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Knowledge-based multi-agent system for manufacturing problem solving process in production plants

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ABSTRACT

This paper proposes a novel approach to develop a production-oriented software system aimed to assist shop floor actors during a Manufacturing Problem Solving (MPS) process. The proposed system integrates the problem-solving method 8D, Process Failure Mode and Effect Analysis (PFMEA), Case-Based Reasoning (CBR), and Product Lifecycle Management (PLM). The system is based on an ontology that enhances and extends existing proposals to allow representing any type of manufacturing problem linked to production lines and reusing PFMEA analysis results. The architecture of the system is based on SEASALT (Shared Experience using an Agent-based System Architecture LayouT), which is a multi-case base domain-independent reasoning architecture for extracting, analyzing, sharing, and providing experiences. A proof of concept prototype was developed, implemented, and tested in a company. The results, which were collected in two different manufacturing plants of the company, show the feasibility of the proposed approach and validate the conceptual proposal presented in this paper.

1. Introduction

Analytical methods are typically applied to prevent failures during the design phase of manufacturing processes and machinery. PFMEA (Process Failure Mode and Effect Analysis) is a preventive technique that allows identifying potential failure modes of a process and the effects of such failures. It also allows assessing the criticality of these effects on the production process. From a conceptual perspective, PFMEA is a preventive technique that helps avoid the occurrence of problems during the execution of manufacturing processes [1]. Nevertheless, despite the application of such preventive techniques, unforeseen failures can still occur during the operation of manufacturing systems.

A failure is an event in which some part of the manufacturing system does not perform according to its operational specifications. As a consequence, production is disrupted and production targets may not be reached. The gap between the resulting state and the intended state is a production problem. When a production problem appears, a procedure to analyze the problem in detail and generate a solution is needed. Several systematic methods such as PDCA, OPDCA, DMAIC, PROACT, Shainin, Kepner-Tregoe, and Eight Disciplines (8D) have been developed with that aim in mind. Such methods are framed under Continuous Improvement Process (CIP) and Manufacturing Problem Solving (MPS) [2–6]. Arguably, 8D is the problem-solving method that is more oriented to the resolution of production problems. Developed by Ford Motor Company in the early 1990′s to support their plants and suppliers in the problem solving activity, 8D comprises eight main steps: (1) definition of a team, (2) description of the problem, (3) definition of containment actions, (4) root cause analysis, (5) definition of potential corrective actions and verification of effectiveness, (6) introduction of corrective actions, (7) definition of preventive actions and lessons learned, and (8) congratulate the team [8]. The knowledge and experience of team members [9,10] are key elements to implement any problem-solving method. These methods provide a structured process

Abbreviations: 8D, Eight Disciplines; AML, Aras Markup Language; CBR, Case-Based Reasoning; CIP, Continuous Improvement Process; ECR, Engineering Change Request; GUI, Graphical User Interface; ID, IDdentification number; KM, Knowledge Management; LLS, Lessons Learned System; MES, Manufacturing Execution System; MPS, Manufacturing Problem Solving; OEE, Overall Equipment Effectiveness; OWL, Ontology Web Language; PFMEA, Process Failure Mode and Effect Analysis; PLC, Programmable Logic Controller; PLM, Product Lifecycle Management; PPR, Product, Process and Resource; PSS, Problem Solving Sheet; SEASALT, Shared Experience using an Agent-based System Architecture LayouT; XML, eXtensible Markup Language

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to facilitate the improvement and finding of solutions. Nevertheless, although training is generally provided to team members, these methods only bring good results when they are driven by actors with enough experience who get additional support knowledge (e.g., provided by a software tool [9,10]). The literature also shows that the industrial application of PFMEA is complex, time consuming, and inefficient [11]. In addition, it provides a low outcome, its results are not revised during regular continuous-improvement activities, and there are issues to keep an efficient feedback [11]. Part of the problem with PFMEA relates to the fact that it is based on a spreadsheet approach, which makes it difficult to reuse results and identify similarities [11].

This paper proposes a Knowledge Management (KM) approach that aims to:

- Facilitate the reuse of PFMEA analysis results.
- Facilitate the capture and reuse of data and knowledge of manufacturing processes, at shop floor level, in any manufacturing plant, during daily MPS activities linked to the Overall Equipment Effectiveness (OEE) improvement. Among the different topics considered by OEE, the focus is set on quality issues with product and processes (i.e. quality claims and scrap), abnormal production speed, and breakdowns.
- Provide shop floor actors with a problem-solving software tool based on the 8D method, which can be used even by users with very low knowledge of the manufacturing system with which they work.
- Support manufacturing knowledge sharing and integration across different manufacturing plants.

The proposed KM approach comprises the integration of the 8D MPS method [8] with Case-Based Reasoning (CBR) [12,13] on an agent-based distributed architecture with a Product Lifecycle Management (PLM) system [14,15] and PFMEA [1]. The 8D method provides a structured way to guide the resolution of problems step by step. CBR is used as an artificial intelligence tool to search for similar manufacturing problem cases collected previously in multiple locations. PLM is used as a source of extended context information about Product-Process-Resources (PPR) that will enrich the similarity calculation of the CBR application. PFMEA is used as source of the initial set of cases to feed the CBR application. One main contribution of this work is the integration of these four techniques: 8D method, CBR, PLM, and PFMEA.

The reminder of this paper is structured as follows. Section 2 contains a literature review of the main topics related to this work: manufacturing problem knowledge representation, PLM and CBR. Section 3 discusses the created models, which are the basis of the ontological approach adopted to define the data structures needed to manage manufacturing problem knowledge. Section 4 describes the developed prototype application and its validation. The paper ends with the conclusions and future works.

2. State of the art

2.1. Representation of manufacturing problems and PFMEA

Manufacturing problems need to be described in a consistent and systematic way in order to allow for a common understanding by the MPS personnel and an appropriate processing by a software system. One way to address this need is by means of an ontology [16]. Literature shows proposals of different ontologies focused on manufacturing related issues [17,18]. Manufacturing is a very wide domain and, depending on the specific area of interest, ontologies comprise a variety of manufacturing related concepts.

Chungoora et al. [18] propose a manufacturing core ontology with a manufacturing planning orientation, which comprises concepts related to product design and manufacturing processes and resources. The main concepts are: PartFamily, DesignFunction, Feature, ProcessPlan, ManufacturingMethod, ManufacturingProcess, ManufacturingResource, and ManufacturingFacility.

When considering the representation of concepts dealing with MPS and PFMEA, Kamsu-Foguem et al. [19] propose an ontology based on conceptual graphs to formalize knowledge in an experience feedback process. However, PFMEA concepts are not supported. Experience feedback is considered a relevant approach to support MPS with lessons learned formalized knowledge. The ontology comprises the following main concepts: feedback_object, experience_element, experience, action and attributes. The ontology also includes their corresponding specializations: activity, product, process, resource, competency, solution, context, analysis, event, positive_event, and negative_event. Scippacercola et al. [20] propose the use of SysML to create a system model where artifacts contain FMEA related information. The FMEA information is represented as a description of the logical states of the input flows, blocks, and their corresponding constraints. A transformation translates the annotated FMEA SysML model elements into facts and rules of a Prolog base. A Prolog engine queries the created model to derive FMEA results. Ebrahimipour et al. [21], Dittmann et al. [22], and Mikos et al. [23] present three examples of ontologies to support FMEA concepts, with the aim of facilitating the reuse of information stored in FMEA analyses.

Ebrahimipour et al. [21] propose an upper ontology where three concepts related to FMEA information (i.e., deviation, cause and consequence) are modeled as an event and activities. A deviation is modeled as an event, which is the beginning of a consequence. A consequence is an activity. A cause is an activity that causes a deviation.

Dittmann et al. [22] propose a ROOT_CONCEPT class that is specialized into seven subclasses: FMEA, Component, Function, Failure_mode, Control_method, Risk_priority_number, and Containment_action. They also propose a set of relationships among the classes. For instance, the "fulfills_a_function" relationship relates a Component to a Function, and "has_failure_mode" relates a Function to a Failure_mode. The classes Component and Function have associated taxonomies.

Mikos et al. [23] use the standard SAE J1739 and AIAG FMEA Reference Manual to define a PFMEA ontology. In addition to the PFMEA concepts modeled as classes (LocationOfFailure, PotentialCausesOfFailure, PotentialEffectsOfFailure, EndEffect, LocalEffect, PotentialFailureMode, and FMEADescription), the ontology seems to support the concepts of product, process, and function.

After reviewing the mentioned ontologies, the works from Chungoora et al. [18] and Dittmann et al. [22] were taken as reference. Section 3.2 explains the selected concepts that were adopted and the new concepts that are proposed, which are part of the contribution of this work.

When analyzing a manufacturing problem, it is important to know the context where it happens. The context information can be structured into three main areas: product, process and resource (PPR). PLM systems are considered the main source of PPR information. Therefore, the ontology must consider concepts managed by such systems.

2.2. Product lifecycle management as data repository for manufacturing problem solving

A PFMEA analysis is performed in a specific process and, thus, the information to be used is restricted to the components of that process. The identified potential failure modes relate to a specific manufacturing context, i.e. process, process step, machine, tooling, process parameters, and product manufacturing feature. Therefore, it is necessary to compare the context where a manufacturing problem occurs with the context of each existing PFMEA analysis in order to evaluate their similarity. In that way, PFMEA knowledge can be reused to assist in the solution of a specific manufacturing problem. The context of the problem can be described in the form of PPR data, which sets clear differences among problems. Lundgren et al. [11] consider PFMEA as part of the quality assurance activities and end up using a similar approach.