An Intelligent Framework for Automatic Maintenance Plan Generation based-on Product Features Recognition

by

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ABSTRACT

Maintenance takes care of the health of equipment and/or mechanical system. Currently, maintenance is considered as one of the most labor-intensive and expert-centered manufacturing process, since disassembly/assembly procedures and its level of difficulty, makes it very difficult to automate the process. Therefore maintenance planning for naïve operators represents a difficult task, sometimes even for experienced operators. An extensive and structured maintenance knowledge is required to be able to plan for maintenance execution at large companies as the number of equipment and systems are high. Sometimes old equipment information is not available, therefore maintenance planning and execution only depends on experienced operators, which ultimately increases maintenance costs.

The development of a framework that is able to generate a maintenance procedure automatically by feature-based product recognition as well as providing intelligent guidance to operators represents a big step towards maintenance process automation. The proposed framework integrates different algorithms for knowledge-based decision, robust reverse engineering, CAD (computer-aided design) model features-recognition, product identification, and maintenance plan generation. A method recognizes the selected product from a CAD model by extracting geometrical information and then associating it to a knowledge-base to identify the product using a feature recognition algorithm. An adapted robust reverse engineering module is able to reconstruct the CAD model from points-cloud data generated through a laser scanner or Time-of-Flight (ToF) sensor. Once the product is identified based on features-recognition from the CAD model, it is automatically linked to a knowledge-base to provide existing maintenance procedure or generate a new

maintenance plan from similar a case-base. Corrective maintenance procedure currently depends on human knowledge and decision in order to locate the damaged component, repair it and reduce downtime. For these cases, a component level module is developed and integrated, which uses disassembly precedence graph and Failure Mode and Effect Analysis (FMEA) data from a specific product to generate the efficient (shortest) disassembly path for inspection and repair. The method supports naïve operators to efficiently execute disassembly tasks without relying on their expertise. The presented framework is a generic in nature, as it is designed to accommodate new modules to support other applications, for example remanufacturing planning.

PREFACE

This thesis is the original work by Pedro J. Yepez H. One conference paper and two journal papers related to this thesis have been submitted or published and are listed below. As such, the thesis is organized by following the paper-based thesis guideline.

1. **Pedro Yepez,** Basel Alsayyed, Rafiq Ahmad*, "Automated Maintenance Plan Generation Based On CAD Model Feature Recognition" *Procedia CIRP, 70, pp. 35-40, 2018.*
2. **Pedro Yepez,** Basel Alsayyed, Rafiq Ahmad*, "Intelligent Assisted Maintenance Plan generation for Corrective Maintenance" *Manufacturing Letters.* (Under review)
3. **Pedro Yepez,** Yufan Zheng, Zilu Liu, Basel Alsayyed, Rafiq Ahmad*, "An Automated Intelligent Feature-based Maintenance Plan Generation Method" *Journal of Computers in Industry.* (Under review)

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Pedro J. Yepez H.

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List of Abbreviations

CAD	Computer Aided Design
UDF	User Defined Feature
FMEA	Failure Mode and Effect Analysis
ToF	Time of Flight
MRO	Maintenance Repair and Overhaul
AFR	Automatic Features Recognition
CMMS	Computerized Maintenance Management Systems

Chapter 1 Introduction

In this chapter, background and motivations are introduced, followed by a brief discussion on the different research areas explored, which are related to the work presented. In addition, the objectives and the framework of the project is presented at the end of the chapter.

1.1. Background and Motivation

Maintenance is defined as *"all actions taken to retain equipment in serviceable condition or to restore it serviceability"* [1] and they are divided into three types: preventive, predictive and corrective. Preventive maintenance are those activities performed in order to keep equipment in good condition before failure occurs [1]; corrective maintenance are the actions taken to put equipment back into an operating condition [2]; predictive maintenance uses data to monitor the health of equipment or system to predict failure before it occurs to take the necessary actions [3]. The main goal for maintenance process is to extend a product or component's life through the application of each of the existing maintenance types in order to continue providing its designated functions. For this reason, there has been a constant need to improve this process, which is considered as complex, human-intensive and expert-centered. Physical inspections, preventive component replacement, repair, failure mode and effect analysis (FMEA) and Fault Tree Analysis (FTA) are some of the complex activities involved in maintenance process, which are mostly performed manually. Experienced personnel are required to conduct all these activities in order to achieve the desired maintenance results and at the same time be economically feasible. However, this is not always easy for naïve (entry-level) operators, as they lack the required capabilities, experience and structured knowledge. This means, there will be a training cost and an associated learning curve, which comes from the time taken to perform a maintenance task from the first time subsequently until an acceptable execution time is reached. The training time not only depends on every new operator skills but also on the training strategy used, the medium used to deliver the knowledge and the instructors experience. There is a need to improve or reinvent the existing maintenance processes to overcome these problems. Automation, as a general solution to increase process efficiency in industry, is one of the main focused area with great scientific contributions especially in implementing Industry 4.0 (4^{th} revolution in industry). Industry 4.0 represents an era where data exchange is possible between equipment and systems for re-configurability. For this reason, it is important to take maintenance information into digital data in order to automate maintenance process in an intelligent manner.

1.2. Automated Maintenance Processes

Automating a process is done by integrating equipment, software and information systems to achieve a common goal of increasing productivity and industrial safety [4]. Maintenance is the process that takes care of the health of mechanical equipment and/or mechanical systems. Even though multiple technologies are helping to measure and monitor the health of equipment or system, maintenance is still planned and executed by humans. Products can have multiple disassembly sequences for inspection, repair and/or component replacement. The level of difficulty of these tasks requires human knowledge and skills. For experienced operators, the process of identifying a product, planning and executing a maintenance procedure to it, is done relatively fast. Therefore, the experience in a maintenance operator determines the efficiency and accuracy when planning and executing a maintenance task. For entry-level operators, product ID numbers are used in order to look for its related maintenance procedure. For some cases, ID numbers are not available and the operator is expected to recognize the product and its information. In general, these procedures are stored in the form of a document. For the worst cases, this are still kept in a hardcopy as un-structured knowledge. This medium used to deliver the knowledge can be very difficult for some operators to follow and to execute a maintenance task. It also require more time for the operator to read it and truly understand it. For these reasons, many research areas have contributed to ease maintenance processes. The implementation of 3D MRO cards in a single file are existing methods, which includes all the technical information along with a 3D model with a simulation of the proper assembly-disassembly procedure to make it easy to the user to understand [5]. Computerized maintenance management systems (CMMS) are also used to reduce the cost by maintaining the knowledge in a company after experienced operators retires, which reduces the learning length for new operators [6]. This kind of contributions are good to improve manual maintenance methods.

The main maintenance activities that are moving towards automation are:

- Assembly / Disassembly
- Maintenance planning

1.2.1. Assembly / Disassembly

Part of maintenance execution is to disassemble the product for inspection and repair. The majority of the methods developed for assembly and disassembly processes are related manufacturing and End of Life (EOL) processes [7]. Initially it started to be improve at the design stage, where the easiness to disassemble a product was needed for remanufacturing purposes [8], [9]. The evaluation of the best sequence for disassembly at the design stage is very important since the optimal path can be obtained by simply using CAD models [10]. Contact matrix or contacting graph are used to stablish the relationship between components and later define the disassembly path [11], [12]. Each of the design for disassembly (DFD) methods were proposed to reduce the work and level of difficulty of this tasks as well as the cost associated at early stage of product life. The integration of a disassembly process into an assembly line is also considered to reduce costs by using the same resources for both processes and labor time saving [13].

Automated assembly/disassembly processes started by developing semi-automated methods, which consisted in the integration of electronic tools instead of manual tool for the disassembly process [14]. Robot-assisted disassembly can be difficult due to the actual condition of the product. This requires to have a user interaction in order to receive initial product condition information to plan the disassembly [15]. Human-Robot collaboration for assembly process is currently a feasible solution, which unfortunately need further investigation due to unstructured knowledge for the maintenance process. One of the sincere efforts in this direction is the disassembly automation process [16], where difficult tasks are assigned to the human operator, while the easy and repetitive tasks are assigned to the robot to improve the execution efficiency.

Automated disassembly sequence generation is the initial step to automate the entire maintenance process. It is necessary for a method to first identify the product, and at the same time be able to determine its components relationship. Automated Features-recognition (AFR) algorithms are developed and used for multiple applications in industry as good number of methods are being developed [17], [18], [19], [20]. This methods makes possible the identification of products, its components and their relationship by using feature detection on CAD models to generate a disassembly sequence considering the restrictions associated [21], [22], [23]. Therefore, autonomous identification and sequence generation for disassembly is necessary at maintenance planning stage in order to move towards automated maintenance execution.

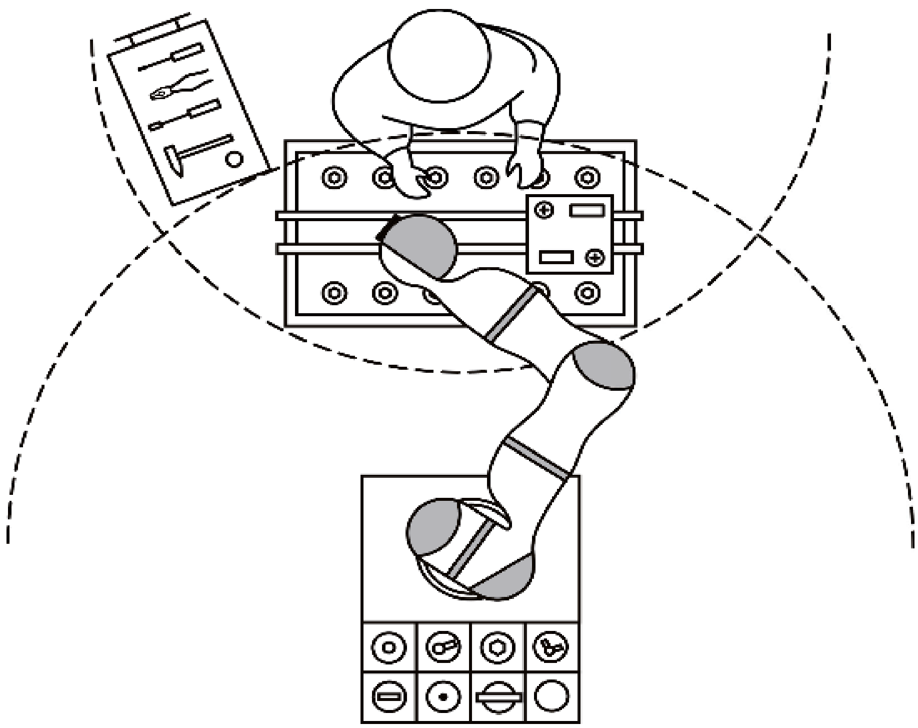


Figure 1.1, Human-Robot disassembly workstation concept. [16]

1.2.2. Maintenance Planning.

Maintenance planning is the primary step towards automated maintenance process as it determine the actions to be taken, how it is going to be performed and the required resources and time needed for its execution. The majority of the cases, production or manufacturing plants need to stop in order to provide maintenance to equipment and systems. This generates production downtime, hence downtime cost. For this reason, operations and maintenance processes in general need to be planned together [24]. The cost for maintenance can be significantly reduced if a maintenance plan is done properly, for example changing the maintenance strategy [25].

Many automated technologies are currently available to help maintenance planning. Automated data acquisition and data analysis are supporting maintenance decisions. These technologies autonomously acquire real-time health data from equipment and are able to determine the maintenance policy and spare parts needed. The use of product visual recognition to access maintenance information is also becoming important. 2D image recognition automatically link the product to its database where the pre-existing maintenance procedure is provided [26]. CMMS are tools used to schedule and plan maintenance process with the involvement of different departments. However, humans are expected to setup the link manually between the product and maintenance documents or input information to a CMMS, therefore expert-knowledge is required.

In order to have an autonomous maintenance planning, an intelligent framework is required to generate maintenance plan using a knowledge-base, learn from each case-base and to be able to extract information for the new unknown product. This way, human intervention to make maintenance decisions can be reduced, or eliminated in some cases.

1.3. Thesis scope

Maintenance process initiates when a maintenance work is required. Then maintenance planning is done to decide what kind of maintenance strategy, how to implement it and the time required for it. Later the Scheduling is done to plan production breakdown for maintenance. Ultimately, maintenance is executed and the data is collected for improvement analysis and implementation. The scope of this thesis automates maintenance planning and supports operators during maintenance execution (figure 1.2).

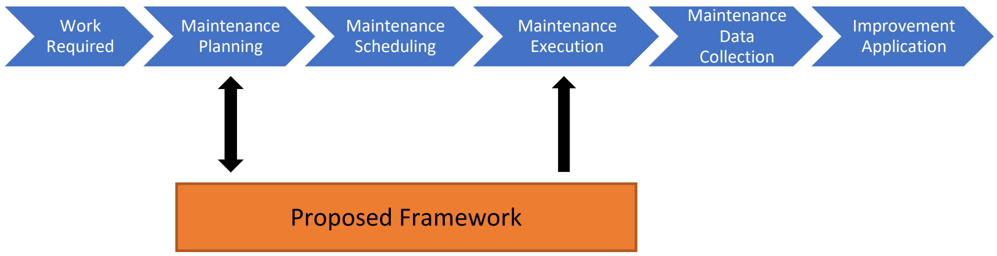


Figure 1.2, Thesis Scope.

1.4. Challenges for maintenance planning.

The current challenges to implement automated maintenance planning processes are:

- The current maintenance process knowledge is unstructured and complex.
- Some of the industrial products requires maintenance after many years of its deployment therefore; CAD models and maintenance procedures are not always available.
- Maintenance planning is one of the main labor-intensive and expensive task in the overall maintenance process.

1.5. Research objectives

The research objectives are derived from an extensive review of existing methodologies for maintenance planning process. The main research objective is:

"Develop an intelligent maintenance plan generation framework capable of automatically identifying real products from 3D points-cloud, CAD-models using features-recognition, and generate maintenance procedure at a product and component level, using case-base analysis, to assist naïve operators on efficiently executing maintenance tasks."

To achieve the main goal, the following **Objectives (Os)** are outlined.

O1. Develop an Automatic Features Recognition (AFR) method for product identification and a knowledge-based framework for maintenance plan generation at a product level.

O2. Develop and integrate an intelligent component-level module capable of providing and assisting operators with fast disassembly sequence (efficient path) for component inspection and repair.

O3. Integrate a reverse engineering module in order identify real products from the 3D points-cloud data obtained through a laser scanner or Time of Flight (ToF) camera.

The research have fulfilled the objective through the developed framework, which integrates different technologies and methodologies. Companies and researcher can use this framework as a tool to enhance their maintenance planning efficiency especially for naïve operators.

1.6. Organization of the thesis

This thesis comprises of five chapters. Chapter 1 presents a brief introduction to background and motivation, automated maintenance processes and existing technologies; maintenance automation challenges and describes the research objectives. Chapter 2 presents the article "Automated Maintenance Plan Generation Based on CAD Model Feature Recognition" [27] addressing the first research objectives. The article "Intelligent Assisted Maintenance Plan Generation for Corrective Maintenance" [28] in Chapter 3 fulfils objective number two. In Chapter 4, the article "An Automated Intelligent feature-based maintenance plan generation method" [29] integrates the achieved results from chapter 2 and 3 with a method that addresses objective number three. Finally, Chapter 5 presents the conclusion, research contribution, current limitations and future work is discussed. Figure 1.3 represents the layout of the thesis.

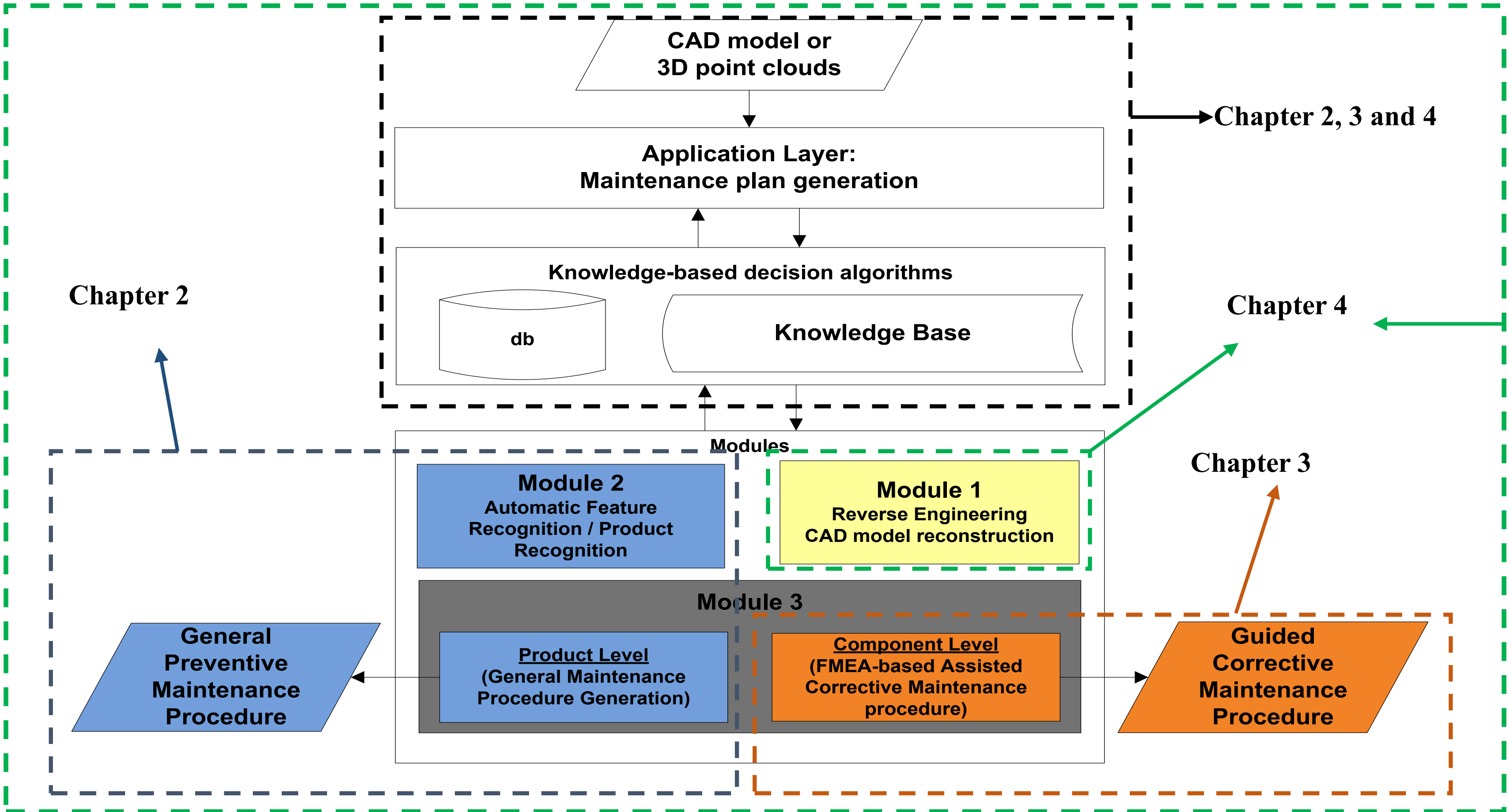


Figure 1.3, Thesis Structure.

Chapter 2 Automated Maintenance Plan Generation Based On CAD Model Feature Recognition

2.1. Introduction

Automation has been a very popular research and development area to improve production processes in order to increase productivity and improve safety. One of the most important areas for automation is maintenance, which is lately improved by introducing multiple techniques such as reliability analysis, condition based maintenance, new inspection methods, etc. However, in terms of task automation, it has not been fully developed due to its level of difficulty in knowledge extraction and utilization.

The goal of this paper is to take the first steps towards maintenance automation, by introducing a framework that is able to automatically identify a product by the detection of the user-defined features (UDF) in CAD models and establish a link of the product to a knowledge-base.

This paper begins with a literature review section with the recent progress in automatic feature recognition (AFR) systems, knowledge-base systems and maintenance automation. Then the concept of AFR for product identification and maintenance plan generation is introduced, followed by validation and results. Finally, a conclusion and future work is presented in the last section.

2.2. Literature review

A considerable number of research papers in the automation area provide good contributions to maintenance automation. Starting with AFR, there are numerous papers of different methods for different applications. Chow et al [30] present a feature detection in CAD models for automated simplification of the model to generate computer-aided engineering (CAE), that is done by identifying products based on its geometric characteristics (edges, faces, holes, etc.). Sunil et al [31] proposed an approach to recognize interacting features from Boundary Representation (B-rep) CAD models by developing a part face adjacency graph, and later decomposed into the feature face adjacency graph, based explicit feature graph and no-base explicit feature graph. By applying some rules to the last two graphs they were able to recognize the part. Niu et al [32] worked on finding CAD features using database optimization. All feature declarations are translated into Structure Query Language (SQL) to take advantage of the existing database engines that optimizes query plans and can be applied for feature recognition. Rahmani et al [33] uses a hybrid hint-based and graph based framework for the recognition of interacting milling features by obtaining the cavity feature volume (CFV) to compare it with the features previously defined. Babic et al [34] focused on finding solutions for AFR challenges such as extraction of geometric characteristics from CAD models, feature identification and finally feature pattern recognition. They discuss several feature recognition ruled-based methods highlighting their advantages and disadvantages. Other AFR methods were developed to help with manufacturing task descriptions for robotic welding, in this case Kuss et al [35]. Rules are used in their method to describe a specific weld feature, if the conditions of these features are not met, then it is not a weld feature. Among these methods, there are other methods using rules to automatically detect features [36], [37], however these methods have not been applied to maintenance applications.

Some AFR methods involve knowledge-base systems to help feature recognition processes. Wang et al [38] proposed a method capable of comparing translated STEP files into OWL (Ontology Web Language) with features defined also as OWL to identify a feature. Brousseau et al. [39] focused on creating a framework that is able to automate the knowledge acquisition that are useful to AFR developers. They created an algorithm to generate generic feature recognition rules without the limitation of the application domain. These methods only use a knowledge-base system to improve the AFR itself.

Other areas of applications of AFR, more specifically involving maintenance, have proposed some methods to contribute to the first steps towards maintenance automation. Akrout et al. [40], and Farnsworth et al. [41], worked on capturing maintenance tasks, decomposing them into multiple actions needed to complete the task and identify which action can be automated by evaluating the motion steps of each action. Cusano et al [26] proposed a method to develop a system capable of identifying mechanical aircraft components for what they call "smart maintenance". It works by taking a 2D image of the component using a tablet camera, and the image is matched with another actual image of the component stored in a database containing all the maintenance information about the component. However, the method results in many errors (missed detection) due to the low quality image or the inappropriate tilting angle of the camera. This work is limited to a 2D recognition, which might not work in all scenarios. The existing methods are also unable to generate the knowledge required to identify an adequate maintenance procedure.

There exists an important gap in the existing research for maintenance automation. An AFR methods combined with a knowledge-base system designed for maintenance processes has not been developed. In the next section, a framework capable of identifying a product in 3D and make a relationship of this product to a knowledge-base will be introduced.

2.3. Automated Feature Recognition and Maintenance Plan Generation.

This section will explain how the proposed AFR algorithm works to identify a model from a CAD file for maintenance plan generation. The system has been developed to use STEP CAD files as input for the algorithm since it is a standard format among different CAD softwares. The proposed method is divided in 3 sections as followed.

2.3.1. Automatic Geometric Feature Extraction.

The AFR framework is developed to extract all geometric features from a CAD model and send it to a database in order to have an easier access to all the information when searching for the UDF. As mention before, the algorithm is designed to use STEP files as input for product identification. However, the geometric feature extraction had been design to support solidworks Part files (SLDPRT), which will be used in future work described in the last section of this paper. For features recognition in maintenance automation, the proposed method is based on the following geometric data:

- The number of faces in the model.
- The number of edges in every face
- The normal vector and surface type of every face.
- The coordinates of every edge.

The edge coordinate information to be extracted will depend on the type of edge being evaluated. There are only two types of edges that are relevant for this method: circular edges and line segment edges. For circular edges, it extracts the center coordinates, the radius and the axis. For line segments, it extracts the start and the end point coordinates only.

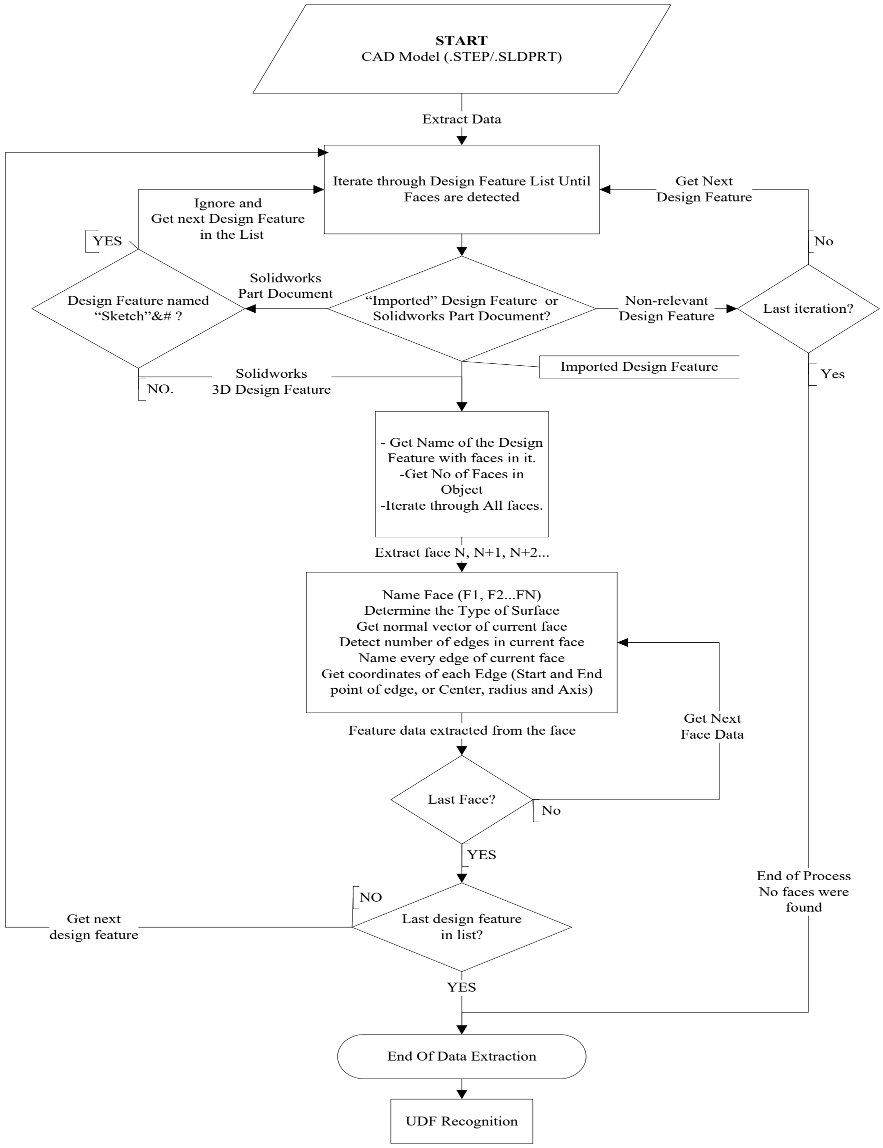


Figure 2.1, Geometric Feature Extraction algorithm

In Figure 2.1, the algorithm of the geometric feature extraction process is shown. The first step is to open the CAD model, STEP file or, in further development SLDPRT file. When the algorithm starts running, it iterates through each features in the feature manager design tree from solidworks software until all faces are detected. The algorithm will then check whether the design feature containing faces is imported (from STEP file), or created in solidworks (SLDPRT file). If the case is solidworks part file, then it checks if the design feature is a sketch object or 3D design feature object. All sketch objects are rejected since the only important features to detect faces come from 3D design features. This makes sure all faces of the model are covered. If the design feature is not relevant (no faces detected), then it moves to the next design feature. The process ends when all design features are covered. If the current design feature under evaluation is imported, then it proceeds to get the name of the design feature and the number of faces in it. At this point, an iteration through each face begins in order to rename each face, extract the type of surface, extract the normal vector, rename each of the edges belonging to the current face, and finally get all the coordinates of each edge. The next check makes sure all faces are covered. When the iteration reaches the last face, the algorithm moves to the next feature to cover all design features containing faces. Once all design features are covered, the process of extracting data ends. All relevant data extracted has been stored in a database and each record of this database consist of every edge coordinates and other relevant information of every face of the CAD model.

Having all the geometric information of the CAD model in a database makes it easier to look for UDF, as will be explained in the next section.

2.3.2. User Defined Feature Recognition

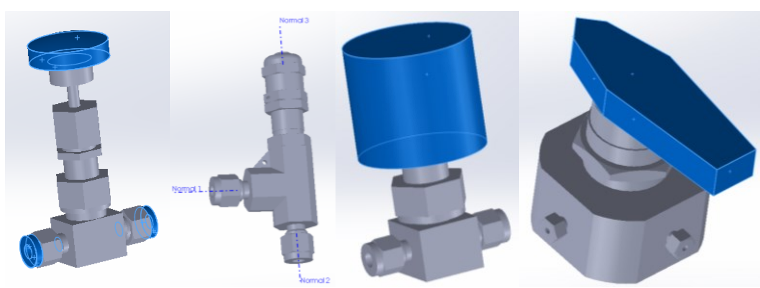
To develop a UDF recognition algorithm, it is necessary to define which features we want to identify in the CAD model. This research area falls in maintenance automation, and it has been decided to use nine (9) pneumatic valve models of five different functional classes as a proposed domain. Each pneumatic valve class has a different functionality and each valve model has its own specifications. Generally, the functional difference between one model to another is internal. A different classification of this domain was needed in order to identify external features from each CAD model. All valves were classified in four different levels. The first level of classification is the shape of the valves, which can be T-shape, X-shape or I-shape. The second level of classification is the type of handle. In this case, four different types were considered: no-handle, circular handle, pneumatic actuator and L-shape handle. The third level is the angle between the connections, and additionally for some valves is the number of connections or surface type on handle. Finally, the fourth level falls in the connection size, which represents a specific feature of each valve once the other levels had been identified.

This classification allows us to create UDF by establishing some rules. Since there are three different possible shapes, then a rule for each shape is created at first place. Similarly, for the other levels of classification, UDF and rules are developed as shown in Table 2.1.

User Defined Feature	Rules
T-Shape	-Three circular faces with only 1 edge shared by a cylindrical face must meet: 2 faces having a normal vector 180° to each other and the third face normal vector is 90° to the initial 2.
X-Shape	-Three or four circular faces with only 1 edge shared by a cylindrical face must meet: 3 or 4 faces having the same radius with normal vectors at least 90° to each other.
I-Shape	-There are only 2 circular faces with only 1 edge shared by a cylindrical face and must meet: the 2 faces must have a normal vector 180° to each other.
Circular Handle	-One of the circular faces with only 1 edge shared with a cylindrical face must meet: the edge must have an angle of 270° and the radius must be greater than the length of the cylinder. Spherical and Plane surface circular handle will be identify by its surface type data.
Pneumatic Actuator	-One of the circular faces with only 1 edge shared with a cylindrical face must meet: the edge must have an angle of 270° and the radius must be less than the length of the cylinder.
L-Shape Handle	-A plane face with seven edges must meet: All edges have an angle of 270° between that face and adjacent plane faces.

Table 2.1, User Defined Feature Rules

To illustrate some of the rules, in Figure 2.2(a) and 2.2(b) shows how the T-shape is detected in the geometric data of the model, where there are three circular single edge faces in the model and they share that edge with a cylindrical face (the two connection ports plus the circular handle). This model meets the rule of having 2 of the 3 faces with opposite normal vector (180° to each other) and one face with a normal vector 90° from the first 2 normal vectors. In Figure 2.2(c). The type of handle in Figure 2.2(a), the condition of having a single edge circle that meets the criteria of an angle of 270° between the faces and the radius value is greater than the length of the adjacent cylinder face is met. On the other hand, in Figure 2.2(c), the length of the adjacent cylindrical face is greater than the radius of the single edge circle face; therefore, the pneumatic actuator rule is met. In Figure 2.2(d), a plane face with seven edges meets the criteria of having all edges with an angle of 270° with respect to all its adjacent plane faces. The following section will describe the model recognition and the link to the knowledge base.



a b c d

Figure 2.2, (a) T-shape and circular handle (b) T-shape (normal vectors)

(c) Pneumatic actuator (d) L-shape handle [42]

2.3.3. Model Recognition and link to the knowledge-base.

The model recognition algorithm sequence is shown in Figure 2.3. First, it searches for a UDF shown in table 1 to determine the shape, followed by the type of handle, the angle between connections and connection diameters. A key ID needs to be created for the new model to be able to link it to the knowledge since this one is saved in the database based on the functional classification of the valves.

Each step in the UDF recognition process (Figure 2.3) contributes to the building of the key ID. Since there are four levels of classification, a key has the following nomenclature: Shape-Handle Type-Connection Angles-Connection Diameters. For example: a key ID = TNH180-1/16 refers to a valve with a T-shape (T), no handle (NH), an angle of 180° between connection ports (180) and a connection diameter of 1/16 inches.

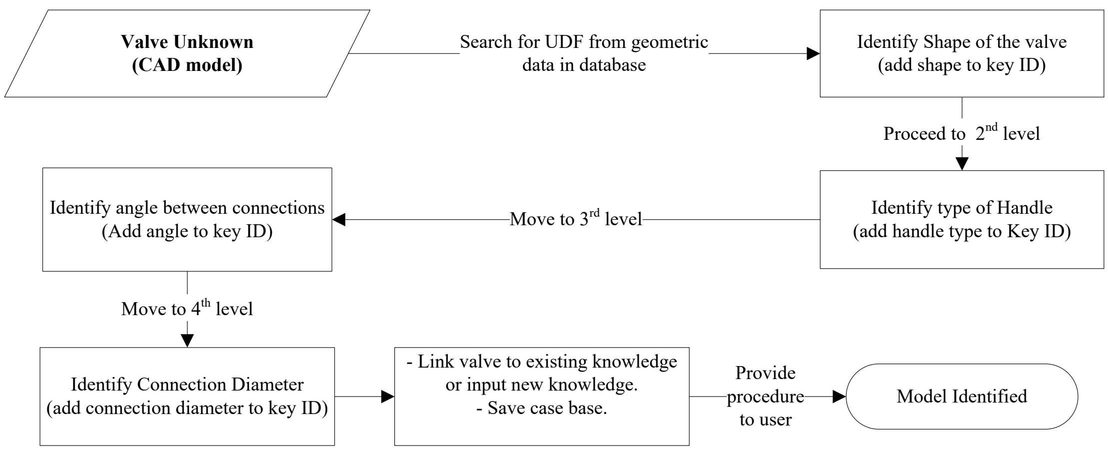


Figure 2.3, Model Recognition Process

The conclusion at the end of the process provides the user a new key ID for the valve identified, which makes possible the link between the geometrical classifications of valves to the original functional classification stored in the database. This is done as long as the knowledge for this model or class of valve exists. There are two other scenarios. In the first scenario, the maintenance procedure does not exist and the user is required to provide a new procedure. The second is where the system provides an existing maintenance procedure based on the features identified in the new model and its relationship with the existing valves. In this second scenario, the user is able to modify and fit the procedure for the new model if needed. Both cases are saved for future usage, and the new key ID generated is stored in the database and linked to each CAD model. To prove the proposed framework, all nine models were tested and results are discussed as detailed in the next section

2.4. Validation results and discussions.

The CAD models used and the maintenance procedure documents were taken from the valve company Swagelok online services [42]. Microsoft Access database, Visual Basic for application and Solidworks are the softwares used to perform the method validations.

An interface form is designed in order for the user to open the CAD model to be identify, extract all the geometric information and identify the product (Figure 2.4). First, the CAD model needs to be opened and subsequently the following information will be ask to the user: valve key ID, shape of the valve, class of the valve, type of handle and number of connections. Depending on the information of this initial check, four different cases may result. Case1, the user knows the valve, the valve key and knowledge exists in the database. This output then will only address this known case to the correspondent knowledge without having to extract geometric data and the need to recognize features. Case 2, the user does not know the valve, therefore the information requested is not provided. However, the valve key ID and knowledge of the model exists in the database. For this case, the system first detects the key ID linked to the CAD model stored in the database and then associate it to the maintenance procedure. In Case 3, the key ID is unknown, the user does not know the valve but the maintenance procedure knowledge exists in the database. In this scenario, the geometric data needs to be extracted, the model is identified by the method, and a new key is created. Then a link to the existing knowledge is established subjected to user revision and approval before the case is saved for future use. Finally, in case 4 the user does not know the valve, the key and the knowledge does not exist in the database. As in Case 3, the geometric data is extracted, model is identified, key ID is created and the maintenance procedure and all the relevant information is requested to create the knowledge and also save the case in database.

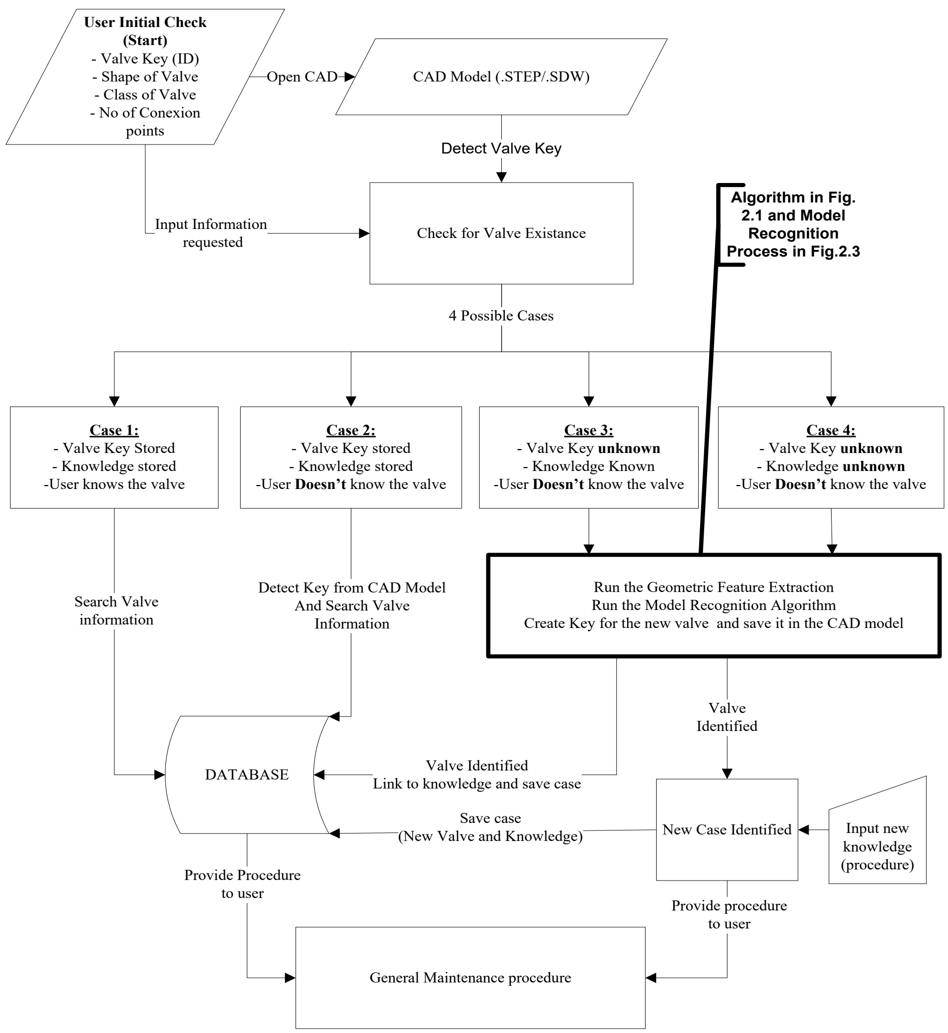


Figure 2.4 User Interface and how the system works.

During the validation tests, minor issues were solved, providing more flexibility to the algorithm. One of these issues was the existence circular plane faces in 2 CAD models that had 2 equal arcs as edges instead of 1 circular edge. This type of issue is common in STEP files. To address this problem, a circle detection loop was included in the model recognition algorithm. Since the current circular face contains two edges (edge1 and edge2) with a start and end points as coordinates, then check if the start point of edge1 coincides with the end point of the other edge2; likewise check if the end point of edge1 coincide with the start point of edge2. If the condition is met, then this two-edge circle plane face is equivalent to a single circular edge face. After adding this check in the algorithm, these two models were successfully recognized.

The Application Programming Interface (API) for Visual Basic and Solidworks, showed that the time taken for the data extraction of the CAD model is directly proportional to the number of faces and edges. For this reason, the model recognition algorithm is developed to search for UDF in the database. The usage of database along with the algorithm developed made it possible to establish a link of the recognized CAD model to an existing knowledge-base.

All proposed models were successfully identified, linked to a maintenance procedure and provided to the user. In cases where the maintenance procedure knowledge was not available, the generated existing procedure was provided to the user with the option to modify and save it as a new case. In Figure 2.5 and Figure 2.6, the results of existence of geometric information in the database and model identification are shown.

Figure 2.5 shows the result of trying to extract geometric data from a CAD model, which already exists in the database, by clicking “Extract Geometric Data”. In this case, the geometric data was previously extracted and saved in the databased, therefore a messaged was sent to the user notifying the existence of this data and asking to proceed to product identification.

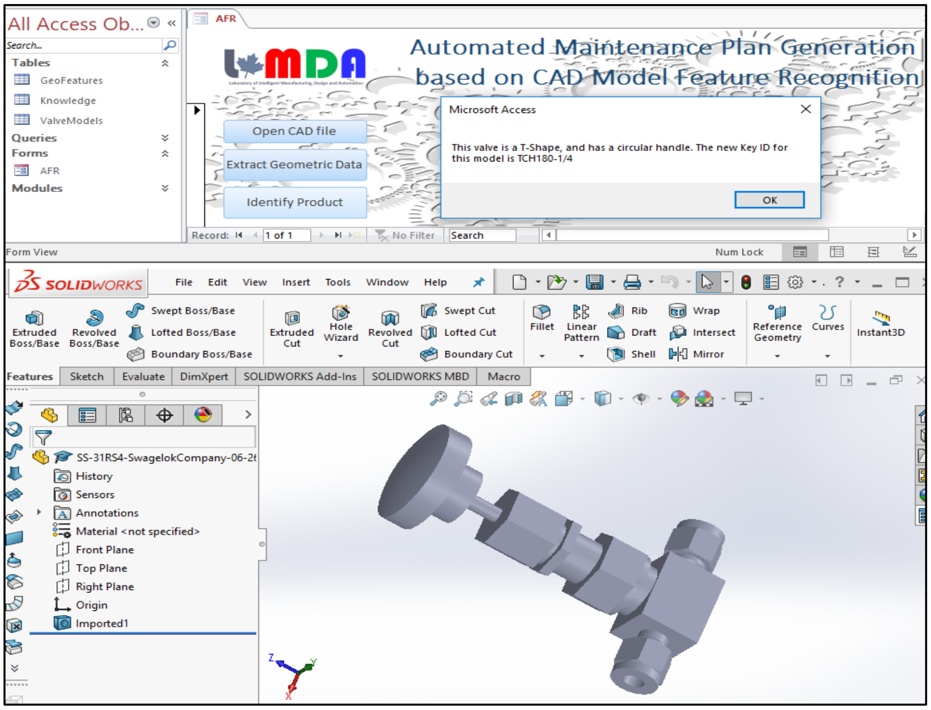


Figure 2.5, Geometric data exists in database. [42]

Figure 2.6 shows the result of starting the product recognition algorithm by clicking "Identify Product", where the user receives a message with the type of valve identified and its new generated key code, which represents the saved case.

The proposed method is able to extract the geometric data from a CAD model and store it in a database in a way that can be utilized by generating features and identifying a product by detecting the presence of those features. This product is then integrated to a knowledge-base for maintenance process applications. These results proved the existence of a productive research area that can highly contribute to maintenance automation and other similar processes.

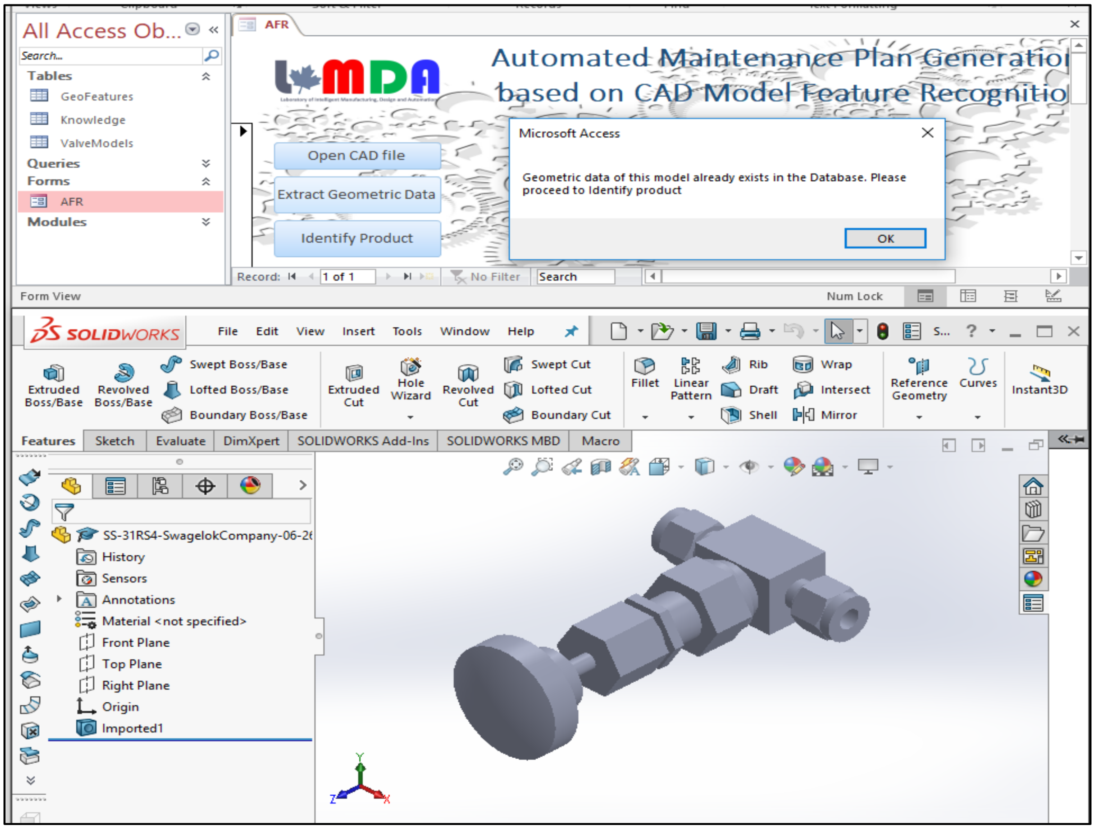


Figure 2.6, Model identification. [42]

2.5. Conclusion

The fact that the proposed method can identify a product by extracting its geometric features and their data from a CAD model and save it to a database, search for UDF to identify the product, then link it to a knowledge-base and save the case for future maintenance plan generation, is an important progress towards maintenance automation. Current work is focused to extend the domain of products and range of feature detection to make this system a powerful tool for new maintenance operators who may not have experience to quickly identify a product and perform the proper maintenance procedure. In future, the method presented will be extended to provide maintenance procedures at the component level, where an optimal sequence for disassembly and maintenance procedure will be generated for each component of the product.

Chapter 3 Intelligent Assisted Maintenance Plan Generation for Corrective Maintenance

3.1. Introduction

Remanufacturing and maintenance has been getting more attention from all industries since it helps to extend the life of equipment and/or mechanical system with the objective to minimize downtime, make production more efficient and reduce waste [43]. Certainly, in terms of efficiency, automation and knowledge-base systems has been two of the answers for many areas in industry [44], and it is now being applied to improve maintenance processes [27]. One of the most recent developments is by assisting non-experienced operators when executing a maintenance procedure step by step, since it has become a challenge for industries after hiring new employees. A new method is introduced in this paper to solve the old feasible strategy maintenance problem, in order to automatically guide a maintenance operator during a corrective maintenance execution.

First, the existing technologies and methodologies will be discussed in the next sections followed by the introduction of the proposed method "Intelligent Assisted Maintenance Plan". Next, a case study and discussions will be provided as well as the conclusion and future work in the last section.

3.2. Literature Review

This section is covered in three research areas. The first area is Augmented Reality (AR) and guided Maintenance, where the current approaches that supports maintenance processes are discussed. AR has been a powerful tool due to the combination of physical scenario with computer graphics in real time, which turns out to be a very easy way for operators to understand and follow procedures. Yew et al [45] proposed a method to integrate AR technology to teleoperation of maintenance robots. Another approach developed consist on a system that is able to generate all the disassembly sequences, find the optimal one and generate the animation for an AR interface which is used for maintenance or re-manufacturing purposes [46]. Others created a system for manufacturing companies and their clients to improve the existing maintenance support [47]. There are AR system to provide step by step guidance to technicians to conduct the maintenance procedure [48]. Osti et al [49] developed a similar system but also included the ability of the system to learn from the user new disassembly sequences. All of these methods are great contribution to assist maintenance operators; however, most of them depend on experienced personnel interaction and/or preprogramed procedures to assist entry-level operators.

The second research area falls into optimal disassembly. One method automatically generates precedence chart and performs line balancing for disassembly [50]. Other works are focused on generating disassembly sequences and getting the optimal sequence to reduce cost or reduce effort [51], [52]. Fang et al [53] use product dissassembleability as a metric to plan for remanufacturability. Disassembly methods are most of the time designed for end-of-life (EOL) processes, and the few methods supporting maintenance processes depend on human.

The last area to cover is FMEA. The majority of the work supports maintenance by identifying failure modes and measuring its associated risk priority number (RPN) [54], [55]. This information is also used to design a risk-based preventive maintenance plan for products [56]. Other methods uses historical data to build occurrence, detection and severity indices matrix [57]. Struss et al [58] in the other hand proposed an approach to automatically generate an FMEA for a braking system providing qualitative results. FMEA is also used as a tool to support optimal maintenance procedure and fault isolation on HVAC systems [59]. This last method, ranked RPN values are used in order to facilitate building managers for fault identification and isolation. However, this method do not autonomously use FMEA to improve maintenance processes.

To address some of the existing limitations, the proposed method is presented in the following section.

3.3. Proposed Method

An algorithm has been designed to automatically use FMEA data and a general disassembly sequence of a product to assist maintenance operators during corrective maintenance execution. The main goal is to guide the operator to reach to the components with the highest RPN value, where the chances of locating the failure are high. After the repair is completed, the case will be saved in the knowledge-base for future usage. The method will be described in the following sections.

3.3.1. Method Considerations and Limitations

- Only relevant information from the FMEA of the product is considered. These are: component number, component names, failure modes and ranked RPN values.
- A general sequence for disassembly of the product is known in the form of a precedence graph.
- Although the current implementation of the method only optimizes the path to reach the first and second most critical components, it is scalable to many levels.

3.3.2. Precedence Graph of Disassembly Sequence

The disassembly sequence used for this methodology is represented using precedence graph [60]. Each node represents a component to be disassembled. The arrows connecting the nodes, represents the order in which the product must be disassembled. Starting from the initial node N0 (assembled product), the first following node represents the first accessible component to be removed. Some products may have multiple nodes as first task to disassemble the product. For these cases, each arrow connected to a node will be called branch in this paper. The disassembly can continue through any of this braches.

3.3.3. Variable definitions

- i = branch number
- Bc = number of branches from component c.
- Ci = Accessible Component through ith branch.
- n = disassembly task number
- Rc = RPN rank number of component C.
- TC = Top critical component inspected (TC=True or False)
- T= total number of disassembly tasks of the product.
- r = target rank number.

3.3.4. Intelligent Assisted Maintenance Algorithm

The proposed algorithm (Figure 3.1) starts when the assisted corrective maintenance plan is requested from the user. The first check determines if the disassembly sequence have multiple branches from the initial node (N0) on the precedence graph. This is done to identify which branch has the shortest path in the graph to reach the most critical component (Rc=1). Once the ith branch is chosen, the component of this branch Ci is disassembled and n (No of disassembly tasks completed) is updated. The algorithm then checks if Rc = r (initially r=1), meaning if the current component disassembled is the top

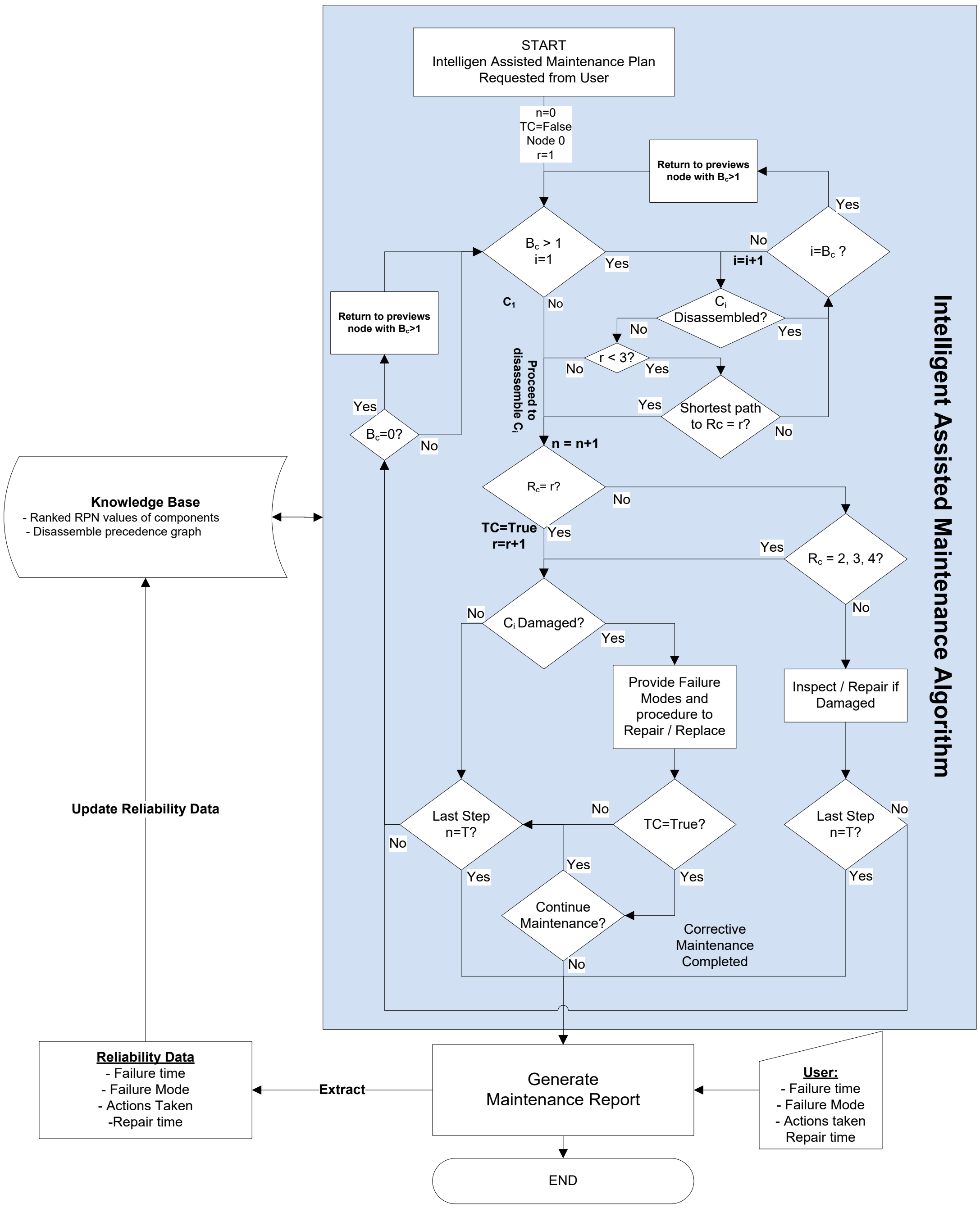


Figure 3.1, Intelligent Assisted Maintenance Algorithm

critical (TC). If this is the case, then "TC = True" and next the user inspect Ci for damaged. If Ci is not damaged, the algorithm verifies the existence of more components to disassemble on the precedence graph. If Ci is not the last component, n≠T, then it verifies the existence of subsequent components to disassemble on the precedence graph. If the case is Rc ≠r, then the following check is Rc = 2, 3 or 4, which are the second, third and fourth most critical components. If a component is damaged, then the failure modes and corrective actions are given to the user. Then if TC=true, the corrective

maintenance is completed. If resources are available to continue, the user can fully disassemble and service the product. Otherwise, the process ends, and a maintenance report is generated. The case where the current component Ci disassembled is not among the most critical components (Rc ≠ 1, 2, 3 or 4), then the user can inspect and repair and keep moving through the sequence. If n≠T, the algorithm will loop until all components had been disassembled and inspected, or until the top critical component had been inspected and at least one of the top

Component	RPN
C1 Plug	20
C2 Cap	28
C3 Lock nut	50
C4 Spring	**392**
C5 Spring Support	224
C6 Bonnet	200
C7 O-ring	343
C8 Quad seal	172
C9 Retainer	210
C10 Stem	196
C11 Seat Retainer	168
C12 O-ring	350
C13 Insert	220
C14 Body	54

Table 3.1. FMEA values for R3A pneumatic valve class.

Component	RPN	Rank
C4 Spring	**392**	**1**
C12 O-ring	350	2
C7 O-ring	343	3
C5 Spring Support	224	4
C13 Insert	220	5
C9 Retainer	210	6
C6 Bonnet	200	7
C10 Stem	196	8
C8 Quad seal	172	9
C11 Seat Retainer	168	10
C14 Body	54	11
C3 Lock nut	50	12
C2 Cap	28	13
C1 Plug	20	14

Table 3.2. RPN Rank from highest to lowest.

4 had been repaired. Maintenance report is generated by requesting the user to input failure time, failure mode, actions taken and repair time. The information is updated in the knowledge-base and the case is saved. An experiment is discussed in the following section.

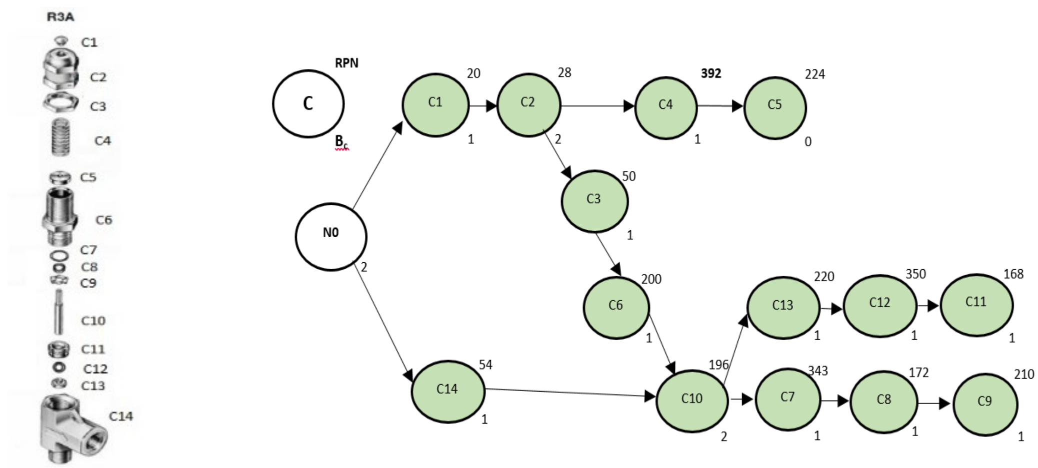


Figure 3.2, Disassembly Precedence Graph for R3A pneumatic valve and valve exploded view [42].

3.4. Case Study and Discussions

To prove the methodology, a pneumatic valve with a given FMEA values (Table 3.1 and 3.2) and precedence graph (Figure 3.2) is used. The values shown in Table 3.1 are calculated using a severity, occurrence and detectability tables from reference [61]. Since the purpose is to prove the method functionality, these values are calculated based on the assessed values. In Table 3.2, the highest RPN value belong to the spring, which is component number four (C4) in Figure 3.2.

First, the precedence graph has two initial branches Bc>1 at N0. The number of possible disassembly task for this model is T=14 and the initial disassembly task number n=0. Then the algorithm checks in the first branch, where i=1, if the component Ci is already disassembled. If not, then it verifies that the current target has not been inspected yet (r<3). Since ith branch has the shortest path to the component with Rc=1, the first component in the current branch is C1 (Plug) with RC1=14. Once disassembled, n=n+1 (n=1). Then, since $RC1 \neq 1$, the next step checks the value of RC1. The result leads process and requests the user to perform inspection and repair if necessary. The algorithm moves to the next component, since $n \neq T$. The current node is C1, which has a Bc=1, this means that there is one subsequent component. Since at C1 "Bc>1" is false, the only component to disassemble is Ci=1 = C2 and n is updated. Once gain C2 not on the top four critical components. The component is inspected/repaired and then moves to the following components. The current node C2 has BC>1, therefore for i=1, the component C1=C4 which is not disassembled yet, r<3 and it shows the (shortest or only) path to Rc=1. In this case, C4 has RC4 = 1, which means it is the top critical component (TC = True). Now that C4 is disassembled, r = r + 1 and now the 2nd most critical component will be the next target. Two scenarios will be simulated from this point. In the first scenario, the damaged component is C4. Therefore, the different failure modes and corrective actions are provided to user. Finally, since TC=true, the user can end the process or continue to inspect the remaining components. The corrective maintenance is completed and a report is generated. In the second scenario, the damaged component is C12. The iteration of the algorithm of this and all possible cases are shown in Table 3.3.

This case study shows that the proposed methodology can assist an operator step-by-step to inspect and repair the product during a corrective maintenance. For the first scenario, the damaged component had the highest RPN value and the method guided the user to repair it and then finish the procedure in three steps. The second scenario, even though the repaired component was not ranked first, the process was completed only because C4 was already inspected before. Otherwise, it would have guided the user to keep disassembling until C4 was inspected.

Iteration	Current Node	Bc	Ci Disassembled	Rc	n	r	TC	Possible Algorithm Outputs
1	N0	2	C1	14	1	1	FALSE	Continue
2	C1	1	C2	13	2	1	FALSE	Continue
3	C2	2	C4	**1**	3	2	TRUE	**Case 1 : Maintenance Completed or Continue**
4	C4	1	C5	4	4	2	TRUE	User can end or continue process
5	C5	0	---	---	4	2	TRUE	Return to previews node with Bi>1
6	C2	2	C3	12	5	2	TRUE	Continue
7	C3	1	C6	7	6	2	TRUE	Continue
8	C6	1	C10	8	7	2	TRUE	Continue
9	C10	2	C13	5	8	2	TRUE	Continue
10	C13	1	C12	2	9	3	TRUE	**Case 2: Maintenance Completed or Continue**
11	C12	1	C11	10	10	3	TRUE	Continue
12	C11	0	---	---	10	3	TRUE	Return to previews node with Bi>1
13	C10	2	C7	3	11	3	TRUE	Continue
14	C7	1	C8	9	12	3	TRUE	Continue
15	C8	1	C9	6	13	3	TRUE	Continue
16	C9	0	---	---	13	3	TRUE	Return to previews node with Bi>1
17	C10	2	---	---	13	3	TRUE	Both Bc disassembled. Return to previews node with Bc>1
18	No	2	C14	11	14	3	TRUE	n=T, therefore process is force to be end.

Table 3.3, Algorithm Iteration with all possible outputs.

3.5. Conclusion and Future Work

The proposed method presented is able to assist naive operators while conducting corrective maintenance tasks. Knowledge-based systems can use information from an FMEA report and automatically integrate it to a disassembly sequence. The user is guided to the most critical components of a given product and specific maintenance plan is generated. The current method reduces the time within the given general disassembly sequence. Therefore, future work will use optimization methods to use the shortest/fastest sequence, integrate it with FMEA data and generate a guided maintenance task to reduce repair time even further. The proposed solution is generally able to generate a feasible maintenance plan for any kind of part, which solve the old maintenance plan generation problem with novel precedence and FMEA method.

Chapter 4 An Automated intelligent Framework for Maintenance Plan Generation at a Product and Component level using 3D points-cloud.

4.1. Introduction

Maintenance is a labor-intensive industrial process that is still planed and performed manually. Currently, industries are aiming to automate as many industrial processes as possible to improve production and service, as well as industrial safety. For maintenance, the time taken to complete a preventive or corrective task depends on the operator's knowledge and experience. New maintenance operators are starting at industries with an entry-level experience every day. It takes time for them to be trained by experienced operators, which are not always available. Automating maintenance processes will help to solve these current problems. However, maintenance is one of the areas that represents a great challenge when it comes to automating the entire process. Planning and execution of maintenance tasks, for example, are still very difficult to automate with the existing technology due to the complexity and level of difficulty of disassembly tasks. On the other hand, knowledge-based decisions are needed for maintenance planning to reduce downtime, which is a task currently done by experienced professionals.

There are some research areas that are contributing to improve maintenance processes. Many researchers have worked to improve specific areas of maintenance processes to make it more intelligent, efficient, safe and easy to perform. Even though it will take a long time to fully automate all maintenance processes, the development of a method, which is capable of autonomously generating maintenance plans and assistance during the process, represents a big step forward. The framework integrates different methods to support maintenance process at the product and component levels. Existing methods are discussed in section two, followed by the proposed methodology. Three different case studies are discussed and finally the conclusion and future work.

4.2. Literature Review

Many existing research integrates new existing tools and technologies to support maintenance processes. 3D scanning and reverse engineering are important processes leading to robust maintenance, which are research areas that are growing very fast. Some methods use 3D scanning to reconstruct the CAD model [62], [63]. This has many advantages, one of them being able to 3D print the scanned product for different applications [64], [65]. Another popular application of this technology is the mapping and inspection of systems on “as is” conditions [66], [67], [68]. These represent powerful and efficient tools for industries to make maintenance decisions. A reverse engineering method is presented to compare the actual condition of a real product against the original design model to ultimately plan for remanufacturing [69], [44]. Based on the difference between the two models, 3D printing and machining tasks are provided to restore the real product features and integrity. Even though there are numerous methodologies and applications for reverse engineering contributions, it has not been integrated to identify products and support maintenance processes.

Automation has been the answer for many problems in industry for multiple processes [70] and for construction [71]. Maintenance planning scheduling for repair or inspections is one of the areas that is being automated to be able to complete daily activities with the available resources [72]. Likewise, other methods at design stage automate a system that predicts the time taken to perform maintenance tasks to a product [73], which is a very important consideration when designing a product and changes can be made before it is manufactured. An even more automated concept is discussed to use autonomous mobile robot to perform inspections in a production plant [74]. Even though these are good contributions to automate maintenance processes, there is a gap when it comes to automating maintenance intelligent planning and execution.

Knowledge-based systems has been applied on several methodologies supporting maintenance for many years. Some systems use Augmented Reality (AR) and/or Virtual Reality (VR) to provide support during maintenance operations [75]. Jo et al [76] proposed a framework with a knowledge-base to support aircraft maintenance operation by displaying information and procedures related to the context of the real time vision. Others developed a knowledge-based system to support maintenance operations at different organizations for building's maintenance [77]. Planning [43] and maintenance decision problems are also being modeled with knowledge-based systems. One method integrates optimization models to make maintenance decisions in a given region with multiple concrete bridges, where available resources, criticality and impact on users are factors that need to be considered [78]. However, there is no knowledge-based system designed to replace the need of experienced operators for maintenance plan generation and assistance for execution.

The closest work related to maintenance plan generation, which provided maintenance procedure using image recognition was presented by Cusano et al [26]. Other efforts developed a vision-based system to inspect and detect the absence or presence of fastening bolts to take maintenance actions [79]. Lately, laser scan technology had been used for the road marks inspection and maintenance decision [80]. While these methods are great contributions to maintenance automation, they are focused on very specific cases and limited to 2D image recognition. They are also only capable of providing pre-defined maintenance procedure.

In each of these areas, there are gaps that represent many opportunities to make great contribution for maintenance automation. First, reverse engineering methods have not been applied to maintenance planning and execution. Second, automation methods are still dependent on humans when supporting maintenance execution. Finally, knowledge-based systems for maintenance applications are still dependent on humans in order to save new knowledge. By developing an intelligent automated method combining different technologies to support maintenance processes, these problems can be covered. Our previews work presented a method of maintenance plan generation based on CAD model automatic feature recognition (AFR) [27]. The system is able to automatically identify a product from a CAD model and link it to a knowledge-base where the maintenance is provided or generated from existing procedures. However, more work is done to develop a new generic method, which integrates a module to recognize real products without the need of a CAD file and a component level critical path planning for efficient maintenance procedure. Product are recognized from CAD models built using points-cloud data. The component level maintenance plan generation is introduced, where intelligent assistance is provided to the user for optimal disassembly sequence for inspection and repair. This new integration driven by a knowledge-base can assist operators to automatically identify the product, have access to the right procedure and be assisted to execute tasks in a safe and efficient manner. The proposed method is explained in the following section.

4.3. Proposed Method: Feature-based Intelligent Maintenance Plan generation (FIMP)

The framework in Figure 4.1 is designed to support maintenance operators by automatically identifying real products, generate or provide the maintenance procedure and receive a step-by-step guidance (if required) for corrective maintenance procedure at the product and component level.

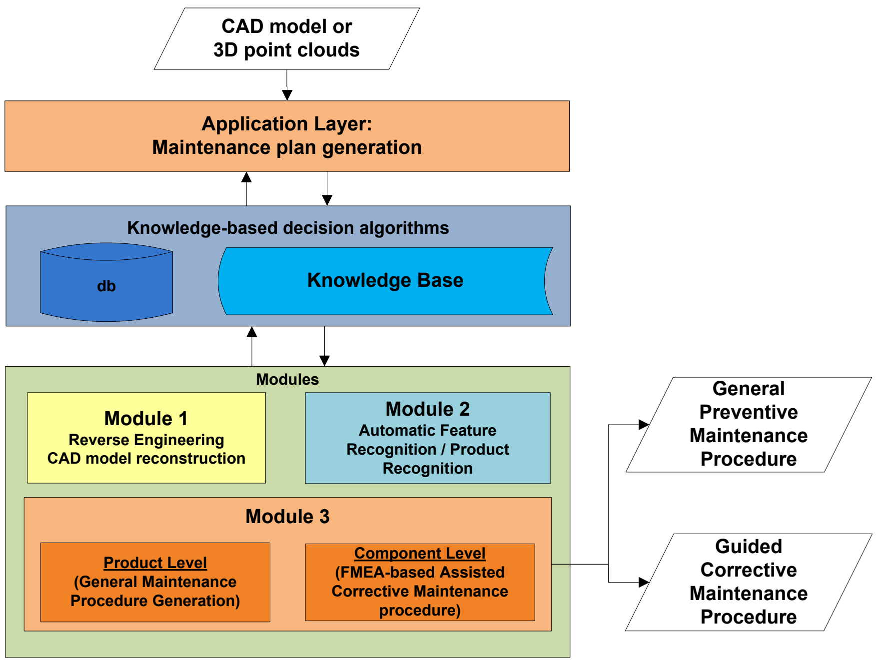


Figure 4.1, Feature-based Intelligent Maintenance Plan Generation Framework.

First, CAD models and 3D points-cloud data are supported as an input to the system. The developed application for maintenance plan generation is linked to the knowledge-based decision algorithms. Three different modules are available and driven by the knowledge-base when required. A reverse engineering module is able to reconstruct the CAD model when the real product is 3D scanned to generate points-cloud data. Another module is an algorithm proposed in our previews work [27], which automatically extract the geometric features of the model. Then, user defined features (UDF) are searched on the CAD model extracted data to identify the product. Once identified, the product is linked to the knowledge-base where the maintenance information is stored. If the knowledge does not exist for a particular model, the last module is able to generate a new procedure from existing knowledge at a product level. The component level maintenance plan generation is another contribution of this paper, which assist operators in performing corrective maintenance path towards the defective component. A step-by-step guidance is provided to reach components with higher chances of failing for inspection and repair. The method proposed is a generic knowledge-based framework, which can allow other applications and new modules integration. The description of the proposed three modules followed by the knowledge-based algorithms and developed application are presented below.

4.3.1. Module 1: Reverse Engineering

Commonly, a mechanical component behaves as a property of having a limited number of primitives (regular shape). In this paper, our study is focusing on these mechanical products and a comprehensive reverse engineering method for CAD model reconstruction is used. This method enables a fast and accurate reconstruction from raw points-cloud to a CAD. The flowchart of the proposed method is presented in Figure 4.2. First, 3D points-cloud is collected as an input through a laser or depth-cameras. Then, a random sample consensus (RANSAC)-based [81] algorithm is introduced to efficiently obtain parameters of primitives by surface fitting. Modelling operations are performed depending on the topological relations of primitive surfaces to construct CAD model. Finally, the CAD model is sent to the AFR module for product recognition. A brief description of the functionality of the RANSAC-based algorithm is as follow.

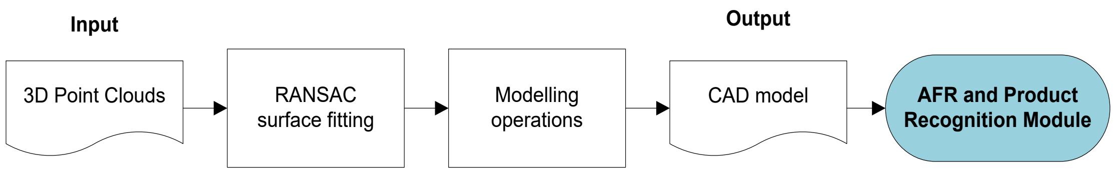


Figure 4.2, Flowchart of the proposed reverse engineering method.

4.3.1.1. RANSAC-based algorithm for surface fitting

The algorithm of RANSAC-based method is presented in Algorithm 1. Input $\boldsymbol{P} = \{\boldsymbol{p}_i \in \mathbb{R}^3, i = 1, \ldots, m\}$ is a set of points-cloud. Output BS (Best Shape parameters) is a set of parameters of the best primitive detected.

Algorithm 1: RANSAC

Input: $\boldsymbol{P}$: a set of point clouds
Output: $\boldsymbol{BS}$: best shape parameters
$\boldsymbol{V} \leftarrow \boldsymbol{0}$: number of valid points
repeat
  1. $\boldsymbol{CS}$=rand($\boldsymbol{P}$) ;
  2. B=sum(d(CS,P_i)$<T$)
  3. **if** $B > V$ **then**
    4. $V \leftarrow B$;
    5. $\boldsymbol{BS} \leftarrow \boldsymbol{CS}$;
  end
until *Reach the maximum iteration times*;
6. $\boldsymbol{VP} \leftarrow$ record($\boldsymbol{P}$)

- Step1: A minimal number of points, which enable to construct the target shape, are randomly selected from the points-cloud P to construct a candidate shape (CS).
- Step2: Algebraic distance (equation 1) is calculated as the distance from points-cloud to candidate shape. The number of valid points (B) which have distances less than the pre-defined threshold (T) are counted and stored.
- Step 3 to Step 6: The better candidate which has more valid points is accepted in iterations and the best candidate for target shape is kept until reaching the maximum iteration times. The parameters of best shape are stored in BS and the valid points (VP) for the best candidate are remained.

$$D = \sum_{k=1}^{m} F^2(\boldsymbol{p}_k) \quad (1)$$

Where F is left hand side of the implicit representation $F(\boldsymbol{p}) = 0$ of the fitting surface; $\boldsymbol{p}_k \in \boldsymbol{P}$.

4.3.1.2. CAD model Reconstruction.

The information of surfaces of the model is obtained after surface fitting. A model operation is required to build a solid model based on the information obtained. In conventional modelling method, CAD systems provides functions to create primitive solids such as block, cylinder, cone, sphere, torus and wedges. The parameters of surfaces obtained in surface fitting process are used for generating their corresponding primitive solids. Basic Boolean operations are performed to construct the final model based on their topology relations. In our study, a commercial CAD software is used for the modelling operation. For the purpose of this paper, any other reverse engineering commercial software can be adapted to the framework to achieve similar results.

4.3.2. Module 2: Automatic Feature Recognition and Product Identification

The product level method of this module is presented in the previous work [27]. The Automatic feature recognition is designed to extract all the geometric features from the CAD model (STEP file or Solidworks part file) to a database. After which, the fast searching engine of database allows the system to look for UDFs, which defines the product. A key number is generated based on the features found from the product, which ultimately constructs the link to the knowledge-base. Depending on the case, the system is capable of providing existing maintenance procedure for the identified product and able to create a new procedure in the next module using existing knowledge.

4.3.3. Module 3: Product Maintenance plan Generation

This module integrates a product level submodule and a component level submodule. The product level generates a maintenance procedure from existing knowledge. The system automatically finds a similar procedure that can be modified by the user and adapted for the new product. The case is saved and ready to be used in future. Geometric similarities of the product are the main criteria used to provide existing maintenance procedure.

The component level submodule integrated is designed to provide guidance to operators specifically when performing corrective maintenance procedures. The system consists of a step-by-step guidance to disassemble the product with real-time user interaction. A precedence graph for disassembly and the failure mode and effect analysis (FMEA) are used to generate an assisted disassembly sequence for maintenance. The risk priority number (RPN) from FMEA information is an indicator of the risk associated to the failure mode or component [61]. The higher the RPN number, the more critical the component will be. In a given product, each component RPN value is ranked from highest to lowest. This rank number is used as a criteria to follow when making disassembly sequence decisions within a given precedence graph for the disassembly of the product using knowledge-base. The user contribution relies on the physical disassembly and inspection of each component. Depending on the user observation and action taken in every step, the method will guide the user until at least the most critical components (1st and 2nd most critical) had been inspected and a faulty component had been repaired or replaced including the most critical one. The reason for using RPN value is that there is a higher chance to find faults in those components ranked first. If the FMEA information and disassembly precedence graph are not available in the knowledge-base, the system will provide information from the similar products. The user can then make the necessary modifications and ultimately save the case for the future usage. For the disassembly sequence precedence graph, the user is required to review and modify the suggested graph to match the information of the new product. This is done in a table where all components are listed along with the precedence relation to other components for disassembly. For FMEA data, each verified component name will be assigned to its corresponding RPN value and ultimately rank from the highest to the lowest.

4.3.4. Module 4: Knowledge-based decision algorithm

The knowledge-base is designed to drive all the modules and make the decisions needed depending on each possible case. It automatically provides maintenance procedure and also assistance to the operator for product identification. However, and more importantly, it is also capable of saving new generated knowledge automatically when a new case base is identified. The application layer allows a two-way interaction between the user and the knowledge-base. A security check is integrated to the system in order to avoid unauthorized personnel to compromise knowledge integrity. Only authorized personnel are able to make modifications. For these reasons, the proposed knowledge-based system gets better every time as used. The database in this layer is used to store all the extracted information and is available to the system every time, if needed.

4.3.5. Developed Application for Maintenance

The user interaction with the system is done through the developed application, which is directly connected to the knowledge-base. Pneumatic valves are used in this paper as the product to prove the proposed method. The user interaction flowchart with the four different cases can be seen in Figure 4.3. For the case where the product is unknown and the CAD model is available, the AFR and product recognition module is called. In the event of using the reverse engineering module to construct the CAD file, the user is required to verify and make product measurement corrections as the standard points-cloud data doesn't count with product information as an original CAD file. General product maintenance procedure is available to the user once the product is recognized. For maintenance procedure at a component level, the application shows the components and sequence to disassemble the product towards the most critical component (ranked 1st). Every disassembly direction is provided after the user inspects each disassembled

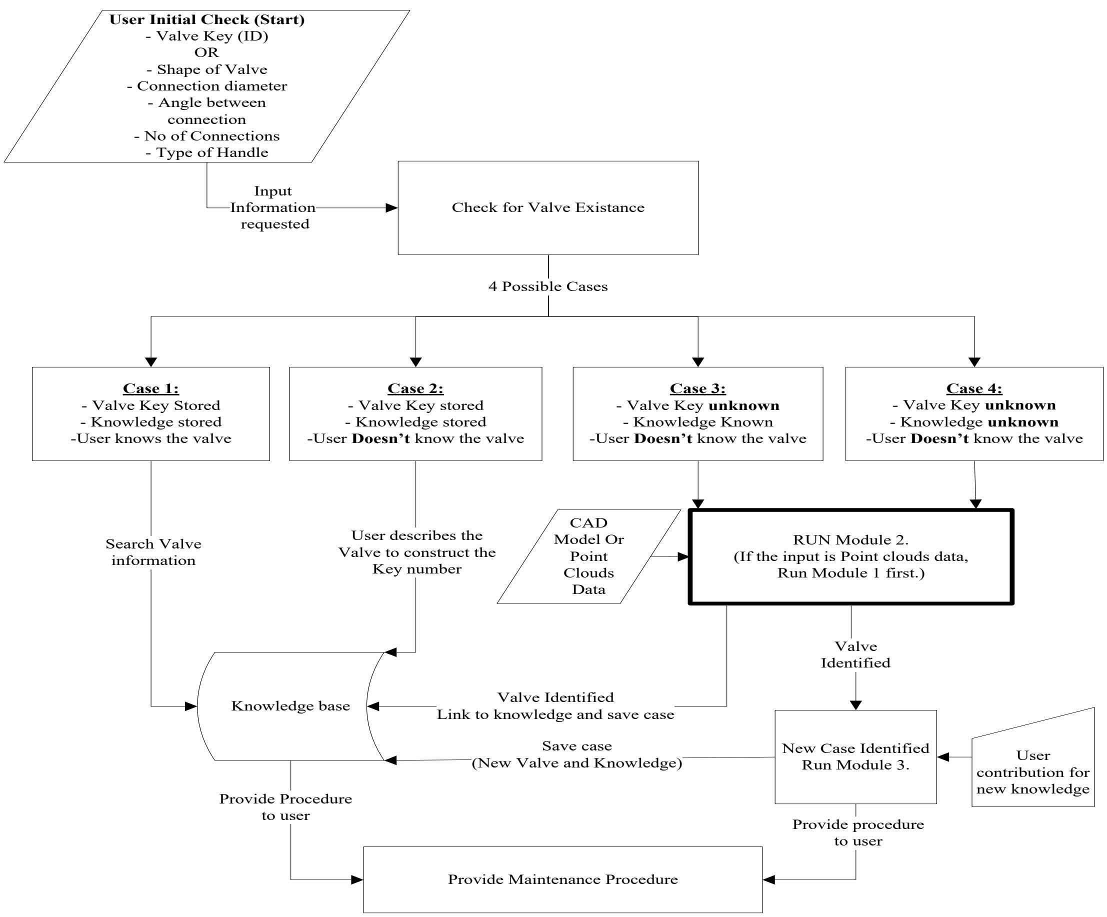


Figure 4.3, Feature-based intelligent maintenance plan generation flowchart.

component. Once the procedure is completed, repair time, failure mode, failure time and failed component are extracted and saved in the knowledge-base.

4.4. Case Study and Discussions

To validate the proposed methodology, commercial pneumatic valves information, CAD models and maintenance procedures were used [42]. To run the experiments, commercial CAD software (Solidworks), database software Microsoft Access (MSA) and Visual Basic for Applications (VBA) were used. The framework is tested using a standard Windows 10 computer with Intel Core i5-6400 CPU and 12 GB RAM. The graphical user interface (GUI) for the developed application "intelligent maintenance plan generation system" is described next.

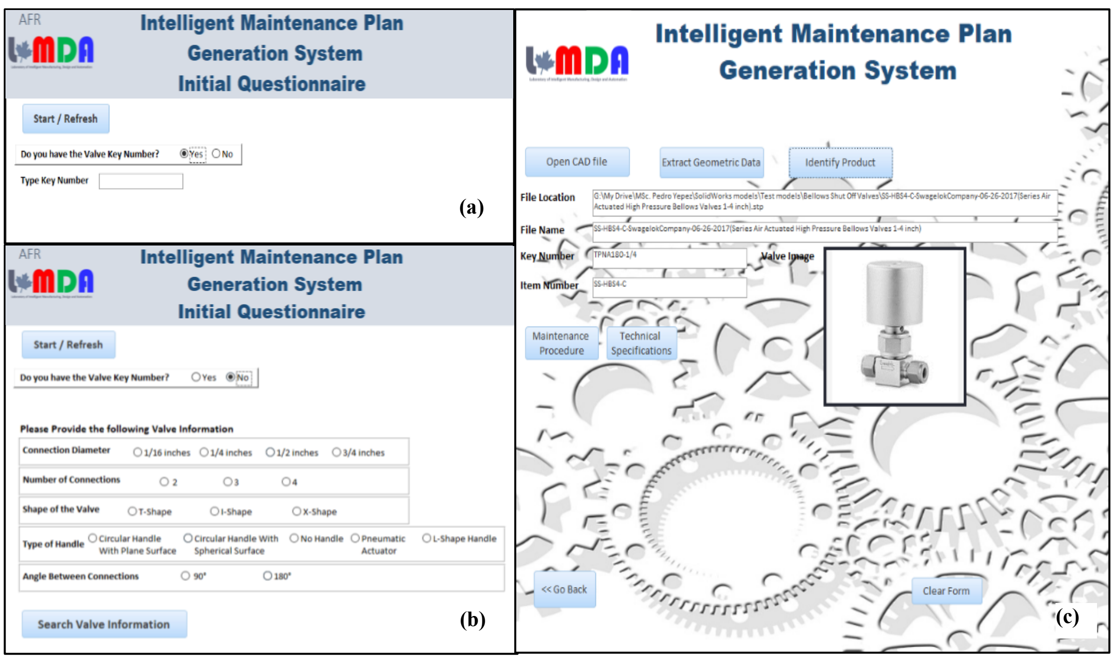


Figure 4.4, Graphical User Interface: a) Initial Questionnaire: Key number known b) Initial Questionnaire: Key number unknown c) IMPGS form.

4.4.1. Developed Application for Intelligent Maintenance Plan Generation (GUI)

The Application for user interface consist of two main MSA forms: "The initial Questionnaire" form and the "Intelligent Maintenance Plan Generation System" (IMPGS) form (Figure 4.4). The first form consists in set of option buttons where the user is expected to answer all the questions made to address the different possible cases. Figure 4.4a represents the case where the user knows the key number of the product. Figure 4.4b represents the case where the user does not know the key number and multiple-choice questionnaire is provided to identify the product to describe it. These are: shape, number of connections, connection diameter, type of handle and angle between connections.

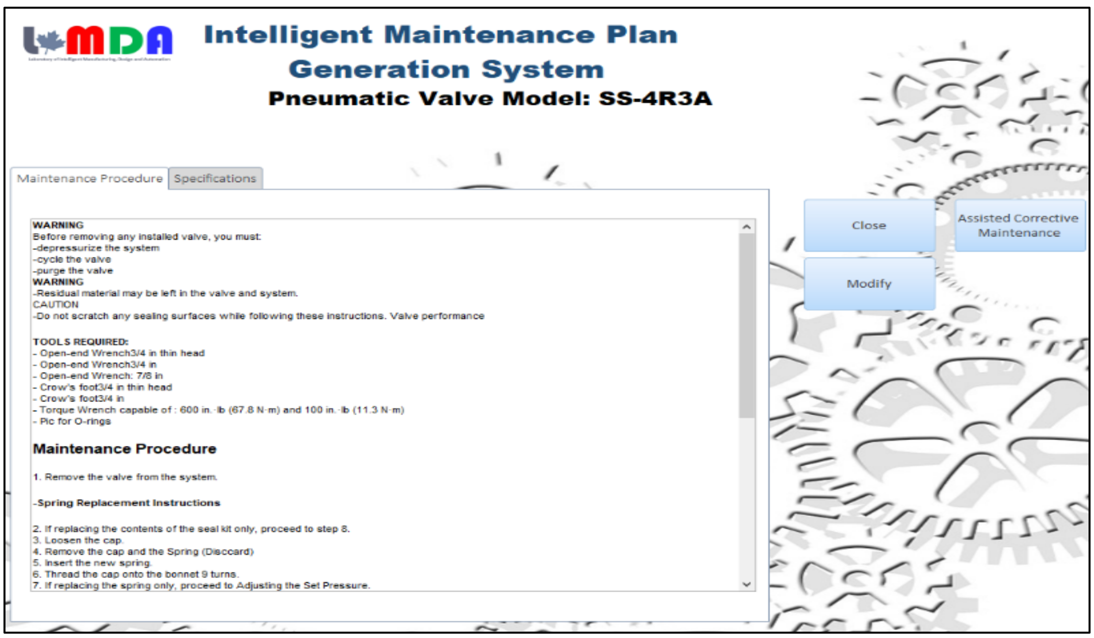


Figure 4.5, Product Maintenance Procedure and Technical Specifications view.

The second form appears to the user once the case at the initial questionnaire is detected. If the product identification is required, a button to open the CAD file is shown, which is linked to the CAD software as it automatically opens the exploration window to find and select the CAD model to be identified. Once this step is completed, the "Extract Geometric

Data" button appears and upon clicking, the required information data is downloaded to the database. Finally, a third button, "Identify Product", appears to initiate the product identification. File location address, file name, key number and manufacturer's item number can be displayed once the product is identified. In addition, "Maintenance Procedure" button, "Technical Specifications" button and product image are shown to the user. These same options are shown to the user if, at the initial check, the case exists in the knowledge-base. Each maintenance procedure is presented in a template form for each product (Figure 4.5). Every template has two tabs: Maintenance Procedure and Product Specifications. This information can be modified. However as mentioned before, it is limited to authorized users. There is also a "Corrective Maintenance Assistance" feature, which will trigger the component level submodule to assist operators. For cases where the procedure does not exist in the knowledge-base, the system will provide similar procedures in an editable form subjected to user modifications. Finally, the buttons to save all the modifications done to existing procedure and save new cases are displayed.

Case #	**1**	**2**	**3**
Valve Class	3-4 Way Ball Valves	Relief Valves	Bellows Sealed Valves
Class usage	Meet your system needs with the broad range of Swagelok ball valves made in a variety of styles, pressure ratings, materials, and end connection choices, configurable for a variety of applications.	Obtain over-pressure protection for a variety of applications with Swagelok proportional relief valves with easy external set pressure adjustments.	Isolate system fluids and achieve reliable, leak-tight performance with Swagelok bellows valves which use a packless design and a welded seal. Bellows valves are ideal for applications where the seal to atmosphere is critical
Series	4 way - 40 Series	R3A (Proportional pressure relief valves)	BN4 (bellows sealed)
Connection Size	1/16 inch	1/4 inch	1/4 inch
Image			

Table 4.1, Pneumatic valves for case studies [42].

4.4.2. Case Studies

In order to validate the method and system, few commercial pneumatic valves have been selected for product recognition and intelligent maintenance generation. Three pneumatic valves in Table 4.1 were selected to demonstrate three different cases.

4.4.2.1. Case 1: Product does not exist in the system.

The product is unknown to the user and to the system. The CAD model is available, but the general preventive maintenance procedure exists in the knowledge-base as well as the disassembly sequence and FMEA information. The first step for the user is to fill the questionnaire form (Figure 4.4b), where the key number or a geometric description is required. In this case, the user describes the pneumatic valve as followed: 1/16 inch connection, 4 connections, X-shape, L-shape handle and 90° between connections. Since

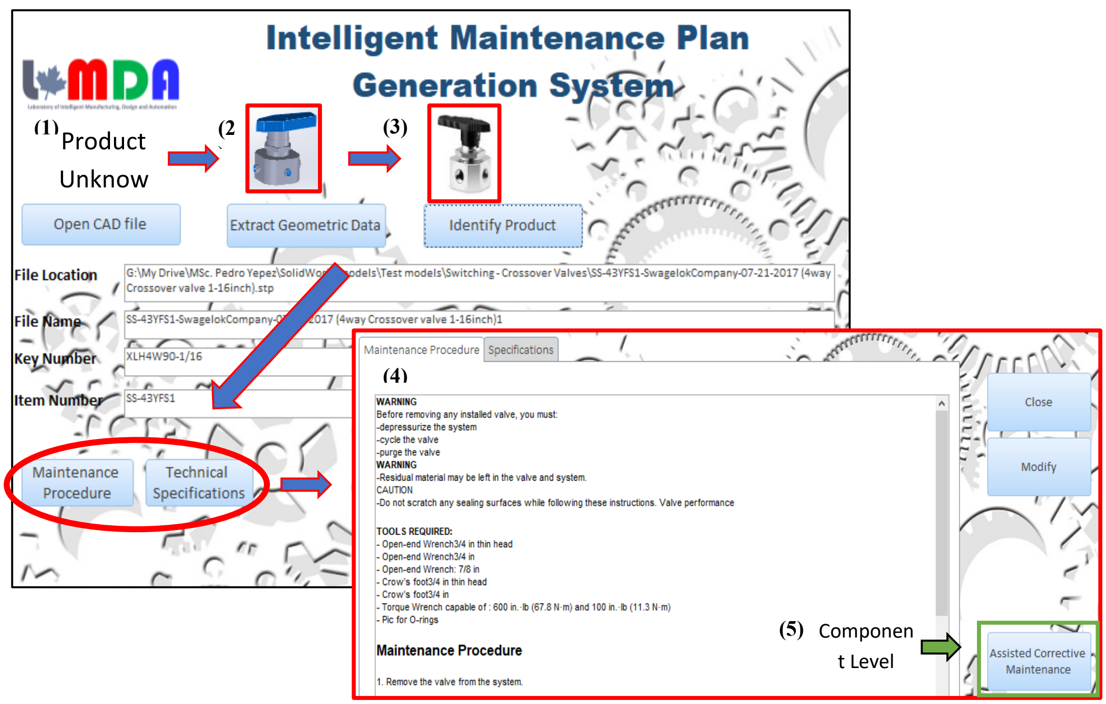


Figure 4.6, Case study 1: (1) Open CAD file (2) Geometric feature extraction (3) AFR and product identification (4) Maintenance procedure and specifications provided to user (5) Maintenance assistance at component level.

the product is also unknown to the system, a CAD model is requested to identify it. In Figure 4.6 step (1), the CAD model is opened in a STEP file which is a standard commercial shareable format. In step (2), geometric features are extracted to the databased and finally the product identification button searches for UDF, which defines the valve and creates a key number in step (3). The recognized product is linked to the knowledge-base through the generated key number. Now the Maintenance procedure and technical specifications buttons are available to the user along with a visual image of the product in the IMPGS form. On click, the maintenance procedure is shown to the user in Figure 4.6 step (4). The Assisted Corrective Maintenance provides guidance to the user in a case where the product has failed and assistance to find the fault component is needed as shown in step (5). The integrated disassembly sequence in the form of precedence graph with the FMEA RPN ranked values will take the user to the fastest path to reach the most critical components, where the chances of finding the failure are higher. As explained in section 3, the assistance terminates once the fault component has been found, repaired/replace and at least the most critical component had been inspected. However, the user has the option to continue disassemble the whole product for complete inspection if resources are available (Figure 4.9).

4.4.2.2. Case 2: Product and knowledge unknown to the system.

CAD model again is available, but the product is unknown to the user and does not exist in the knowledge-base. The system in this scenario provides similar procedure to build a new case and save it for future usage. First the user will again describe the product geometrically in the questionnaire form (Figure 4.4b). Since the product is unknown, the geometric feature extraction and the product identification is done to generate a key number as seen in figure 7. The system finds that the key number does not exist in the knowledge-base in step (2), therefore a similar procedure will be provided to the user in steps (4) and (5). Geometrical similarities for existing products in the knowledge-base are searched to provide similar maintenance procedure. The existing procedure belongs to product named "2B". As seen in Table 4.2, both products have the same shape: no-handle feature, same number of connections and same angle between connections. The user has the option to modify the suggested maintenance procedure and specifications to fit the new product.

At the component level, the user will have access to the suggested procedure. Since the corrective maintenance is automatically provided from the FMEA and disassembly sequence precedence graph, the user can check and modify each information of the suggested product (Figure 4.8 and Table 4.3). Once all this process is done by the user, the maintenance procedure form for the new product can now be saved as a new case (Figure

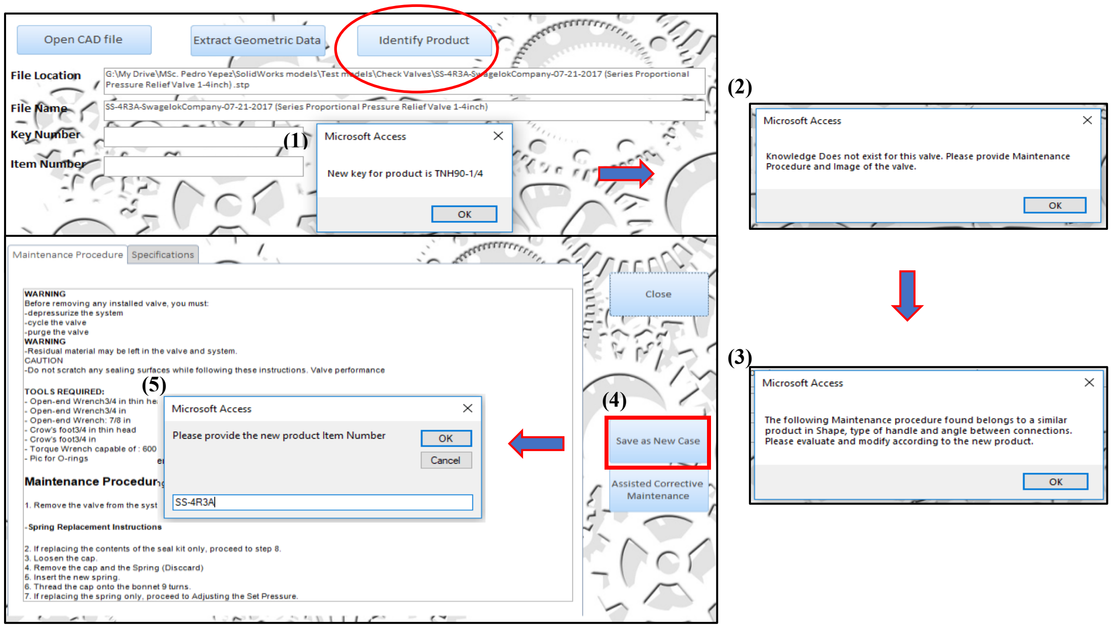


Figure 4.7, Case study 2: (1) Key generated for new product (2) Knowledge does not exist (3) Similar maintenance procedure will be provided (4) User can modify the similar procedure and save as new case (5) Confirm the new product item number after new case is extracted.

4.7, steps 4 and 5). At the end of the process, in future cases the product is known and the maintenance procedure and specifications can be provided to the user without having to identify the product again or looking for similar products.

Product	2	2B
Series	R3A (Proportional pressure relief valves)	R4 (proportional pressure relief valves).
Connection Size	1/4 inch	1/2 inch
Description	New identified product	Existing product and procedure
Image		

Table 4.2, New product vs existing product. [42]

R4 Series	
Component	Precedence
C1	---
C2	C1
C3	C2
C4	C2
C5	C4
C6	C3
C7	C8
C8	C9
C9	C10
C10	C6 and C11
C11	---

Table 4.3, Existing Precedence table for disassembly of product 2B.

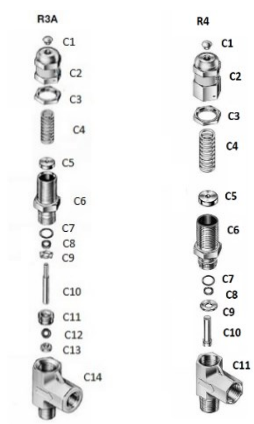


Figure 4.8, Exploded view of the new valve (R3A series) vs existing valve (R4 series) [42]

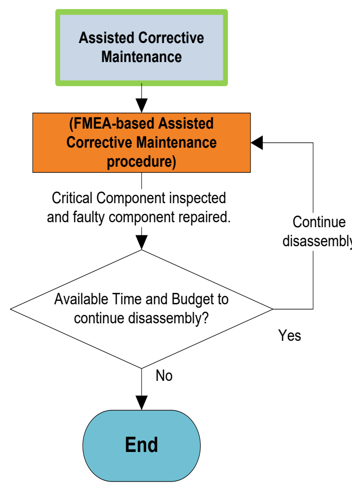


Figure 4.9, Corrective maintenance flowchart.

4.4.2.3. Case 3: CAD model unavailable.

For the third case, the CAD model is not available, therefore reverse engineering module is used to reconstruct the CAD model and identify the product. The maintenance procedure and technical specifications exists in the knowledge-base. Once the user has been prompted that the product is unknown to the system and the CAD model is not available, it is required

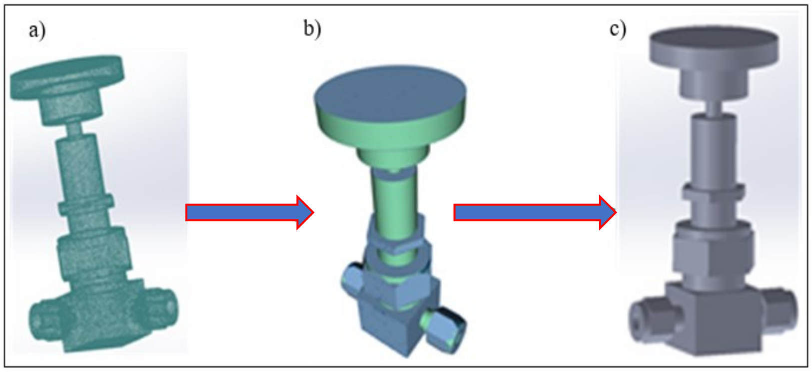


Figure 4.10, Reverse engineering process: a) point clouds data, b) surface fitting, c) reconstructed CAD model (STEP) file). [42]

to 3D scan the product. This will generate the raw points-cloud of the product. The RANSAC-based algorithm in module 1 performs the surface fitting (figure 10b) to ultimately reconstruct the CAD model. The product in the three stages of the reverse engineering process is shown in Figure 4.10 (a, b, and c). The final CAD model is then opened through the system to extract the geometric features and identify the product. The user is asked to declare that the product is 3D scanned, and then make corrections to the connection diameter of the valve. A new key number is generated and the knowledge-based decision algorithms provide the existing product information to the user. The sequence can be seen in Figure 4.11 (steps 1 to 5).

4.4.3. Discussion

For the three different cases, the system is able to identify the product and link it to the knowledge-base. It is also able to generate new cases from existing knowledge, which makes it able to learn and get better in time. The ability to provide maintenance procedure from 3D points-cloud improves the flexibility of the system, which becomes very useful for the scientific community and practical purposes, where CAD models are not always available. On the other hand, the system proves that it can either provide general product level maintenance procedure as well as component level maintenance procedure. This particular case solves the repair time problem when having new operators executing these tasks. At the same time, operators are in a way being trained by following the provided procedures, which will later result in efficiency improvement. The system is designed in a way that can support other applications in the future. New modules can be integrate to and used to support the new application along with existing modules and knowledge-base.

The developed application is limited to work with a sample of pneumatic valves. New UDF needs to be defined in module 1 in order to support other products. On the other hand, the

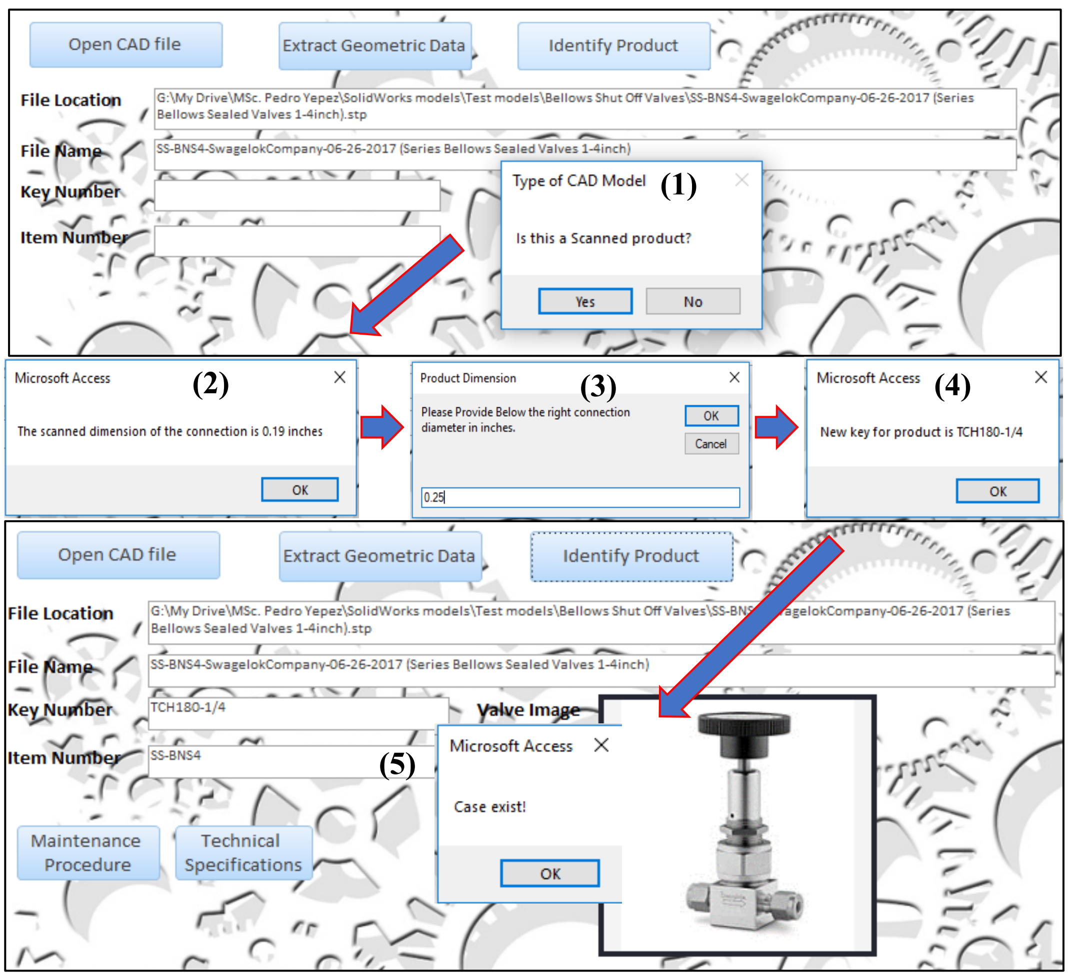


Figure 4.11, Case study 3: (1) Type of input file (2) Scanned dimension (3) Correction of connection diameter (4) Key for identified product (5) Existing maintenance procedure provided for the identified product.

assisted corrective maintenance procedure can only achieve shortest path within the existing disassembly precedence graph. Further work can integrate existing models to actually generate an optimal sequence considering cost and time for disassembly. The reverse engineering module is able to recognize the UDF and define the product. However, since the points-cloud data is not as precise as a CAD model in terms of dimensions, the user is required to provide the exact connection size when the product is being identified. This requested input ultimately makes the link to the knowledge-base possible.

4.5. Conclusions

The developed method proves that it can become a powerful tool for improving and automating the existing maintenance processes. In general, it integrates different technologies such as RANSAC-based reverse engineering method that in the past were not applied to support automated maintenance planning and execution. More specifically, it helps to solve maintenance execution time and knowledge needed, when non-experienced operators are recruited. The proposed method can assist them by automatically providing the proper procedure and a step-by-step guidance for corrective maintenance if needed. It works by simply recognizing a product from a CAD model. For those cases where the CAD model is not available, the system is able to process 3D points-cloud to reconstruct a CAD model and ultimately identify the product to generate a maintenance plan. This methodology is validated to support solutions in three different scenarios: unknown products to the user and system, unknown maintenance procedures and unavailable CAD files.

Future work will focus on integrating more technology and methodologies to support maintenance processes such as augmented reality, virtual reality and optimization models for fast product disassembly. In addition, further complex applications can be developed and validated through the framework to support its knowledge-base.

Chapter 5 Conclusion

5.1. General conclusion

The intelligent maintenance plan generation framework represents a promising solution for current maintenance processes at industries and a significant contribution for the research community working towards the automation of this process. The literature review allowed finding the existing gaps on methods that can support maintenance processes with great potential. The framework is able to integrate different technologies and methods that are useful for the implementation of an intelligent maintenance plan generation system. The first step is the identification of the product at the abstract level for maintenance application. The developed algorithm is able to extract and store new geometrical information from a new product. This information is stored in a database for easy access when needed. A second algorithm is able to search for UDF, which ultimately describes a specific product. The UDF are based on a set of rules that describes the product by its geometrical shapes and dimensions. At the same time the algorithm creates a unique key number that ultimately stablish the link between the product and the knowledge-base. The framework is designed to reuse existing knowledge for similar products. It is able to work in different scenarios that goes from the existence of a product and its information in the knowledge-base, through the to identification of new products and generation of knowledge from existing products. The integration of a component level module provides the capability to generate corrective maintenance procedures and efficient path to the faulty component for inspection and repair. The integration of existing disassembly precedence graph with FMEA generates an intelligent automated step-by-step disassembly procedure to reach those components with higher RPN values through the shortest path. Finally, the framework is able to adapt a robust reverse engineering method to identify products from raw points-cloud data. This module is able to reconstruct a CAD model in order to extract its geometrical information for feature recognition and product identification.

The proposed framework can solve some of the existing problems in maintenance processes, for example the unstructured and extensive knowledge required for maintenance planning. It is a powerful tool for naïve operators that need assistance to identify a product and to find the proper general maintenance procedure. They can also receive a real-time step-by-step assistance when executing corrective maintenance. All this is done automatically, which means no experience operator is needed. The integration of a reverse engineering allows the identification of the product when no CAD model is available. This represents a solution for numerous companies where the information of all their equipment and systems are not available. The framework is generic in order to accommodate new modules and methodologies to support different industrial and/or research applications.

The case-studies presented proved that the framework is able to deliver the proposed objectives. A sample of pneumatic valves of different shapes and functionalities were successfully identified and linked to the knowledge-base. The case of generating new maintenance procedure from existing knowledge is also proved at a product and component level. The intelligent assistance provided a step by step procedure showing the user how to disassemble the pneumatic valve through the shortest path to reach the component with higher probability of failure. On the other hand, the raw points-cloud data of a pneumatic valve model is processed in the reverse engineering module to reconstruct a CAD model for further feature recognition and product identification process. The valve is successfully linked to the knowledge-base the same way as those cases where the CAD model is available. The presented work has provided a good contribution towards maintenance automation.

5.2. Research contributions

The contributions of this research are presented as follows:

1. The use of AFR algorithm to identify from CAD models for maintenance applications and the development of a knowledge-based framework that is able to generate new maintenance procedure from similar products and save case-base for future usage.
2. Component level module capable of assisting naïve operators on executing maintenance by providing a step-by-step procedure to efficiently disassemble the product for the inspection and repair of critical components.
3. Real product identification using points-cloud data as an input to the framework when CAD models are not available.

5.3. Research limitations

This framework and methodologies are subjected to the following limitations:

- The developed AFR algorithm is only validated on pneumatic valves.
- The CAD model product identification works with primitive surfaces only.
- The efficient disassembly sequence provided for the component level module is not optimal at this stage. It is limited to the provided precedence disassembly graph.
- User intervention is required to confirm or correct the connection diameter of the identified pneumatic valves in order to properly generate the key number when points-cloud data is used as input.

5.4. Future Work

The generic framework is capable of new module integration for different industrial process application. Future work will integrate the following upgrades:

- Maintenance plan will be improved by including rules for maintenance decisions as the product is being disassemble. Rules for replacement or lubrication to specific components will be included in the generated maintenance plan.
- Ontology will be integrated to extract and save new knowledge during maintenance planning process. The extracted knowledge is represented in a way that can be used for different processes. Similarly, existing knowledge from other disciplines can be used for maintenance planning.
- Integration of augmented reality module to assist naïve operators during maintenance execution. A step-by-step procedure, though a hands free medium, can provided to operators during maintenance execution.
- Integration of an optimal disassembly sequence generator method. Existing methodologies can be used to generate an optimal disassembly path using component relationship information, such as the degree of freedom of every component [21]. Time and cost will also be used as constrains to minimize the disassembly steps.
- Human-Robot Collaboration maintenance planning module. This will generate a maintenance plan where tasks can be divided and assigned to human operators and robots. [16].
- Development and integration of a re-design application. The existing geometric data can be used to evaluate the physical conditions of the product, which can be

compared to the original CAD model to re-design the product based on frequent failure case-basis.

- The generalized knowledge structure will allow different domains to access, use, modify and improve product specific data for multiple applications, which promotes digitization and industry 4.0 in manufacturing industries.
- The proposed framework will be further developed and extended to include more features and use existing geometric data gathered to identify complex systems, such as a car engine, where the components of the system can be identified and a maintenance instructions can be displayed through AR to the worker [82].

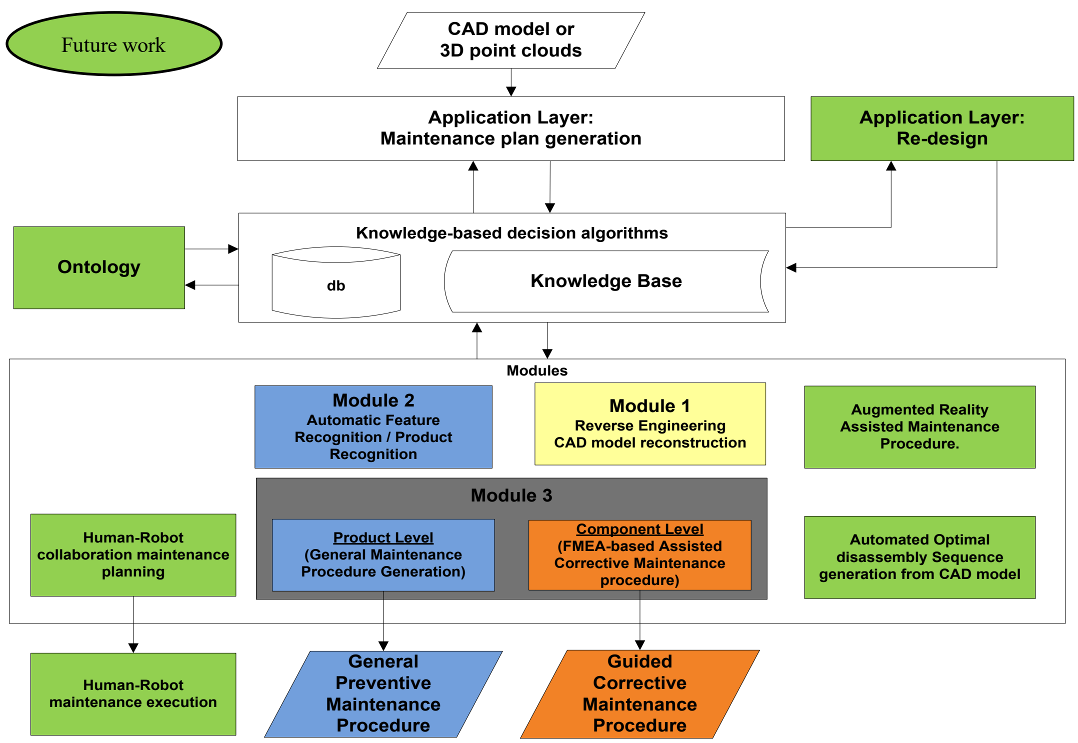


Figure 5.1, Future Work map.

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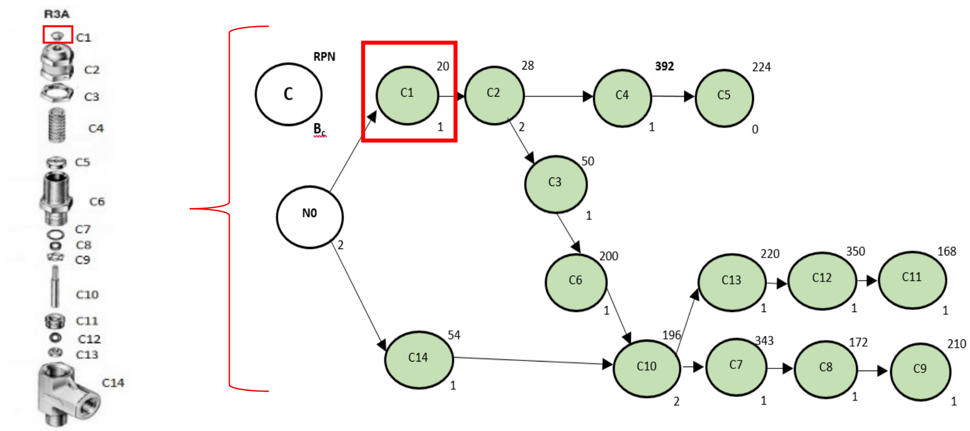
Appendices

Component level intelligent assisted maintenance procedure. Sequence for disassembly (Figure 3.2). Case: damaged component is C4. Images from reference. [42]

1)



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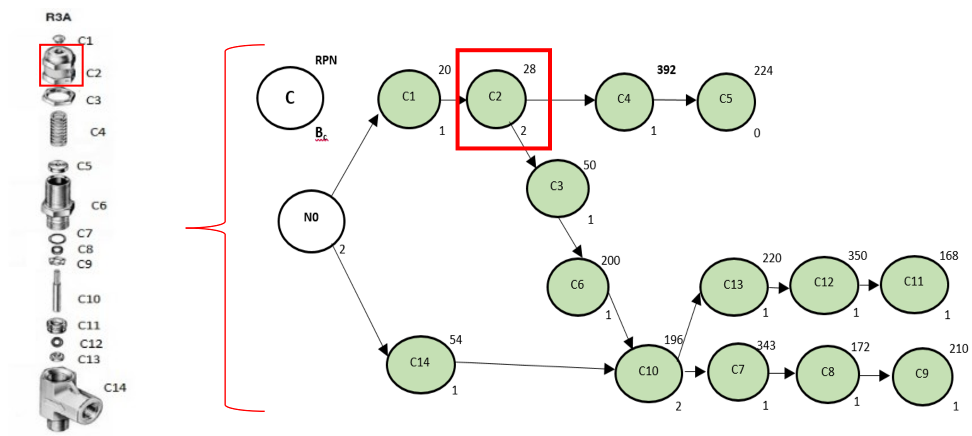

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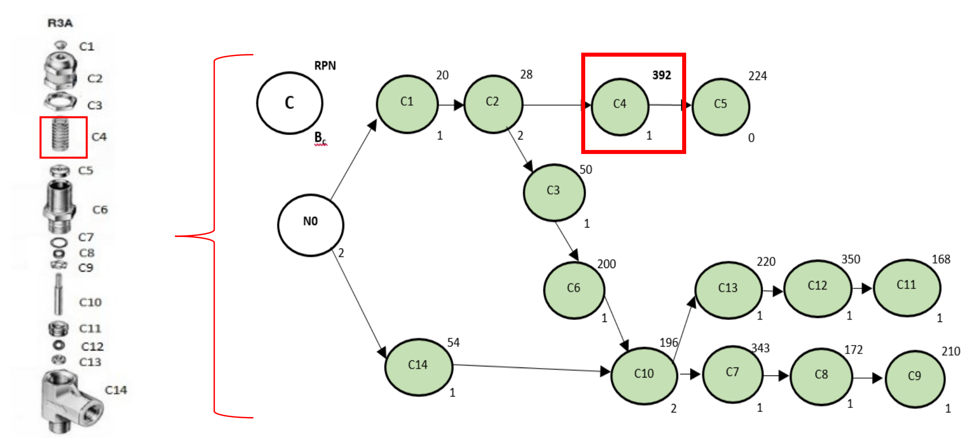
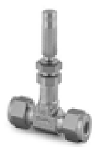
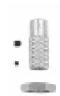
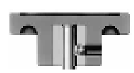
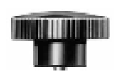
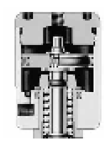


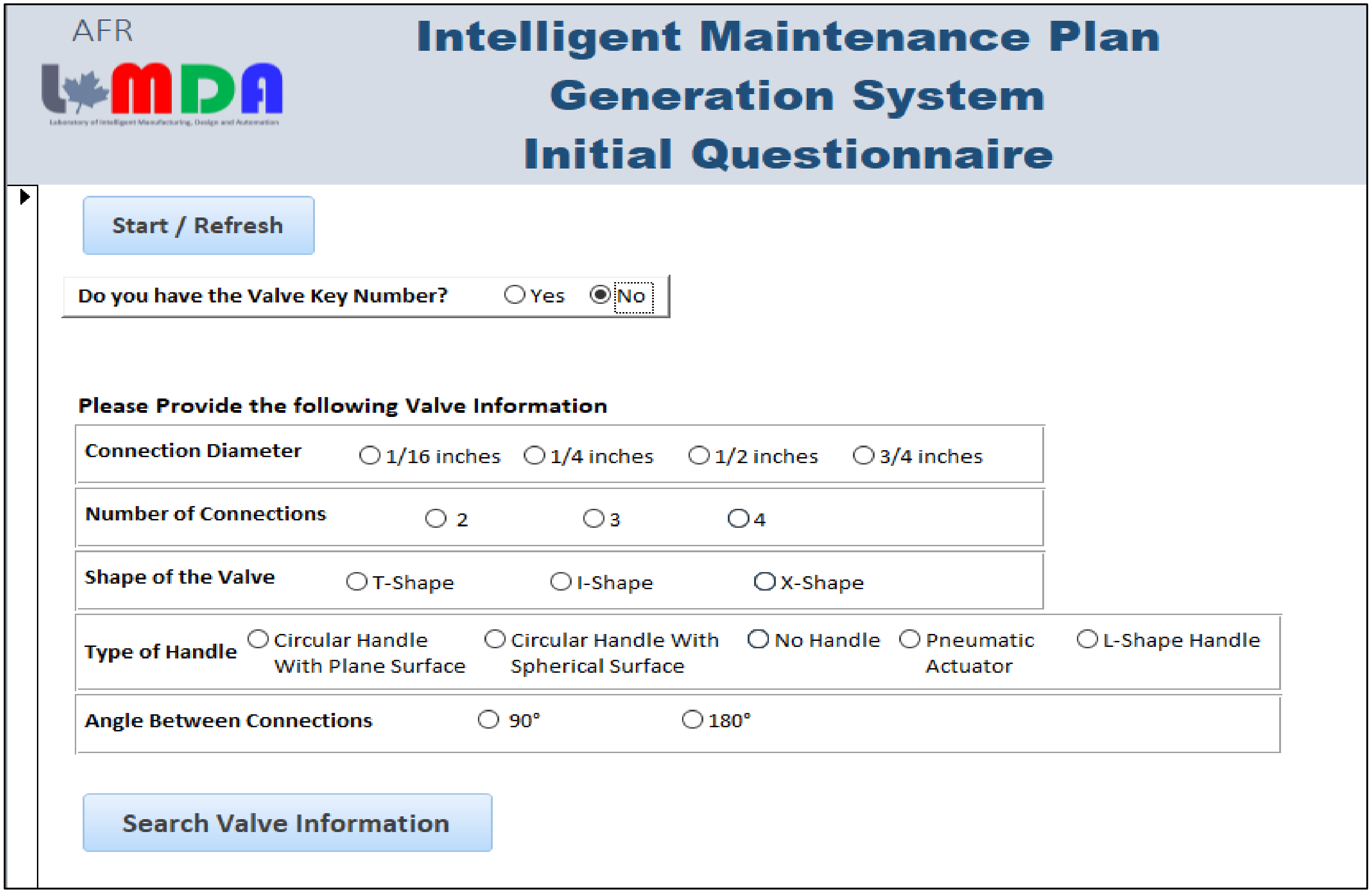
Pneumatic Valves with 4 levels of geometric classification. Images from reference [42]

1 Level Classification (valve shape)	T-shape						X-Shape		I-Shape
2 Level Classification (Handle type)	No handle			Circular Handle: Flat Surface	Circular Handle: Spherical Surface	Pneumatic Actuator	L-handle		No handle
3 Level Classification (Flow angle - in/out)	2 Connections 180°	2 Connections 90°		2 connections 180°	2 connections 180°	2 Connections 180°	4 Connections 90°	3 Connections 90°	2 Connections 180°
4 level of Classification (Connection Diameter)	1/16 inch	1/4 inch	1/2 inch	1/4 inch	1/4 inch	1/4 inch	1/16 inch	1/4 inch	1/4 inch
IMAGE									
Specific handle/head Feature									NO CAP OR HANDLE
KEY Number	TNH180-1/16	TNH90-1/4	TNH90-1/2	TCH180-1/4	TCHS180-1/4	TPNA180-1/4	XLH4W-1/16	XLH3W-1/4	INH180-1/4

Pneumatic Valves original classification. Images and information from reference [42]

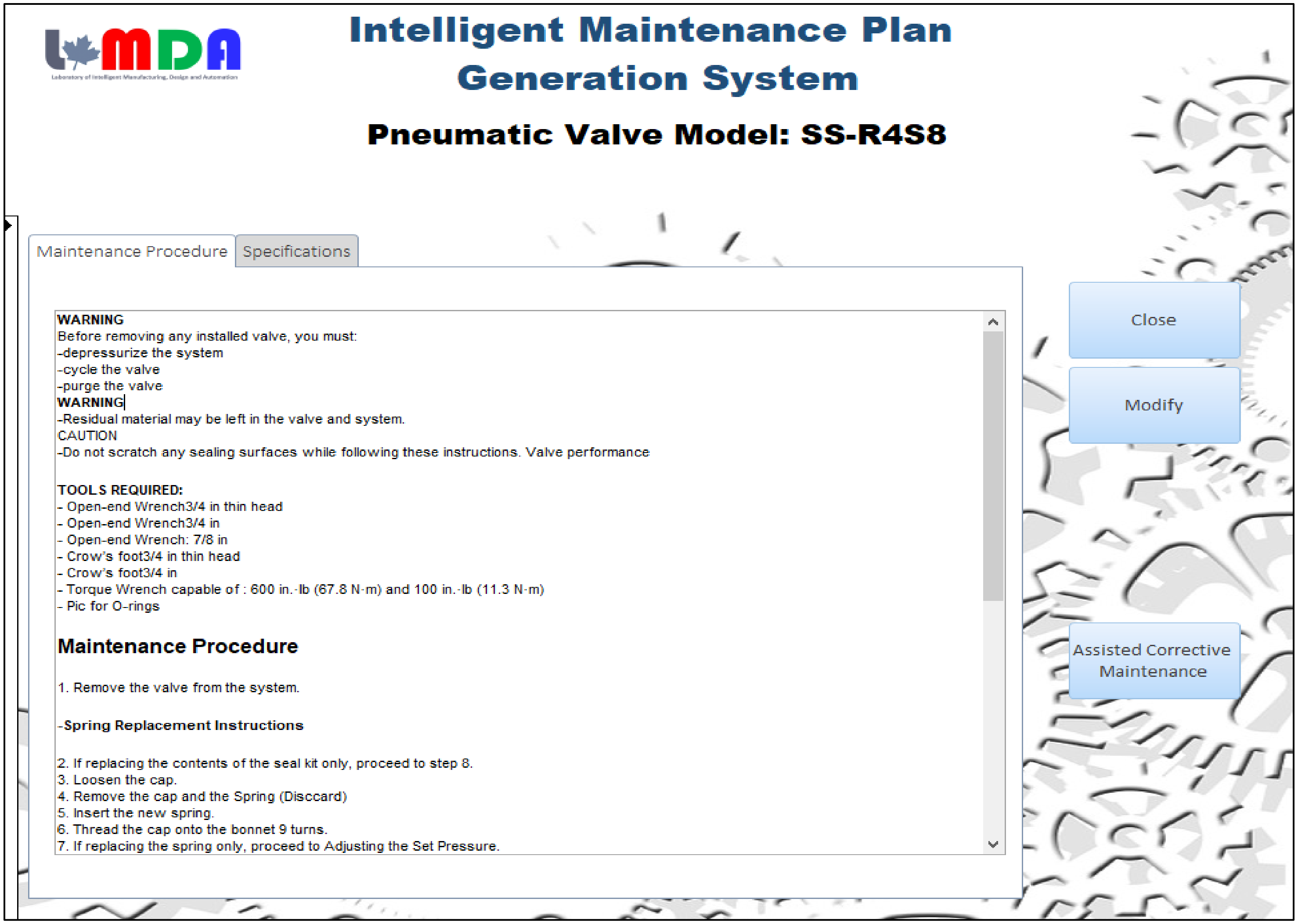
Classes	Bellows Sealed Valves		Relief Valves		Metering Valves		3-4 Way Ball Valves		Poppet Check Valve
Class usage	Isolate system fluids and achieve reliable, leak-tight performance with Swagelok bellows valves which use a packless design and a welded seal. Bellows valves are ideal for applications where the seal to atmosphere is critical		Obtain over-pressure protection for a variety of applications with Swagelok proportional relief valves with easy external set pressure adjustments.		Make fine adjustments in low- or high- pressure, and low-, medium-, or high- flow applications with Swagelok metering valves that deliver accurate flow control when it matters in situations such as analytical or research applications.		Meet your system needs with the broad range of Swagelok ball valves made in a variety of styles, pressure ratings, materials, and end connection choices, configurable for a variety of applications.		Control back flow in general-service and high-purity applications with Swagelok check valves available in a range of adjustable and fixed cracking pressures.
Model #	1	2	3	4	5	6	7	8	9
Series	BN4 (bellows sealed)	HB (Air actuated high pressure)	R3A (Proportional pressure relief valves)	R4(proportional pressure relief valves).	S	31	4 way - 40 Series	3Way - 40 Series	180deg flow - check valve
Item number	SS-BNS4	SS-HBS4-C	SS-4R3A	SS-R4S8	SS-SS1-EP	SS-31RS4	SS-43YEFS1	SS-42GXES4	SS-4C-BU-1/3
Size	1/4 inch	1/4 inch	1/4 inch	1/2 inch	1/16 inch	1/4 inch	1/16 inch	1/4 in	1/4 inch
IMAGE									

User multiple-choice selection for key number generation. Case: product key number is unknown to the user.

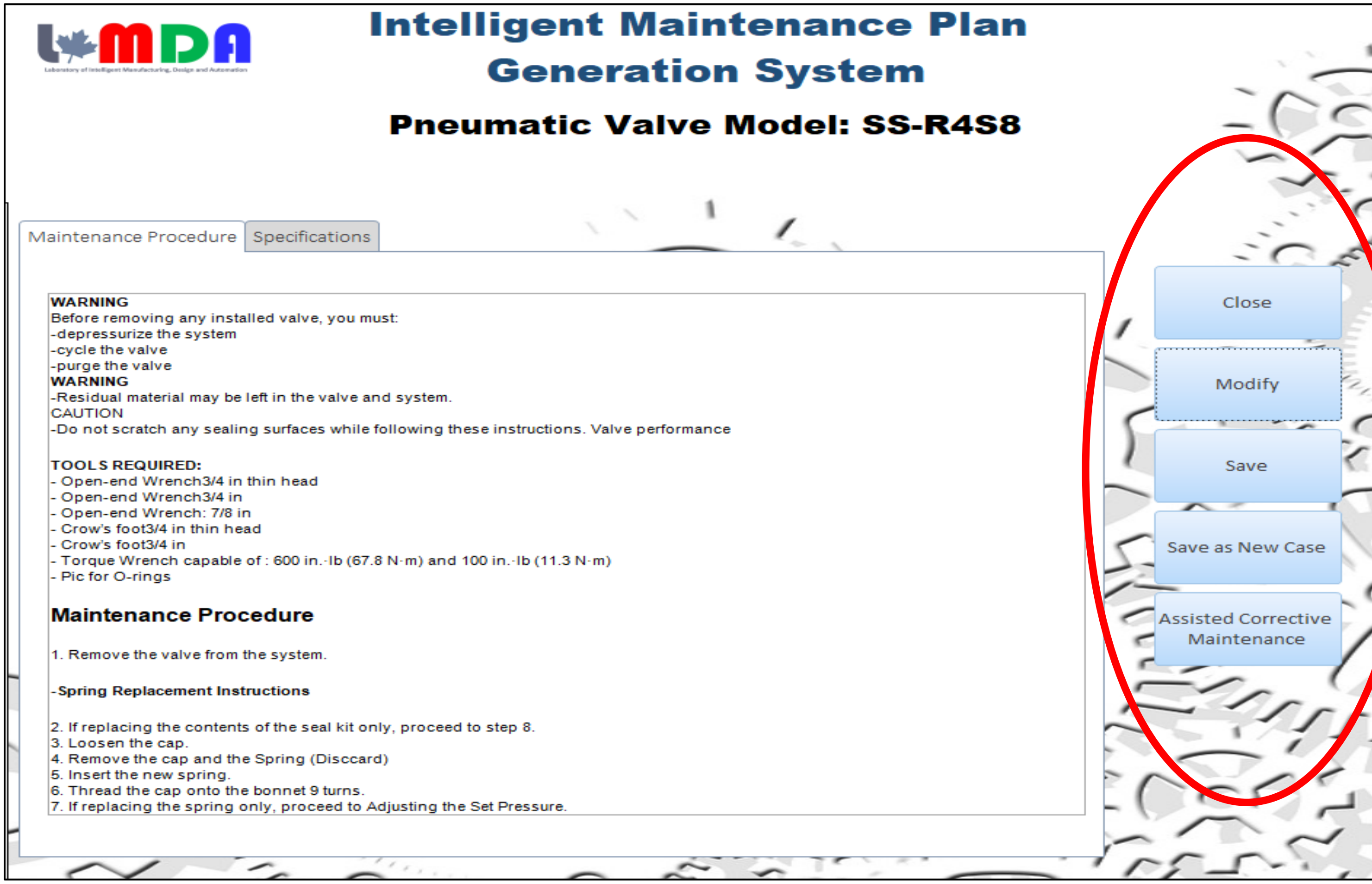


Input field for product identification. Case: the user knows the product key number.

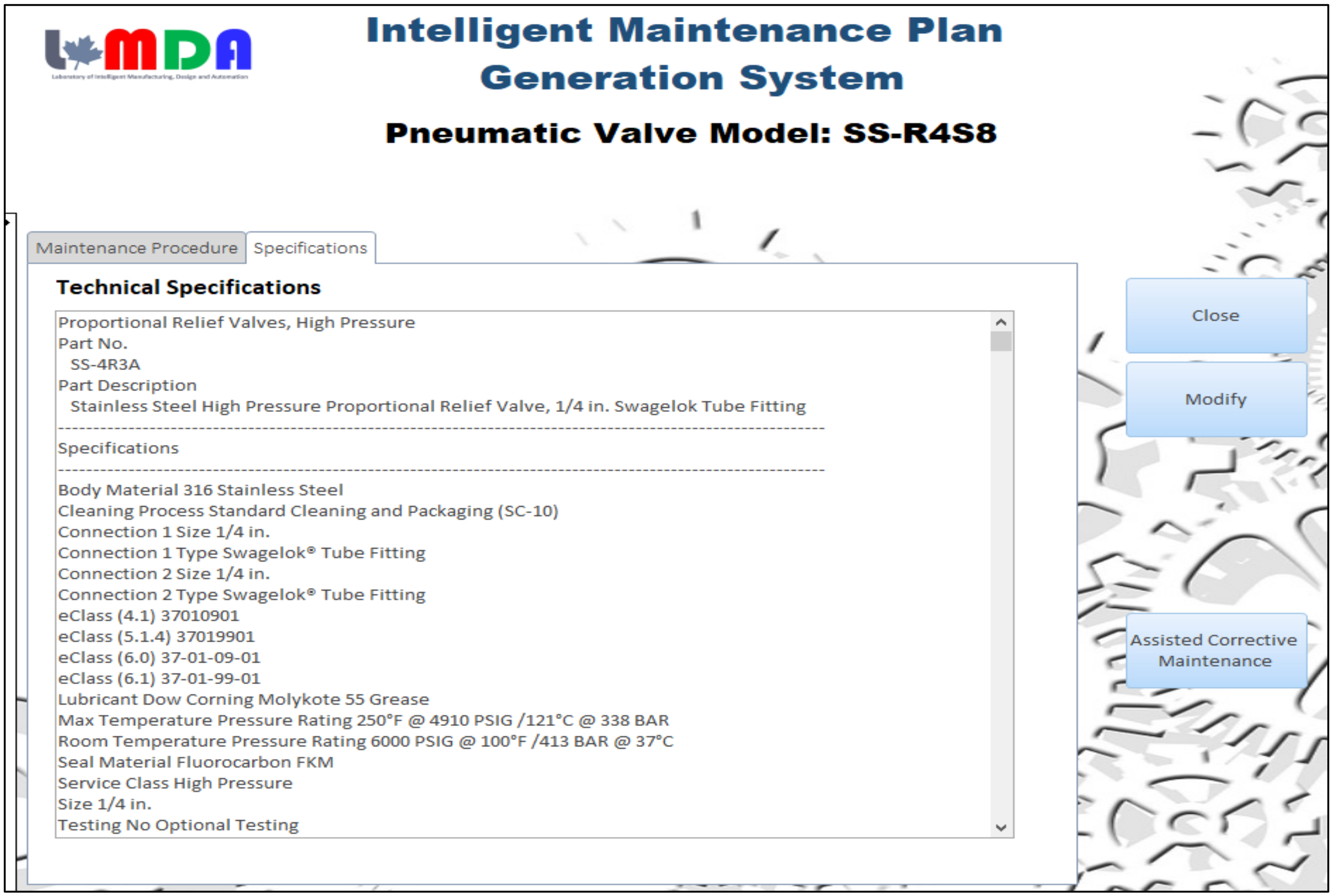
Existing general maintenance procedure view.



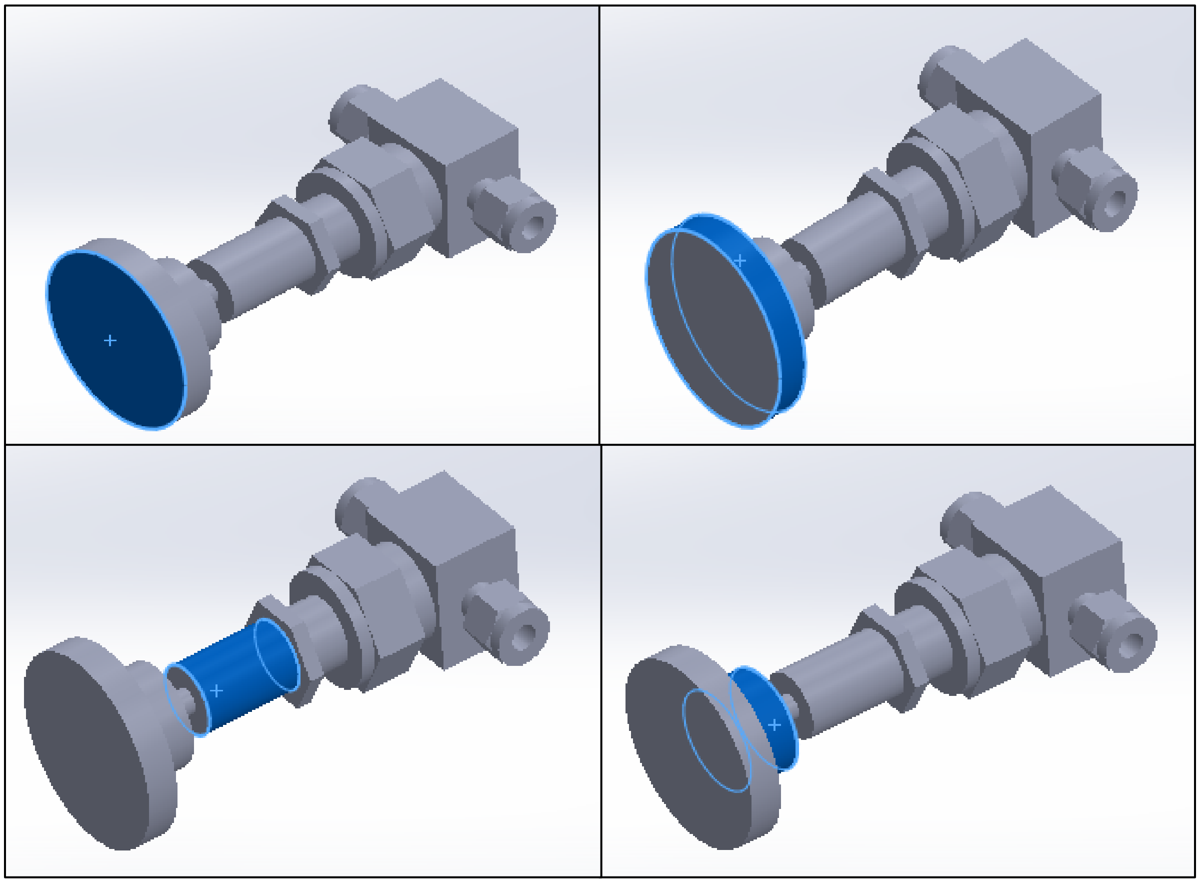
Maintenance procedure view. “Save” and “Save as New Case” buttons available when authorized user clicks Modify button.



Technical Specifications of the product view. Authorized user can modify this information as well.



Pneumatic Valve CAD model during geometric feature extraction. The algorithm iterates trough all faces on the CAD model and extracts face surface type and each edge coordinate data. CAD model from [42]



Geometric data stored in Microsoft Access database. Data available to the framework. (Circle edges with center coordinates and radius).

QUESTIONNAIRE | AFR | GeoFeatures

CADModelName	Object	NoofFaces	FaceId	SurfaceType	NumberOfEdges	Edge	Coordinatereference	x	y	z
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F15	CYLINDER	2	F15E0	circle	0.00	0.00	1.59
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F15	CYLINDER	2	F15E1	circle	0.00	0.00	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F1	PLANE	2	F1E0	circle	0.00	0.00	3.15
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F1	PLANE	2	F1E1	circle	0.00	0.00	3.15
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F24	CYLINDER	2	F24E0	circle	0.00	0.00	1.09
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F24	CYLINDER	2	F24E1	circle	0.00	0.00	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F2	CYLINDER	2	F2E0	circle	0.00	0.00	2.78
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F2	CYLINDER	2	F2E1	circle	0.00	0.00	3.15
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F33	CYLINDER	2	F33E0	circle	0.00	0.00	0.53
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F33	CYLINDER	2	F33E1	circle	0.00	0.00	0.62
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F34	PLANE	2	F34E0	circle	0.00	0.00	0.53
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F34	PLANE	2	F34E1	circle	0.00	0.00	0.53
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F35	CYLINDER	2	F35E0	circle	0.00	0.00	0.53
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F35	CYLINDER	2	F35E1	circle	0.00	0.00	0.38
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F3	CYLINDER	2	F3E0	circle	0.00	0.00	3.15
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F3	CYLINDER	2	F3E1	circle	0.00	0.00	3.46
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F42	CYLINDER	2	F42E0	circle	-0.60	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F42	CYLINDER	2	F42E1	circle	-0.50	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F43	CYLINDER	2	F43E0	circle	0.60	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F43	CYLINDER	2	F43E1	circle	0.50	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F44	CONE	2	F44E0	circle	-0.64	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F44	CONE	2	F44E1	circle	-0.60	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F45	CONE	2	F45E0	circle	0.64	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F45	CONE	2	F45E1	circle	0.60	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F46	CYLINDER	2	F46E0	circle	-0.70	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F46	CYLINDER	2	F46E1	circle	-0.64	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F47	CYLINDER	2	F47E0	circle	0.70	0.00	0.00
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F47	CYLINDER	2	F47E1	circle	0.64	0.00	0.00

Geometric data stored in Microsoft Access database. Data available to the framework. (Line segment edge with start point and end point coordinates.

QUESTIONNAIRE | AFR | GeoFeatures

CADModelName	Object	NoofFaces	FaceId	SurfaceType	NumberOfEdges	Edge	Coordinatereference	x	y	z	Xe	Ye	Ze
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F10	PLANE	4	F10E3	Line Segment	-0.22	-0.38	2.33	-0.22	-0.38	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F11	PLANE	4	F11E0	Line Segment	-0.43	0.00	1.67	-0.22	-0.38	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F11	PLANE	4	F11E1	Line Segment	-0.22	-0.38	2.33	-0.22	-0.38	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F11	PLANE	4	F11E2	Line Segment	-0.43	0.00	2.33	-0.22	-0.38	2.33
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F11	PLANE	4	F11E3	Line Segment	-0.43	0.00	2.33	-0.43	0.00	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F12	PLANE	4	F12E0	Line Segment	-0.22	0.38	1.67	-0.43	0.00	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F12	PLANE	4	F12E1	Line Segment	-0.43	0.00	2.33	-0.43	0.00	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F12	PLANE	4	F12E2	Line Segment	-0.22	0.38	2.33	-0.43	0.00	2.33
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F12	PLANE	4	F12E3	Line Segment	-0.22	0.38	2.33	-0.22	0.38	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F13	PLANE	4	F13E0	Line Segment	0.22	0.38	1.67	-0.22	0.38	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F13	PLANE	4	F13E1	Line Segment	-0.22	0.38	2.33	-0.22	0.38	1.67
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F13	PLANE	4	F13E2	Line Segment	0.22	0.38	2.33	-0.22	0.38	2.33
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F13	PLANE	4	F13E3	Line Segment	0.22	0.38	1.67	0.22	0.38	2.33
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F17	PLANE	4	F17E0	Line Segment	0.43	0.00	1.47	0.22	0.38	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F17	PLANE	4	F17E1	Line Segment	0.22	0.38	1.47	0.22	0.38	1.59
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F17	PLANE	4	F17E2	Line Segment	0.43	0.00	1.59	0.22	0.38	1.59
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F17	PLANE	4	F17E3	Line Segment	0.43	0.00	1.59	0.43	0.00	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F18	PLANE	4	F18E0	Line Segment	0.22	-0.38	1.47	0.43	0.00	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F18	PLANE	4	F18E1	Line Segment	0.43	0.00	1.59	0.43	0.00	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F18	PLANE	4	F18E2	Line Segment	0.22	-0.38	1.59	0.43	0.00	1.59
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F18	PLANE	4	F18E3	Line Segment	0.22	-0.38	1.59	0.22	-0.38	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F19	PLANE	4	F19E0	Line Segment	-0.22	-0.38	1.47	0.22	-0.38	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F19	PLANE	4	F19E1	Line Segment	0.22	-0.38	1.59	0.22	-0.38	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F19	PLANE	4	F19E2	Line Segment	-0.22	-0.38	1.59	0.22	-0.38	1.59
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F19	PLANE	4	F19E3	Line Segment	-0.22	-0.38	1.59	-0.22	-0.38	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F20	PLANE	4	F20E0	Line Segment	-0.43	0.00	1.47	-0.22	-0.38	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F20	PLANE	4	F20E1	Line Segment	-0.22	-0.38	1.59	-0.22	-0.38	1.47
SS-31RS4-SwagelokCompany-06-26-2017(31 Series 1-4 inch Fine metering)	Imported1	97	F20	PLANE	4	F20E2	Line Segment	-0.43	0.00	1.59	-0.22	-0.38	1.59

Existing feature recognition methods comparison and evaluation for the maintenance application. [83], [19], [20], [32], [33], [34]

AFR Method	Octree Representation	Standard Triangulation Language (STL)	Virtual Loop recognition	SQL Database optimization	Hybrid hint-based and graph-based	Syntactic pattern recognition
Research Authors	[Automatic Assembly Feature Recognition and Disassembly Sequence Generation.] Sung 2001	[Automatic Recognition of features from freeform surface CAD models]. Sunil 2008	[Recognition of virtual loops on 3D CAD models based on the B-rep model] Lai 2016	[Rapidly finding CAD features using database optimization]. Niu 2015	[A hybrid hint-based and graph-based framework for recognition of interacting milling features]. Rahmani 2007	[A review of automated feature recognition with rule-based pattern recognition.] Babic 2008
Definition	Contact adjacent and Spatial adjacency are features to look in each octan. This define the boundaries of each component inside the entire model.	For automatic recognition STL files are used to be able to define the relationship between all triangles, define regions, and merge all regions to stablish them as one of the feature.	This method focuses on loop recognition from B-Rep 3D models since the loop data of B-Rep are insufficient to describe the geometry required for feature recognition.	Features declarations are translated into SQL(Structure Query Language), use of database to optimize the query plans can be applied for feature recognition. The real features (e.i.: simple notch) are define by queries with all information related to this features, such as faces, edges, vertices and sub features that are related and later called predicates.	B-rep information is extracted from the 3D model to create AAG (Attributed adjacency graph) which consist in stablishing the relation between faces. Volume features are defined.	A model of a part is described using semantic written language where all form primitives are described and then translated in a part description previewsly defined in a string (syntax analisys).
Advantages	Applicable to all 3D models to determin the contacts of every component. Brakedown of a product into components	Good resolution to detect details in freeform surface designs.	Great at detecting all loops and determining continuity between faces.	Faster processing	Rules can be defined to create multiple feature.	Rules can be defined to create multiple feature.
Disadvantages for this research	Complex methodology for product identification.	Files are too heavy to run a feature recognition.	Designed to recognize virtual loops.	Advance knowledge on SQL database optimization required.	None	Limited to 2D. It will take more processing time to translate 3D models in 2D for feature recognition.