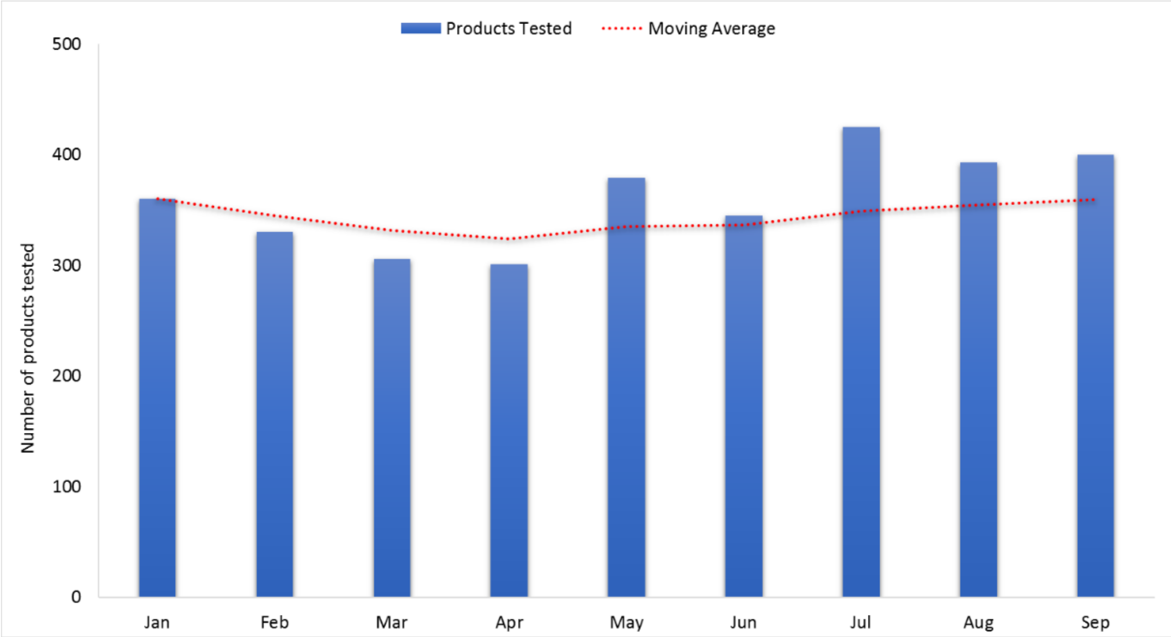

Figure 4.21. KPI—Capacity (monthly electronic products tested).

In Figure 4.22., the monthly time booked, and the moving average is shown. Manufacturing companies at the time of receiving customer orders, select an estimated test time for the UUT. This estimated test time is used as a benchmark for checking capacity and performance. Manufacturing companies can also set a target threshold and can compare this with moving average plots.

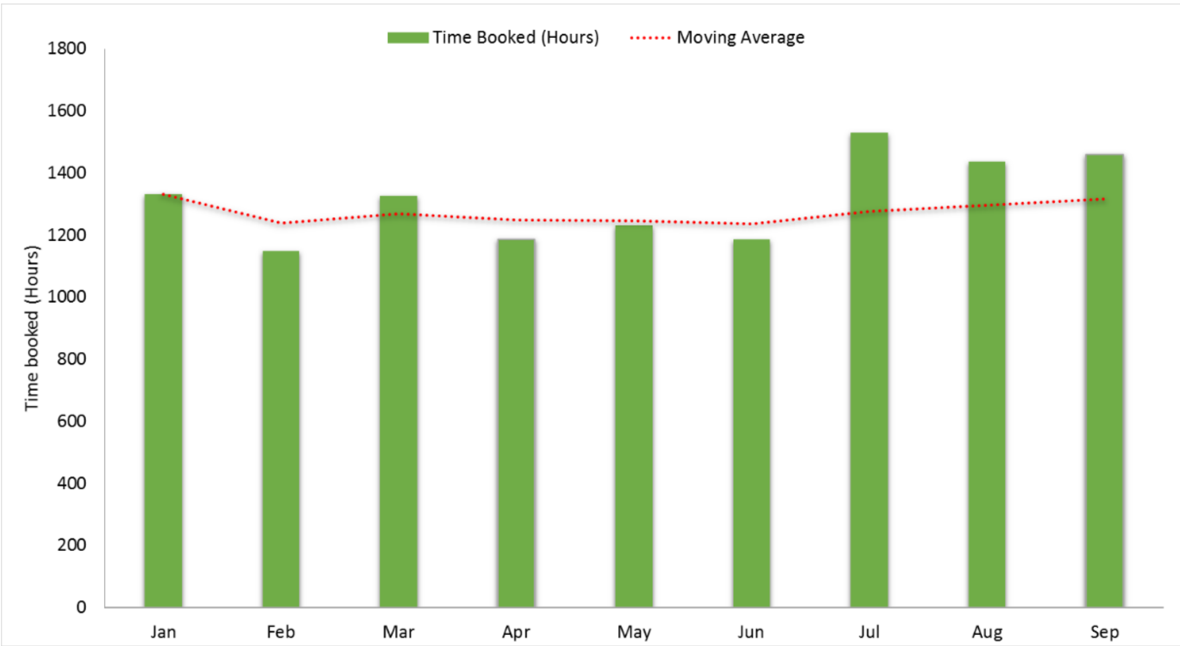

Figure 4.22. KPI—Capacity (monthly test time booked).

4.5.9. Manufacturing data presented by customer returns

Customer returns also play an important role in the Electronic product manufacturing business. Customer returns faulty goods which may be either within warranty or outside warranty. Repairing customer returns can be a bit tricky due to components or parts etc becoming obsolete. Some customer returns are beyond repair and in such a situation the manufacturing companies provide a replacement depending on the agreement with the customer.

Customer returns depend on the quality of the first-time manufacturing process. Improving and optimizing the manufacturing test can directly result in fewer customer returns. Customer returns take longer to test as compared to the normal manufacturing test. The operator first needs to check and confirm the fault reported by the customer, then check the test coverage for the product returned by the customer i.e. check if the fault reported is within the part of the circuit which was tested during the manufacturing test. If the reported fault is not within the test coverage, then the operator contacts the customer to discuss the next course of action. If the fault is recreated and within the test coverage, then the returned item is repaired or reworked and then retested. If the retest is PASS, then it is returned to the customer.

Table 4.3. shows the details of the monthly customer return status.

Table 4.3. Manufacturing test data report by weekly customer returns

Customer	Week 1	Week 2	Week 3	Week 4
Customer 2	12	12	12	12
Customer 3	9	10	12	10
Customer 5	16	14	14	14
Customer 6	6	5	5	5
Customer 10	19	0	0	0
Customer 12	2	2	2	2
Customer 13	1	0	0	0
Customer 16	9	9	10	10
Customer 17	1	1	1	1
Customer 18	1	1	0	0
Customer 19	70	68	62	53
Customer 21	79	77	74	35
Customer 22	1	3	1	1
Customer 24	0	53	53	48
Customer 25	31	30	30	31
Customer 26	2	2	2	2
Customer 29	3	1	1	1
Customer 30	4	4	3	3

The first column lists the names of the customers who returned their products within or outside warranty. The next 4 columns list the balance of customer returns weekly. The weekly number can go up if more products are returned than the ones repaired and shipped. Priority is given to returns that are under warranty. The manufacturing companies agree to a timeframe beforehand with the customers for returned products received outside the warranty period.

It is also important to consider the type of fault reported, for example, if there is physical damage to a component i.e. a damaged track on the board or a connector or cable, the UUT should be reworked first. If the product is returned for the same fault, then the test coverage needs updating so that the fault is picked up during the manufacturing test.

The operator also needs to check if the returned product is under warranty. If not, then the cost of repair should also be logged. After initial analysis, if the operator concludes that the product is not viable for repair, the company can decide whether to ship a replacement unit to the customer. Time is very important to quickly complete it.

Figure 4.23. presents the monthly status of customer returns graphically. The y-axis shows the quantity, and the x-axis is the week number. For each week there are 3 bar charts which are returns received, returns repaired and shipped to the customer, and the balance or pending. The horizontal line provides the trend.

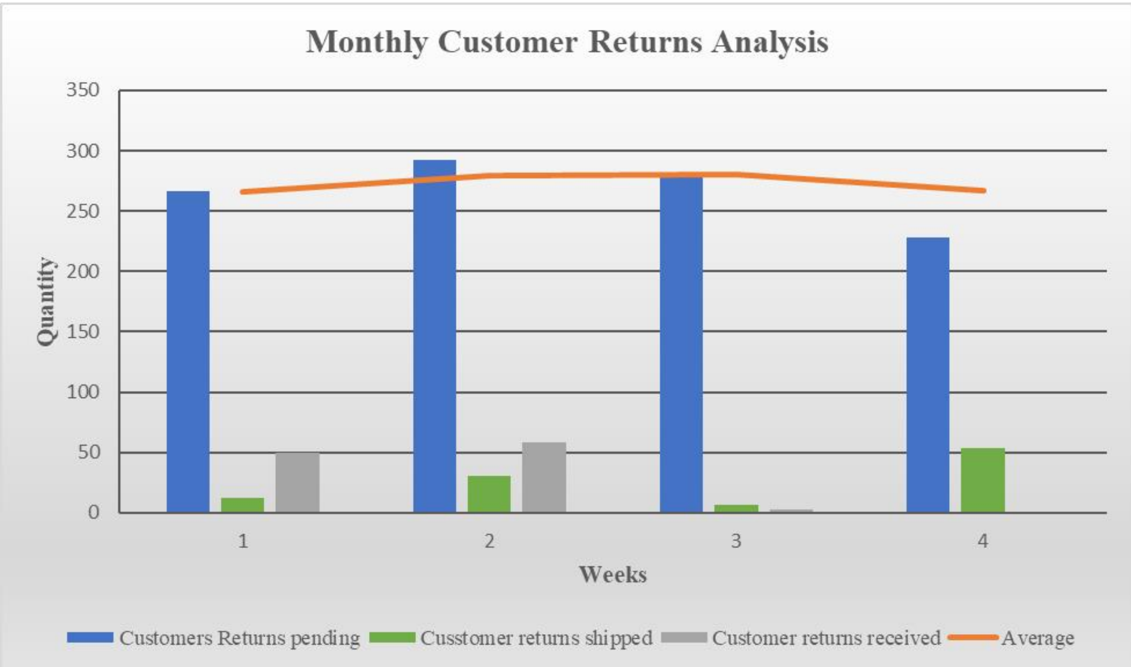

Figure 4.23. Customer returns distribution

4.5.10. Machine-learning based automatic recommendations

In this section, the machine-learning-based automatic recommendation feature is validated through test cases. At the end of testing, UUT test results are stored in the database, and in case of failure, a fault is also entered by test software automatically. TO can also enter any observation, etc., like free text using the interface. The following four recommendations are automatically generated by the proposed system.

4.5.10.1. Recommendation 1

In the first test case, the test results of some failed UUTs are analyzed by the test software. It is found that the first 5 UUTs of a batch failed, but after that, the UUTs continued to PASS the test. The machine-learning algorithm, to come up with a solution, review the fault, which is automatically entered by the test software, and found that a connector J5 is not making proper contact. It is recommended that the test jig is faulty, so we need to perform maintenance and replace connector J5. It would have taken a lot of time to review this fault manually, but using machine-learning, this is completed quickly.

4.5.10.2. Recommendation 2

In the second test case, TO reported through the text box that, although the UUT PASS the test but, one component on the test jig is getting hot. The machine-learning algorithm searches the comments automatically entered by test software and the text entered by TO. As all the UUTs PASS the test, so no software entered comments are found. In the next iteration, the machine-learning application search comments entered by TO and found the details of the components getting hot and recommended to modify the test jig and use heatsink.

4.5.10.3. Recommendation 3

In the third test case, the machine-learning algorithm reviews the test results of a UUT batch. It is found that one TO took 5 minutes average test time per UUT, while the second TO took 9 minutes average test time per UUT. This is a significant difference, where the second TO took almost twice the time. The machine-learning algorithm recommends that the first TO should be used when testing this specific UUT, and the second TO requires training before testing this product again.

4.5.10.4. Recommendation 4

In the final test case, the machine-learning algorithm reviews the average test time for a UUT. It is found that this is on average 3 minutes more than the estimated test time, i.e., test time per UUT agreed with the customer. Due to this, the CEM company is losing revenue. The automated recommendation, in this case, is to discuss the issue with the customer and propose a new test time.

Chapter 5: Conclusion and Future Work

5.1.Test sites design based on the figure of merit and machine-learning

5.1.1. 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.

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 research, 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 2.2. while details of some of the electronic products are presented in table 2.1. 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.

5.1.2. Conclusion

This research 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 here. 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 research. 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.

This research work presents a methodology to design a test site based on the figure-of-merit. The software application is developed in LabVIEW to gather various inputs mainly based on the customer requirements and linked to the database containing test equipment and previous tests' details. The proposed approach is reliable and can be easily implemented by manufacturing companies which not only leads to increased revenue but also satisfied customers. The proposed method is applied to an electronic product and results, in tabular form, through various stages are presented. The results show that how the information from the customer 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 to fill the gaps and setup the test site.

5.1.3. Future research direction

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.

The research is a step towards defining a standard approach to setup test sites, however, the figure-of-merit has its limitations. More parameters can be added to calculate the figure-of-merit in the future. Similarly, the database can be expanded to add more values and the test readiness review template can be modified to include setting up test sites for more complex electronic products.

5.2. Machine-learning based automated testing system

5.2.1. Discussion

Collecting quality test data can help the CEM companies to understand the areas where improvement is required or the areas that are creating a bottleneck. These companies can take actions such as redesigning their test jigs, changing the test sequence, adding, or removing certain tests, specific and focused training for staff, and have a clear idea regarding recruitment, investment in test equipment, etc. Based on the review, several limitations are identified in the existing systems used within the CEP test domain of the CEM industry.

A new CEP is normally required to be tested as part of the manufacturing process. A test site is required for this purpose, which includes, COTS test equipment, hardware interfaces, test jigs, test software, etc. Due to a lack of a universal system, the CEM companies are required to carry out all the activities for setting up a test site, which takes a lot of time and effort. The proposed universal system provides a solution for this and saves time and cost for the CEM companies while maintaining consistency and improving quality. To automate testing a test software is also required to be developed, which can take a lot of time depending on the complexity of the UUT. The next issue is the validation of this software application, often it is observed that due to lack of time and urgency to market the product, proper software validation is ignored, which means a faulty product is shipped. Using the proposed universal system, the CEM companies are not required to develop the test application for every new product and just need to integrate their test site. Having a universal software application for testing various CEPs is an important step, but this takes us to the next problem, which is to identify and maintain a library of software sub-routines for test measurements. Due to a variety of UUTs, the type of test measurements also varies depending on COTS or in-house developed test equipment.

The next challenge is to have a process or approach that can automatically decide, based on the input from the TO, what test measurements are required and how these measurements should be taken based on the UUT. A machine-learning approach can resolve this problem, but for a supervised machine-learning technique to work efficiently, a lot of historical data including test code for taking test measurements is required. To solve this issue, around 100 test sites are reviewed for a variety of CEPs. This helped in creating a knowledge base for COTS test equipment, UUT hardware interfaces, and test measurements. The system is designed in such a way that new device drivers and measurement code can be easily added. The test software takes input from the TO, selects the required code from the database, finalizes the test sequence, and the test software is generated quickly. Finally, for the above concept to work, a universal hardware interface is required. This hardware interface should have all the common interfaces to connect to any electronic product test site. This also requires a library of COTS and other test equipment drivers for the proposed system to work. Limitations and features of these interfaces such as data rate, number of devices that can be connected, power requirements are also considered. A vast majority of the COTS test equipment has one of the control ports used in the universal hardware interface.

It should be noted that hundreds and thousands of UUT are tested monthly, and it is not possible to keep track and resolve failures through a manual failure analysis process. The other issue is to categorize the failures so that the relevant department is provided with details so that they can find a solution. The automated process presented here is based on a learning dataset and the faults and repair information is collected and placed into the required category. This process will speed up the fault analysis process with minimum effort. An important aspect of this research is to make sure that the proposed system can be integrated with the existing systems used in the CEM industry. Some CEM companies use the ERP systems; therefore, an interface between the proposed and the ERP systems is proposed. This is a difficult task, as the ERP systems are developed using different technologies and a universal interface requires studying different ERP systems, their interfaces, and plugins. As part of this research, several commonly used ERP systems in the CEM industry are reviewed and an interface is created. Other CEM companies use standalone systems in their test departments, so it is also considered, and the proposed system can also be deployed to work as a standalone system.

The proposed system can also be used outside the CEM industry to validate experimental setups for testing electronic circuits and systems. The researchers can interface COTS test equipment and UUT hardware to connect to their circuits and systems. The universal test software can then be used to automatically control and evaluate their designs. The proposed system is validated in two stages. Firstly, the validation of the universal test hardware interface and universal test data collection sub-systems is done using two experimental test sites. These test sites are used for testing two different product types. This shows that the proposed system can be used to test a variety of CEPs. Secondly, the data analysis sub-system is validated by deploying the proposed system in a CEM environment where data are collected and analyzed, and results are presented in the form of graphs, KPIs, and machine-learning-based recommendations. The proposed system has been designed to cater to the above-mentioned issues using a user-friendly and low-cost approach.

5.2.2. Conclusion

A complete solution is provided in this research for CEP testing that includes a universal hardware interface and a software application based on machine-learning. The proposed system provides COTS test equipment control, test data collection, storage, analysis, indicates KPIs, and automatically generates recommendations. The automated system can be deployed as a standalone system as well as an alternative to ERP systems in the test departments of the CEM industry. Additionally, the proposed system can be used to connect any electronic product test site through a combination of universal hardware and machine-learning-based software subsystems. This approach saves cost and time as no additional hardware interface design and test software development is required for each product. Moreover, the system is user-friendly, flexible, and requires less training before implementation. The proposed system is validated through experimental test sites of two products, a multi-channel RF amplifier, and an analog voice recorder. However, the data processing sub-system is validated by deploying it in a mid-volume CEM environment, and results are presented in graphical form. Finally, a dataset is created, and faults are categorized for the machine-learning-based recommendations, and results are presented through examples to streamline the processes, improve the testing mechanism, and overcome the failures for good quality products.

A solution for the collection and analysis of manufacturing test data for electronic products is provided in this research work. The data collected is for low and mid-volume batch-size for a month, where is weekly analysis is normally done. The manufacturing test data is presented in tabular form along with the graphical analysis. The recommendations and trends shown by the graphs are used to improve the overall manufacturing process of the manufacturing company. From the analysis of four different products, it is concluded the company receives more quantity of complex digital products, but they require less testing time, while the quantity of analog products is low, but they consume more time for testing. In addition, the analog products can be tested by the middle-level skill set, while to test complex digital products low-level technical skill set is required under the supervision of a high-level skill set.

5.2.3. Future research direction

In the future, the dataset size in the database can be increased by adding more test site details that will be helpful for the machine-learning algorithm for further improvement in the decision. Similarly, based on a customer requirement, the approach can be implemented in high-volume manufacturing industries with more options.

In the future, a similar manufacturing data collection and analysis approach can be applied to high-volume manufacturing. The proposed data collection and analysis system can be used by both OEM and CEM companies.

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Appendix A

Curriculum vitae

Experience

Technical Lead — 2020 – date
Airbus Defense and Space, UK

Test System Development Manager — 2018 – 2019
NEMCO, UK

Production Engineer — 2016 – 2018
Global Invacom, UK

Team Lead and Principal Systems Engineer — 2005 – 2016
Cobham Technical Services, UK

Lecturer / Assistant Professor, Electronic Engineering Department — 2000–2005
Sir Syed University of Engineering & Technology, Pakistan

Design Engineer — 1999–2000
Polycom Inc (USA), Thailand

Lecturer, Electronic Engineering Department — 1998–1999
Sir Syed University of Engineering & Technology, Pakistan

Education

Doctor of Philosophy in Telecommunication Engineering — 2018–2021
University of Malaga, Málaga, Spain

Master of Science in Electronic Engineering (Major Telecommunication Engineering) — 2001 - 2003
Sir Syed University of Engineering & Technology, Karachi, Pakistan

Bachelor of Science in Electronic Engineering — 1994–1997
Sir Syed University of Engineering & Technology, Karachi, Pakistan

Training / certifications

Agile Project Management	2020
Machine Learning and Deep Learning	2020
Certified LabVIEW Associate Developer, UK	2014
LabVIEW Core III, UK	2014
Embedded Software Testing, UK	2014
National Instruments (NI) Vision Builder, UK	2014
IOSH 'Managing Safely', UK	2013
Received Personal Management Coaching, UK	2012
LabVIEW Core I and Core II, UK	2011
Report Writing Skills, UK	2006
'C' for Developers, UK	2006

Publications

[SIDD-2021a] A. Siddiqui, M. Y. I. Zia, and P. Otero, "A universal machine-learning-based automated testing system for consumer electronic products," *Electronics (Switzerland)*, vol. 10, no. 2, pp. 1–26, 2021.

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https://doi.org/10.1109/ACCESS.2021.3084545

[SIDD-2020a] A. Siddiqui, P. Otero, M. Y. I. Zia, and J. Poncela, "An Approach for Collection and Analysis of Manufacturing Test Sites Data for Electronic Products," *2020 Global Conference on Wireless and Optical Technologies, GCWOT 2020*, 2020.

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[SIDD-2020b] A. Siddiqui, M. Y. I. Zia, and P. Otero, "A Methodology to Design Test Sites for Electronic Products based on Figure-of-Merit," *2020 Global Conference on Wireless and Optical Technologies, GCWOT 2020*, 2020.

https://doi.org/10.1109/GCWOT49901.2020.9391598

Professional memberships

The Institute of Engineering and Technology, IET, UK	2007 - 2017
Pakistan Engineering Council, Life time member ELECTRO/6959	1999 - to date