Quality 4.0: Entity Relationship Model for Inspection and Repair Processes in Aerospace Domain

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Abstract

For decades, data-driven decisions have become the core of quality improvements. A new paradigm has been introduced for the digitalization of quality management with “Quality 4.0”. Automatic data and information exchange are the essential steps of the Quality 4.0 paradigm to achieve automation of the manufacturing systems. The goal of this paper is to design and manage the database of the automated system as the first stage of data preparation for quality management. For this stage, we use the Entity Relationship (ER) modeling technique to develop conceptual and logical models. This technique is used in a real case study to organize and manage the database of inspection and repair processes in aerospace manufacturing. The real merit of the developed models is to create a well-structured database that describes the system’s data flow with high data quality.

Keywords
Quality 4.0, Database management, Data modeling, Entity Relationship (ER) Modeling, automated inspection.

1. Introduction
Quality 4.0 paradigm is a new concept introduced under the general approach of Industry 4.0. Quality 4.0 represents the digitalization of quality management where it monitors and controls the quality of the process and/or product (Bauchi 2020) (Jacob 2017). Data and information exchange are the cornerstone of the Quality 4.0 paradigm to achieve high reliability in the automation of the manufacturing systems (Jacob 2017). In such systems, a large amount of information flow between sensors and controllers independently of continuous interaction with humans, which poses some challenges for existing traditional systems regarding their ability to handle and manage the sheer amount of data and information due to the lack of the necessary tools and infrastructures (Lucas-Stan 2018). A clear example of such a challenge can be found in the aerospace domain in which visual inspection is the main method for inspecting parts (See 2012) (Rice 2018). Since this process is carried out by talented and experienced human inspectors, it is still prone

to error which can range from 20% to 30% (Johnson 2019). Moreover, there is a great possibility of missing data and the presence of data redundancies and inconsistency. The stakeholders take much time to prepare their necessary information to do the report and/or analysis. Further, the data are entered manually, so there can be an absence of standardization of communication between stakeholders. As such, numerous researches are trending to automate the inspection and repair using the available data in the process (Tiwari 2008) (Aust 2021). This current trend is to replace the human element with more accurate automated inspection and repair machines. In turn, suitable tools for handling and managing the generated data are required. Information modeling should be applied on the events engine parts; inspection, maintenance, repair, and overhaul; to capture the relevant data attributes and describe the current and historical event of the part. This model provides the accurate information required by the stakeholders such as the operators, engineering, and scheduling team to prepare their reports, or analysis or even to make decisions. Consequently, we need to define the necessary data to be managed in the inspection and repair processes in terms of three axes as shown in Figure 1. The axes are: define the information for each engine part such as fan blade, fan disc, and turbine, exhibit a visual representation of the process's steps, and demonstrate the transfer of data through the process. Therefore, the importance of efficient Database management tools grows.

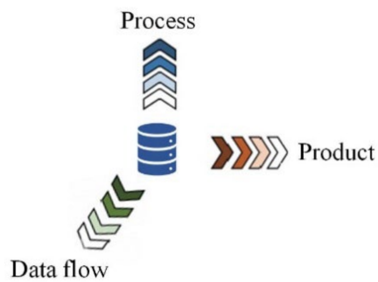

Figure 1. Three axes of Database management

Database management plays an important role in organizing and storing data in an appropriate structure to maximize their value. Implementation of database management does not only provide data structure with the necessary information required by the process but also, governs the data entry in terms of the six-dimensional data quality; accuracy, validity, integrity, completeness, consistency, and timeliness (Moody 1998).

Data modeling is commonly used in database design. It creates an abstract model as a visual representation to describe the structure of the stored data in addition to additional consistent constraints (Shin 2017). The real merit of data modeling is not only to ensure that all required data match the business needs but also, to avoid the presence of any redundant or missing data by respecting its constraints. A data model was proposed as modeling of the maintenance task knowledge of Boeing B737 aircraft (Verhaegen 2008). The model is used to capture all information related to the process and history of the aircraft. It supports the stakeholders with the necessary information for maintenance execution to ensure compliance with airworthiness. Okah proposed a data model that represented the accurate visualization of maintenance tasks applied on the aircraft engines. It supplies the relevant engine information over time which provide new insights and prediction about the lifespan of the engine through-life engineering services. Rodger provided a preliminary data model that was built based on the primary data flow of the aircraft maintenance, repair, and overhaul (MRO). It focuses on the captured information of the repaired parts of Boeing 777 and Sikorsky's UH-60 helicopter.

The data model follows four steps to design a database as depicted in Figure 2. The first stage is Business requirements. It is the most important stage which is dependent on the identification and characterization of the data required in the system. Moreover, understanding the process is the main step to define the necessary information to be collected. The collected information in the first stage is translated into a formal and independent model which is the "Conceptual model". It is a wide coverage picture that identifies the business concepts and their rules. Then, a "Logical model" converts the previous model into a data structure including more details. It defines the data elements in the structure and the relationships between them. The final stage is the "Physical Model" that provides the schema which is implemented physically using Database Management System (DBMS) software (Lemahieu 2018).

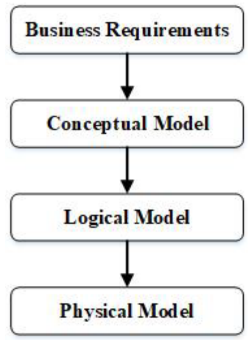

Figure 2. Data modeling stages (Lemahieu 2018)

Entity relationship (ER) model (Chen 1976) is one of the known data modeling for a database design. It is a graphical tool that is used to provide a conceptual form of the database structure (Al-Masree 2015). ER preserves the information of the system and diminishes the data redundancy in storage (Suansook 2019). In this paper, we use ER modeling technique to design a database for inspection and repair in the aerospace domain. We propose a conceptual and logical ER model of a real case as the first step of data preparation for Quality 4.0. The paper is organized in sections as follows. Section II describes the methodology of ER modeling in the design of a database. Section III shows a description of the case study and discusses the first three stages in the data model in Figure 2. Section IV presents the conclusion and future works.

2. ER model Technique

ER is a data modeling technique that represents the database of the system in a set of entities that are stored in a database and their relationships (Guarino 2015). The entity can represent persons (such as inspectors), spaces (such as shop floor), objects (such as Order and inspection machine), or concepts (such as inspection and repair processes) about storing data in the database. The real application consists of several entities. Each entity contains a set of attributes that define the characteristics of that entity. The attribute can be simple, composite, derived, or multi-valued. The simple attribute is an atomic attribute; e.g. Serial number (S/N) of inspected or repaired part. While the composite one is composed of a set of simple attributes; e.g. Defect dimension attribute is represented by depth (D), width (W), and Length (L). The attribute can have more than one value, which is called a multi-valued attribute. This means that each S/N can have more than one defective location. The values of the derived attribute are derived from another attribute(s) that exists in the database; for example, when determining the number of defects per inspected part. Each entity must have a primary (unique) key(s) that uniquely identifies instances of that entity that cannot be repeated; each inspected part has its own S/N. The foreign key in an entity represents a primary key of another entity, which establishes a relationship with that entity. ER modeling defines the relationships between the entities using different types of connecting lines (Kashmira 2018). Each relationship indicates the number of instances of a certain entity relates to one instance of another entity, which is called cardinality. Cardinality can be one to one (1:1), one to many (1: M), and many to many (M: M). The relationship can be mandatory when every instance of one entity must have a relationship with the other entity. The optional relationship does not require the necessary participation of one entity in a relationship with the other entity. Figure 3 summarizes the necessary notations for ER diagram.

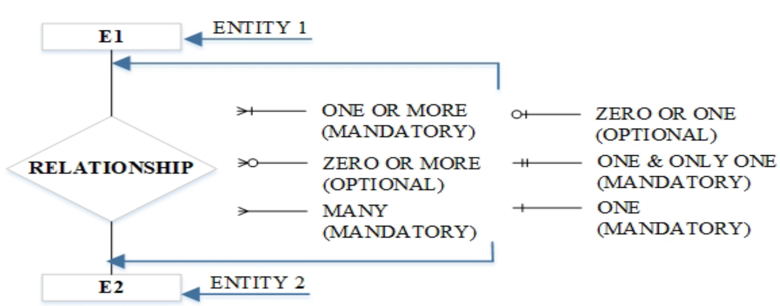

Figure 3. The notations for ER model

ER diagram facilitates defining the terms entities, attributes, and relationships. In addition, it provides a preview for connection between each table, which allows constructing databases quickly. Finally, it provides a better understanding of the information stored in the database (Connolly 2015).

3. Case study: Application on inspection and repair in aerospace domain

3.1 Description of the case study

Rolls-Royce is considered one of the leading companies in the aerospace domain. Rolls-Royce maintenance center is aspiring in cooperation with AV&R Vision & Robotics, Polytechnique Montreal, Conseil national de recherches Canada (CNRC), and Laval university to develop automated system called SARA which is "*Système d'Analyse et de Réparation Automatisée*" (Automated inspection, Analysis and Repair System). In the current system, the inspectors perform Visual inspection on the mechanical parts to find the surface defects based on work instructions and the necessary measurement tools for inspection. They assess the defective locations in the inspected parts approximately and compare them with the limits in the engine manual. The new system aims to develop automated analysis, inspection, and repair systems for mechanical parts of engines using machine vision instead of human vision as depicted in Figure 4. In the inspection stage, the mechanical part is inspected by the inspection machine to check for any surface defects such as nick, scratches, pitting, etc. If any defect is detected, it is assessed and classified in the defect classification step based on measuring the defect geometry (depth, width, length, and type) in the engine manual. Then, the decision in the sentencing step declares whether this part can be repaired or if it is scrapped. In case of being repairable, the defect locations are defined, and the repair service is carried out by the repair machine to meet standard specifications.

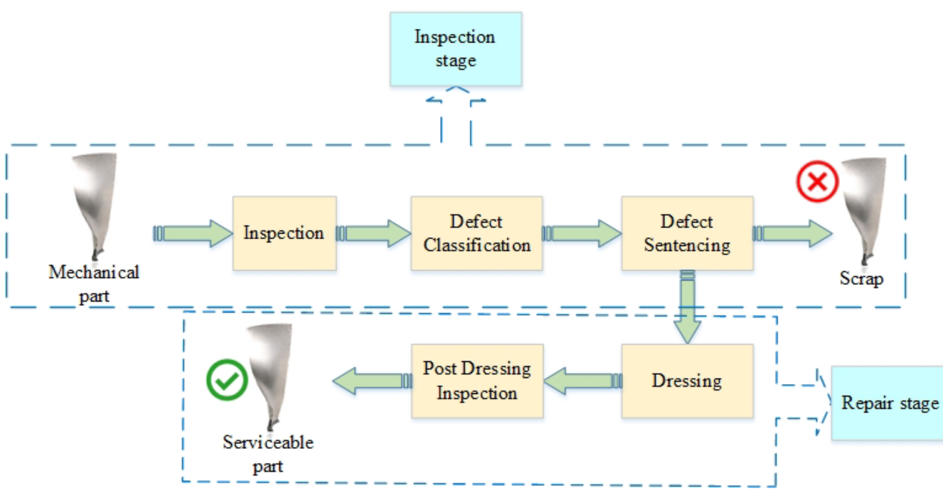

Figure 4. Inspection and Repair stages

Database management (DBM) provides capabilities to access, integrate, cleanse, govern, store, and prepare data for further analysis. Furthermore, it characterizes and controls the information generated by the SARA system and proposes a data management structure for operations. It establishes and standardizes communications between operations' stakeholders such as inspectors, engineers, Material Review Board (MRB), etc. In this paper, we propose an ER model for database design and management. To create the model for the SARA system, we need to follow the steps of data modeling in Figure 2 and those of ER model in Figure 5.

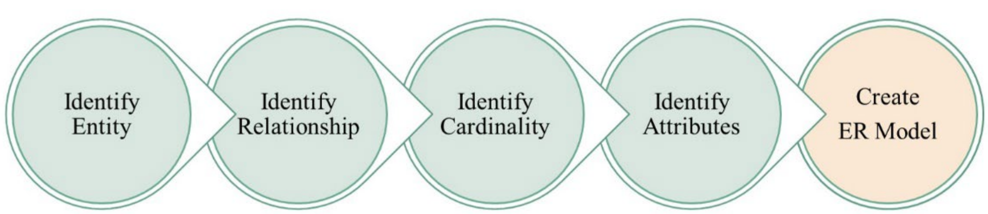

Figure 5. ER Modeling design steps

3.2 Business requirement for SARA system

A strategy has been established to determine Rolls Royce's requirements and objectives. First, we understand the operational processes in the current system; the inspection and repair; and their characteristics and constraints. Three mechanical parts are recommended as candidates for investigations: Fan blade, Curvic teeth of fan disc, and High-pressure turbine (HPT) shaft. Several meetings are organized with the stakeholders, such as inspectors, operators, engineers, Material Review Board (MRB), etc.; to identify and characterize the necessary required data for the SARA system. We conclude that since SARA will be an automated system, the identification of the defect dimensions accurately in the model will shorten the inspection. Some mechanical parts are sent to the laboratory to confirm that the defects are beyond the limits. On the other hand, the data model will provide the necessary information for each stakeholder to prepare their reports and analysis. One of these stakeholders is the Quality engineer who is responsible for process monitoring and of maintaining the inspection and repair process within the quality specifications based on Quality 4.0.

3.3 Conceptual ER model for SARA system

The conceptual ER model for the SARA system defines the system's concept by identifying the entities in addition to the relationships between them. The model has 4 main stages: Sensor and measurement, inspection, sentencing, and repair. SARA model consists of nine entities as depicted in Figure 6: (1) SENSOR, (2) P.C. DATA, (3) ORDER, (4) EQUIPMENT, (5) INSPECTION, (6) DEFECTS, (7) SENTENCING, (8) REPAIR, and (9) RE-INSPECT. The entities are described as the following:

(1) SENSOR: The entity defines the sensors or measurement tools, which are responsible for providing the measurements and scanning of the inspected parts.
(2) P.C. DATA: It refers to the Point Cloud (P.C.) which is obtained by the sensors. P.C. is a group of data points that represent the surfaces of the inspected parts.
(3) ORDER: It includes the essential information related to the engine and defines the mechanical part(s) that is (are) required to be inspected.
(4) EQUIPMENT: It means the mechanical parts that are required to be inspected. Therefore, this entity characterizes the details on the inspected mechanical part.
(5) INSPECTION: This entity encapsulates the system objectives. It defines the information related to the inspection of the mechanical parts in terms of notifications and time duration taken for inspection.
(6) DEFECT: It defines all information related to the characterizations of the detected defects on the inspected part if any.
(7) SENTENCING: It is the decision entity that provides information about the condition of the inspected mechanical part by the automated inspection machine whether being serviceable, repairable, or scrap.
(8) REPAIR: If the decision for the inspection machine is that the inspected part is repairable, so the repair scheme and procedures will be defined automatically by the repair machine, then applied to the part.
(9) RE-INSPECT: After repairing the inspected mechanical part, it is essential to check the repair procedures. Therefore, the inspected part will be sent to the inspection machine to be reinspected. Consequently, the RE-INSPECT entity defines the status of repair operation of the repaired part whether it is confirmed or not.

Furthermore, the SARA model also includes 13 relationships which represent the interactions between the entities (1) COMPOSE OF, (2) ASSIGN TO, (3) SEND TO, (4) CONTAIN, (5) DETECT, (6) PROVIDE, (7) Has, (8) Has, (9) SENTENCED BY, (10) ORDER TO, (11) REPAIRED BY, (12) RE-INSPECT, and (13) CONFIRMED BY to as depicted in Figure 6. The relationships and cardinality are obtained based on the constraints (business) rules required by the inspection and repair process. These constraints are as the following:

(1) ORDER and EQUIPMENT: The inspection machine receives the orders; each order must compose of information of the inspected part(s) and the required task. One or many parts can be included in one order. Engine information is provided in the case of internal order, where parts from an engine that is located on the shop floor are sent for inspection.
(2) EQUIPMENT and INSPECTION: Each part is assigned to the inspection process. However, one or many parts may be included in one inspection order, each part is defined by its own inspection identifier. Therefore, each inspection identifier defines the inspection information of one part even the parts are included in the same order.
(3) SENSOR and P.C. DATA: Each sensor in the inspection machine sends many measurements in terms of point clouds.
(4) EQUIPMENT and P.C. DATA: Each inspected part contains many numbers of point clouds that describe its surfaces.

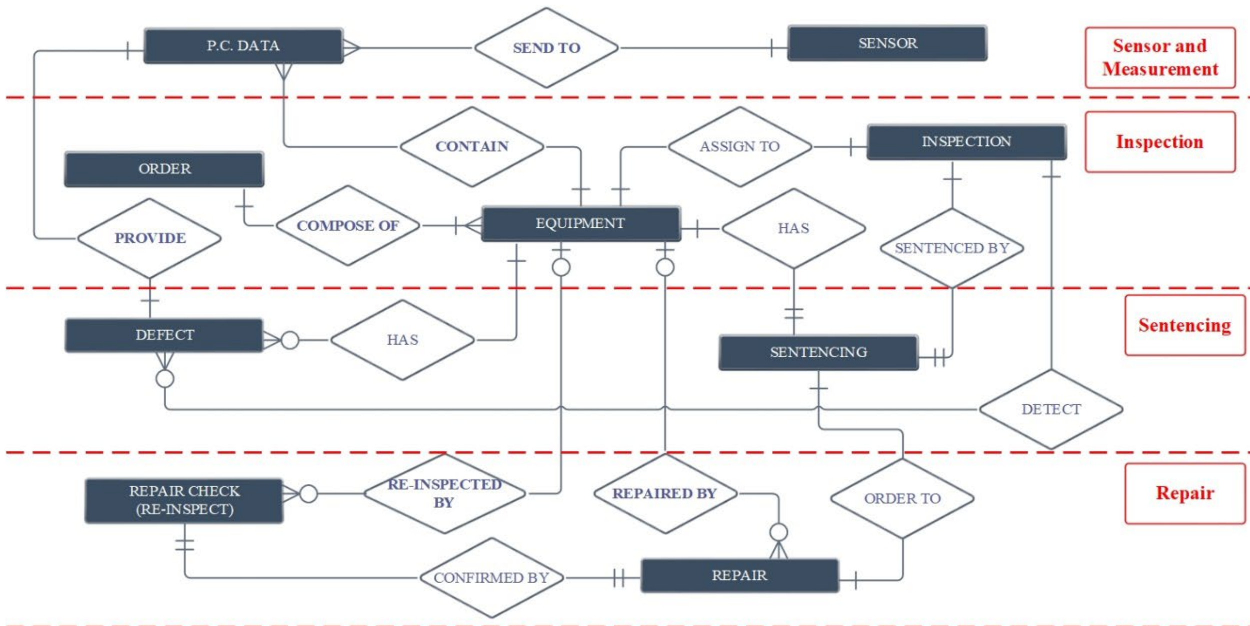

Figure 6. Conceptual ER Modeling for SARA system

(5) INSPECTION and DEFECT: Each inspection order may detect one or many numbers of defects per each inspected part.
(6) DEFECT and P.C. DATA: P.C. DATA provides one point cloud for each defect detected on the inspected part.
(7) EQUIPMENT and DEFECT: During the inspection, each inspected part may have one or more defects. Thus, the information of these defects are determined for each inspected part.
(8) EQUIPMENT and SENTENCING: Each inspected part must have one and only one sentencing notification to identify its condition. Therefore, each notification must be assigned to one and only one inspected part.
(9) INSPECTION and SENTENCING: Each inspection order has one and only one sentencing notification. In other words, each sentencing notification includes one inspection order. When many parts are included in one inspection order, each inspected part; defined by inspection identifier; must have one sentencing notification.
(10) SENTENCING and REPAIR: When the sentencing notifies that the inspected part is repairable, one sentencing notification may be ordered to one repair order. The repair entity may include one sentencing notification, and none is in case of being scrapped part.
(11) EQUIPMENT and REPAIR: One inspected part may be repaired by the repair machine in case of being repairable based on the sentencing notification in the sentencing entity. So, one repair order may include one and only one inspected part for repair. However, one or many parts may be included in one repair order, each part is defined by its own repair identifier.
(12) EQUIPMENT and RE-INSPECT: One part may be reinspected by the inspection machine. One re-inspect notification may include one part. One or many parts may be included in one re-inspect order, each part is defined by its own re-inspect identifier.
(13) REPAIR and RE-INSPECT: After repairing the repairable parts, they are sent to the inspection machine to confirm their repairs. Each re-inspect notification confirms each repair order.

3.4 Logical ER model for SARA system

The logical ER model is converting the conceptual one to data structures. Consequently, the attributes for each entity are identified to describe that entity based on the SARA's requirements in term identification of the primary key(s) per each entity as shown in Figure 7. The description of attributes per each entity are as follows:
(1) SENSOR: A sensor ID acts as a primary key to identify the sensor name and its description. The sensor is used to scan and measure the points on the surfaces of the inspected part.
(2) P.C. DATA: It includes an identifier the describes the zone that is represented by point clouds and the stored location where can be referred to these point clouds for understanding the characterizations of different types of defects if any.

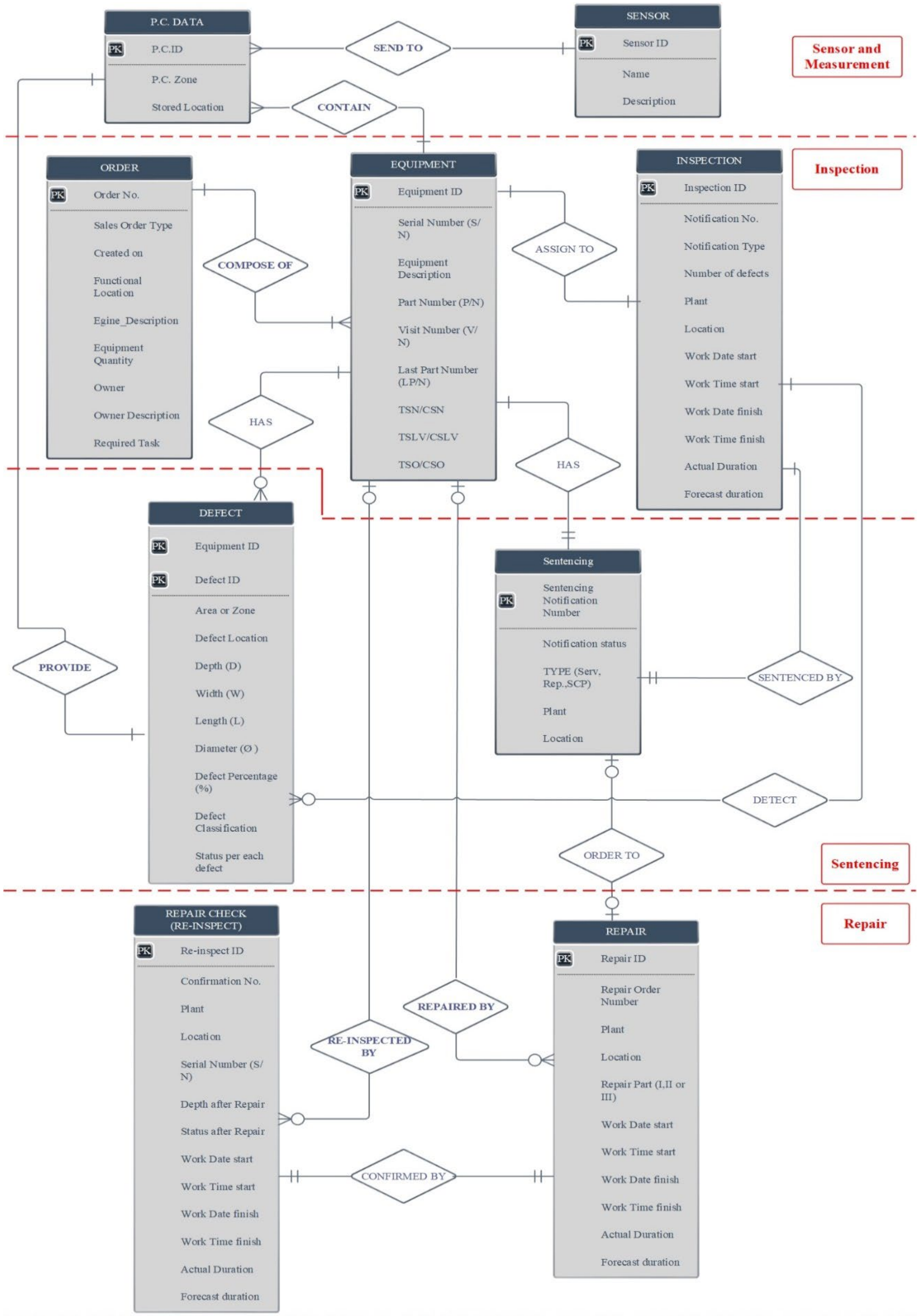

Figure 7. Logical ER Modeling for SARA system

(3) ORDER: An order is carried out with an order number and at a defined date. The order number is considered the primary key of this entity because it is unique. The type of sales order may be internal or external. If it is an internal order, so the functional location, engine description, number of inspected parts, the owner and owner description must be defined. On the other hand, the external order concerns the information of the number of parts required to be inspected, and the required task whether, repair or overhaul.
(4) EQUIPMENT: Each inspected part is defined by a unique identifier. Each inspected part has its own serial number(S/N). The reason for using an identifier instead of S/N as a primary key is that one part can be assigned to inspection, repair, and re-inspect several times, so the identifier differentiates between each time. Part and material numbers are specified based on the type of the inspected part such as fan blade, HPT shaft, or Curvic teeth of fan disc. The Part number can be modified after several repairs, so it is necessary to mention the last part number (LP/N) if any. Generally, these numbers are found in the engine manual. In addition to the inspected part information related to total Time Since New (TSN), Cycle Since New (CSN), Time Since Last Visit (TSLV), Cycle Since Last Visit (CSLV), and Time Since Overhaul (TSO).
(5) INSPECTION: An inspection ID acts as a primary key to describe the notification number of the inspected part(s). In other words, if the inspection order includes many parts, so each inspected part has its own inspection ID. Moreover, it determines the time duration taken by the inspection machine. It includes the forecasting required time to finish the inspection.
(6) DEFECT: The entity is defined with the Equipment ID of the inspected part which is considered a primary and foreign key at the same time. It is a foreign key because it belongs originally to the EQUIPMENT entity as a primary key. On the other hand, it is a primary key, in addition to defect ID because defect ID can be repeated for different inspected parts. for example, defect ID#1 can be found in two or more inspected parts having different Equipment IDs. Thus, the Equipment ID and defect index describe the entity because they are unique together.
(7) SENTENCING: Each inspected part has its sentencing notification that determines its condition. Plant and location attributes are used to mention that the process is carried out using the inspection machine in the SARA system. The decision type can be serviceable or repairable or scrap.
(8) REPAIR: The entity is defined by repair ID because more than one inspected part may be subjected to the same repair procedures when the original task is an overhaul; for example, the 24 fan blades of the compressor. Therefore, these parts have the same repair order. Moreover, it identifies the repair scheme and procedures in addition to the duration time taken for repair and forecasting time.
(9) RE-INSPECT: A re-inspect ID defines the entity. It provides a confirmation number for the repaired part(s) to demonstrate that the repair procedures are carried out as engine manual regulations. This is carried out by measuring the depth after repair. Plant and location attributes are used to mention that the process is carried out using the inspection machine in the SARA system. The duration times taken for re-inspect and forecasting time are determined.

Therefore, all the required information and business requirements related to the SARA system are captured by the proposed logical model. The model documents the inspection and repair process through the previously mentioned entities. It defines the attributes and primary key for each entity and clearly describes the relationships between these entities. To validate the SARA model, the relationships of the model should satisfy the business rules of the application. Figure 8 shows a transaction sample of the EQUIPMENT entity. This transaction presents the necessary information of the EQUIPMENT entity as in Figure 7. Additionally, it shows its relationship with the other entities. The inspected part identified by "Equipment_ID =1" is ordered by the order number "Ordert_Order_No = 14000" which is linked to the primary key "Order_No" of ORDER entity as shown in Figure 9. The essential information of the engine and mechanical part are defined when exploring the "Order_No = 14000", similarly for the INSPECTION, SENTENCING, REPAIR, REINSPECT entities as depicted in Figure 8.

4. Discussion
The SARA model captures all the information relevant to the aspects of the SARA system based on the three axes. The model defines the criteria of the three candidate parts; fan blade, HPT shaft, and Curvic teeth of fan disc; and traces their inspection and repair processes. Moreover, it represents the data flow through the process. The ER modeling technique assists in mapping out and managing the information flow in database management of the SARA system by the representation of the conceptual and logical models. The relevant entities are defined in addition to the identification of the relationships between them. Each entity contains a set of attributes that clearly describe the characteristic of that entity. Consequently, it provides a representation of a structured database with high data quality in terms of completeness, consistency, accuracy, absence of data redundancy, and integrity. The model meets the requisite information for the stakeholders, which were checked with each stakeholder before. The constraints and

business rules are implemented in the model to ensure the completeness and accuracy of fulfilling the mandatory data and check even the optional data (i.e., external order). Therefore, the model reduces data redundancy. Further, the constraints ensure the data entry type, format, and size. The data are consistent as the information is the same and synchronized across the model. The model ensures data integrity where the relationships connect and trace all data in the database. Finally, the model supports the automated system to store, organize and provide the necessary information required by stakeholders.

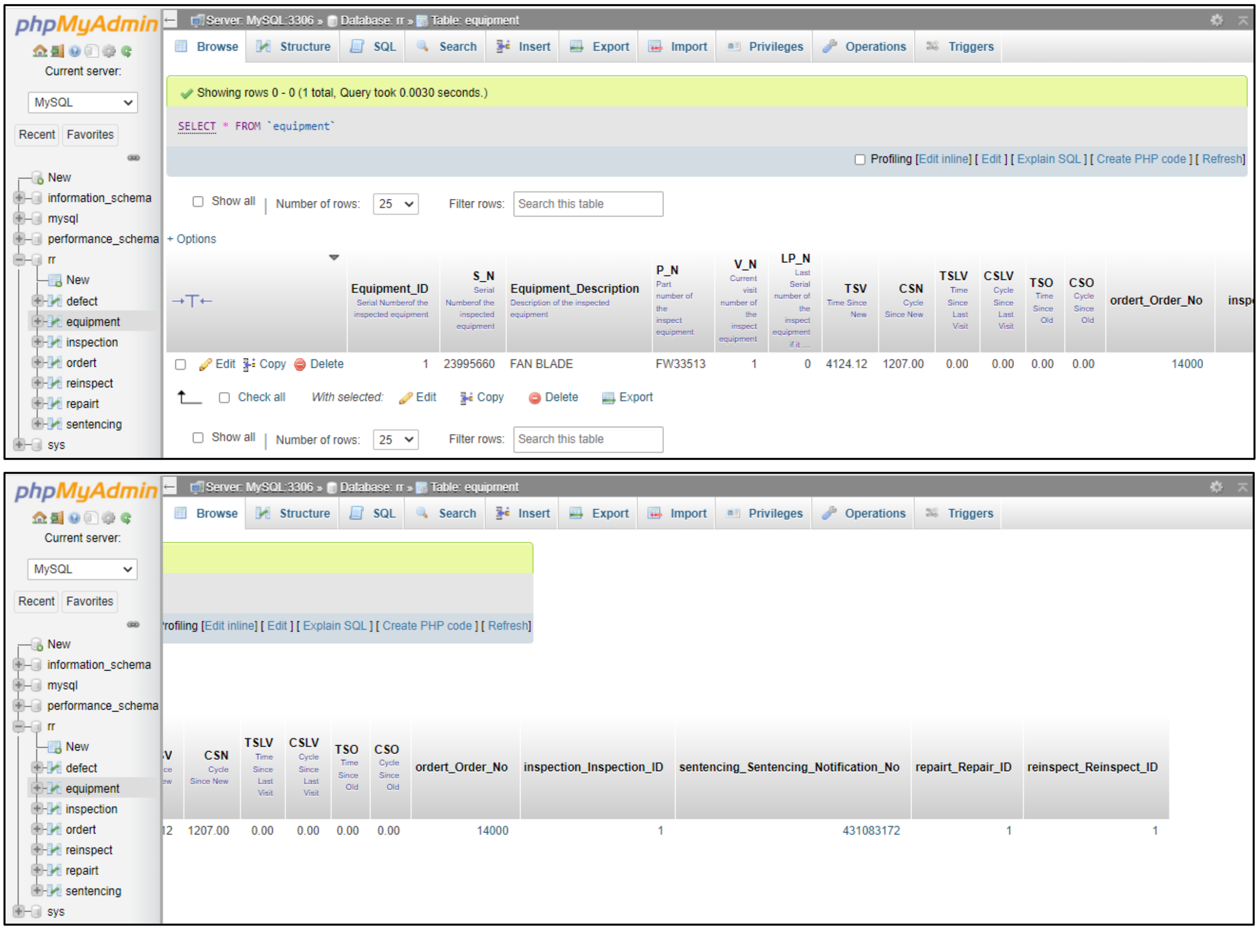

Figure 8. EQUIPMENT entity in the SARA Model

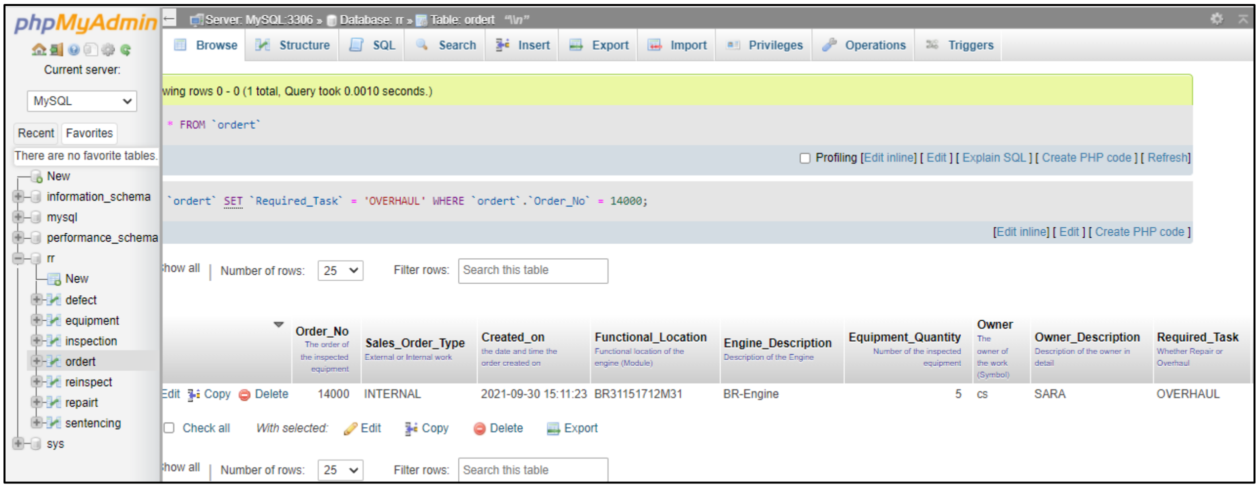

Figure 9. ORDER entity in the SARA Model

5. Conclusion

Quality 4.0 anticipates the digital transformation of quality management will improve the process and/or product quality and will increase productivity. Data automation supports the vision by monitoring the processes and collecting the necessary information. When the data management process is improved, it will be possible to identify the process variables that are required to be monitored by quality tools, for example, the control chart. ER modeling technique is widely used to design a data model that represents the data of the system in entity sets and describes their relationships. Moreover, it provides the key performance indices for quality to detect any anomalies during system operation. In this paper, we developed the conceptual and logical ER models for the SARA system which is an automated inspection and repair in the aerospace maintenance and repair domain. These models aim to organize the data in the system by identification of nine entities that represent the process, and their relationships with each other and their attributes. They characterize and control the information generated by the SARA system. Consequently, the data flow along the SARA model is visually represented and easily understood. The models favor accessibility, traceability, and reproducibility for better communication between inspectors and design specialists and tracking relevant information.

For future works, we will convert the logical ER model for the SARA system to a physical model that is implemented in the system. The physical data model represents the actual database design according to what is carried out in the logical one. The physical model defines the data types; numeric, string, date, or time, etc.; the foreign keys that link the entities, and the necessary constraints. It is used to support the implementation of the database using DBMS software. It provides a Data Definition Language (DDL) file, which is generated by MySQL Workbench software that will be implemented in the SARA system. Consequently, the automation of inspection and repair in the SARA system allows to enter the data that are defined in the model automatically, and provides the information that each stakeholder is interested in. After data preparation, we are targeting the implementation of the Quality 4.0 aspects. By providing the key performance indices for quality of inspection and repair actions, the information's variability of inspection and repair processes will be monitored by quality monitoring control tools based on machine learning and statistical control chart. This tool assesses the quality of the repair process based on the confirmation rate of the repaired parts to be within pre-specified limits. When the repair quality gets beyond these limits, the tool does not only detect abnormal behavior in the process but also, it determines the root cause of that out-of-control process. Then, corrective actions are taken to avoid several reworks of repair and maintain the repair process within the quality control limits.

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Biographies

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