PLM applied to Manufacturing Problem Solving: A Case Study at Exide Technologies

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Abstract

This chapter presents a case study of a prototype Knowledge Management system that supports the process of Manufacturing Problem Solving in a multinational company. The prototype system allows capturing and reusing knowledge generated during the resolution of Overall Equipment Effectiveness (OEE) problems in multiple locations at shop floor level. The developed system was implemented in Exide Technologies.

The system integrates the 8D method, Case-Based Reasoning (CBR) and Product Lifecycle Management (PLM). The PLM system is used as the source of extended problem context information (i.e. Products, Processes and Resources) that will enrich the similarity calculation of the CBR application. Process Failure Mode and Effect Analysis (PFMEA) is used as the source of the initial set of cases to populate the case-base. From the development perspective, the system comprises a multi-agent architecture based on SEASALT (Shared Experience using an Agent-based System Architecture LayouT) and programmed in Java. The development infrastructure comprises: Eclipse, JADE (Java Agent DEvelopment framework) and AML (Adaptive Mark-up Language) studio. The selected software applications are myCBR and Aras. The prototype system was tested and validated in three main steps with an increasing level of complexity. The results demonstrated the feasibility of the adopted approach. An overall description of the system, results, lessons learned, and recommendations are provided.

Case Study Company

Exide Technologies (www.exide.com) is a global provider of electrical energy storage solutions, batteries, and associated equipment and services for transportation and industrial markets. It has about 130 years of industry experience and operates in more than 80 countries. Leading car, truck and lift truck manufacturers trust Exide as an original equipment supplier, and Exide serves the transportation and industrial aftermarket through a comprehensive portfolio of products and services.

For this case study, two plants of Exide Technologies, one located in Germany, and a second one located in Spain, were selected. The selection criterion was that they produce similar products with similar processes. In particular, they produce motive power batteries for the industrial market (i.e. forklifts or similar applications), and both of them use the Wet Filling process to manufacture the positive plates of the batteries. A second Casting process was also selected for testing purposes in the German plant. Casting is used to manufacture the negative grids. More details about these processes are not relevant for this work, and due to confidentiality issues, they are not presented.

Exide Technologies, as most of the manufacturing companies in the world, faces issues related to knowledge management. This work aims to address a few of them, which can be summarised as follows:

- The continuous pressure to reduce costs, and with this, to ensure competitiveness in the market, pushes manufacturing companies to apply Lean Manufacturing methodologies. In some cases, this implies moving the spotlight from highly educated, but expensive staff, to blue-collar employees (i.e. line operators, group leaders, and quality inspectors) as key drivers of the Continuous Improvement Process (CIP) ([1], [2]).
- The point above is reinforced by the Research Global Manufacturing Study conducted by Deloitte [3]. This study shows that manufacturing has nowadays a negative image in the eye of many young workers when compared to the new technologies business. This creates thus a talent attraction problem of highly educated staff and gives even more relevance to the inputs from blue-collar employees.
- When blue-collar employees dedicate time to tasks different from producing parts, it means that the targets at the end of the shift will be missed. Therefore, even when management encourages them to participate actively in the CIP of the company, they are also put under pressure when the production targets are not accomplished.
- Knowledge sharing is a relevant issue, particularly in multinational companies. Most of these companies have different manufacturing plants, distributed geographically in different locations, and with similar processes, but they suffer from communication barriers due to multiple reasons such as distance, language, or belief in knowledge as power or a survival tool ([4], [5]).
- Potential failure modes of the manufacturing processes can be identified during their development phase by using preventive methods like PFMEA (Process Failure Mode and Effect Analysis). Nevertheless, this information is seldom used on the shop floor. The literature shows that the industrial application of PFMEA is complex, time consuming, and inefficient [6]. Additionally, it provides a low outcome, its results are not revised during regular continuous-improvement activities, and there are issues to keep an efficient feedback. Part of the problem with PFMEA relates to its documentation being very often based on a spreadsheet approach, which makes it difficult to reuse results and identify similarities.

Proposed Approach

Despite the application of preventive techniques, such as PFMEA, unforeseen failures can still occur during the operation of manufacturing systems. A manufacturing failure occurs in a specific manufacturing context and generally implies that some part of the manufacturing system does not perform according to its operational specifications, as a consequence, production targets can be missed. To address this kind of situation, a systematic approach is needed to reach and exceed the defined production targets. Typically, manufacturing problems are analysed and solved by teams, following a Manufacturing Problem Solving (MPS) process and working directly at the shop floor. The process comprises the use of different techniques and methods. Although training is generally provided to team members, the process only brings good results when it is driven by people with enough experience and with access to additional support knowledge, e.g. by means of a software tool ([7],[8])

The proposed approach aims at capturing and reusing knowledge generated, across multiple locations, when executing a Manufacturing Problem Solving (MPS) process at shop floor level. It is specified in three models: an MPS process model, an MPS knowledge representation model, and an MPS system architecture model. These models represent the specification to develop a prototype application where the proposed approach is implemented ([8], [9]).

The proposed approach integrates the 8D method [10], Case-Based Reasoning (CBR) [11], Product Lifecycle Management (PLM) [12] and PFMEA [13]. The 8D method is a structured method to guide the resolution of problems step by step. Case-Based Reasoning (CBR) is used as a repository of cases and an artificial intelligence application to search for similar manufacturing problem cases collected previously in multiple locations, and it is implemented on an agent-based distributed architecture. A Product Lifecycle Management (PLM) system is used as the source of extended problem context information (i.e. Products, Processes and Resources (PPR)) that will enrich the similarity calculation of the CBR application. PFMEA is used both as the basic reference to create an ontology, on which the system is built, and as the source of the initial set of cases to feed the CBR application. The specific knowledge to be managed is the one recorded in the PFMEA during the process development phase, as well as the knowledge generated during the daily CIP 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. Information available in the company, e.g. in a PLM system, can be used to improve the efficiency of the knowledge sharing.

From this perspective, this work presents the case study conducted to evaluate a prototype development that implements the created models. The main constraints for the development of the prototype application can be summarised as follows:

- It has to be used directly at shop floor level.
- It has to propose possible solutions to problems that are identified during daily CIP activities linked to the OEE improvement.
- It has to allow recording information related to solutions applied to solved problems, to increase the knowledge base of the system with relevant cases.
- It should be intuitive and easy to use, since the target users are shop floor employees.
- It has to request very few data about the manufacturing problem to compensate the possible lack of time and knowledge of the user.
- It has to follow an MPS methodology to guide the user in the resolution of the problems identified during the CIP activity.
- It has to allow reusing knowledge stored in existing PFMEA documents of the company.
- It should allow simultaneous access by multiple users from different plants, supporting in this way the sharing of knowledge within the company.

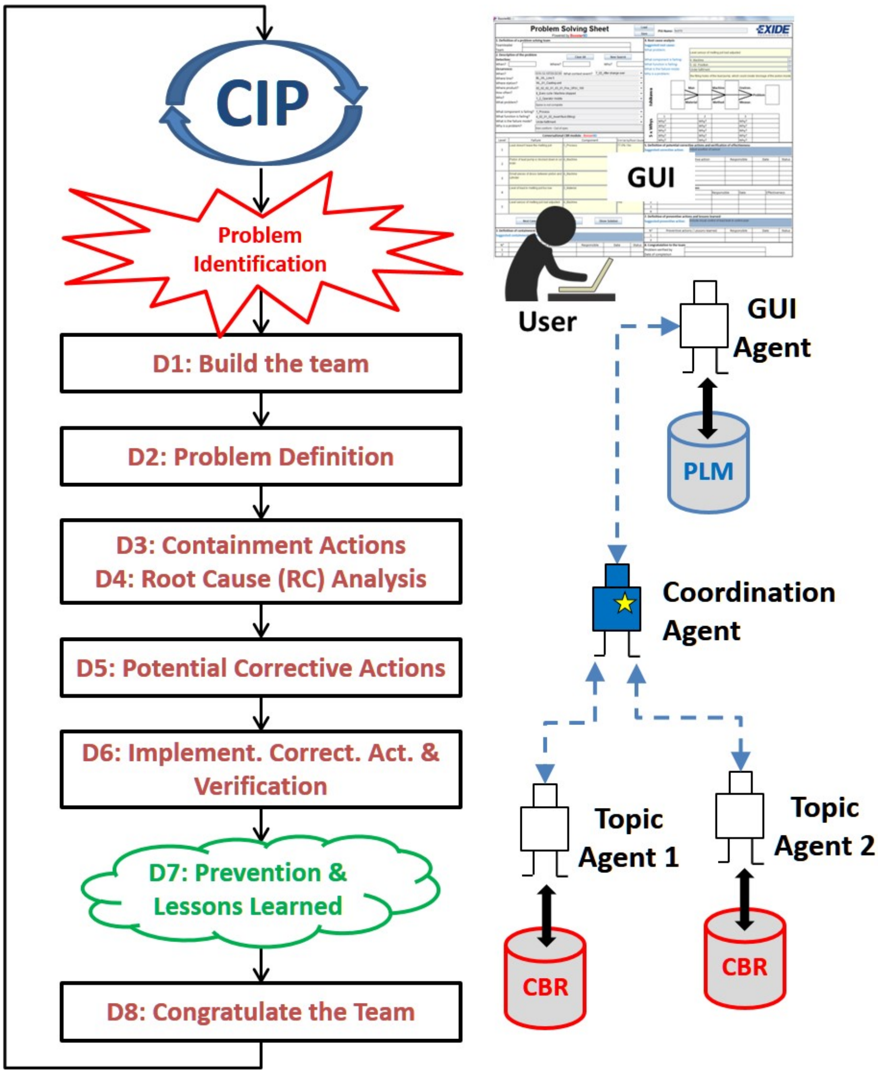

Figure 1: Proposed Manufacturing Problem Solving process and Knowledge Management prototype system

Figure 1 shows a view of the Manufacturing Problem Solving (MPS) process followed by the developed knowledge management prototype system. The communication among user, agents and main applications is also illustrated.

The MPS process model defines the steps to be taken by the user to solve a problem. It follows basically the steps defined in the 8D method [10]. It specifies also the kind of interaction expected at each step between the user and the system. A Graphical User Interface (GUI) was developed to support the interaction with the user along the process ([8], [9]).

The MPS knowledge representation model comprises the following main concepts: Problem, Component, Function, Failure, Context, and Solution. The relations among these six concepts, their associated taxonomies, and their parameters were designed to fulfil several constraints: support a generic definition of a manufacturing process and its location, be compatible with the information structure of the PFMEA method, comprise concepts to describe different aspects of a manufacturing problem, and allow case similarity determination [8].

The proposed MPS system architecture model is based on SEASALT (Shared Experience using an Agent-based System Architecture LayouT) [14], which supports the deployment of the different agents across different manufacturing plants. Within each plant, agents can be deployed across the areas with different manufacturing processes. In this way, each topic agent, hosted in a specific manufacturing process of a specific manufacturing plant, is able to collect and to store knowledge related to its own area, becoming an expert of its process and plant. By means of a coordinator agent, a topic agent can communicate and exchange information with all the other topic agents hosted in different processes and/or plants through the company's intranet. Each topic agent has its own case base and uses CBR technology to find the most similar cases related to a user query. This information exchange supports the MPS process by providing the user with solutions for the most similar failures stored in any topic agent of the architecture [8], [9].

Implementation

The implementation of the proposed approach was conducted in a knowledge management prototype system. The method to develop the prototype system was divided into the following steps:

- Selection of a suitable IT infrastructure: development environment, Case-Based Reasoning tool and PLM system.
- Programming and customisation of the software tools to support the developed models.
- Testing, fine-tuning and validation of the prototype system.
- Population of the system with the information and cases from one manufacturing plant of Exide Technologies.
- Execution of case studies in two manufacturing plants of Exide Technologies to obtain results and extract conclusions.

The selected development environment includes Eclipse to program the prototype software, JADE (Java Agent DEvelopment framework) to monitor the behaviour and communication of the agents, and AML (Adaptive Markup Language) Studio to develop and test the communication between agents and the PLM system. The implemented communication model is a simplified version of SEASALT [15]. SEASALT is a multi-agent architecture from which three types of agents were selected: GUI agent, topic agent and coordination agent; they communicate with each other to provide solutions to the user [14].

The selection of the IT infrastructure was driven by a balance among openness, functionality, compatibility, and easy access to the applications. myCBR (www.mycbr-project.net) was the selected CBR software. Aras Innovator (www.aras.com) was the selected PLM system. Aras Innovator is developed on Microsoft technology, which makes it compatible with all the systems and software infrastructure available in the company. It also offers a communication tool based on an XML (eXtensible Markup Language) dialect language (AML) that allows extracting any type of data from the PLM database.

SEASALT, and its current instantiation, is based on JADE, therefore Java was selected as the programming language. The Luna release of Eclipse was selected as the development environment. Eclipse is an Integrated Development Environment (IDE) used in computer programming and is one of the most widely used Java IDE (www.eclipse.org). Luna was the default release at the time of installation.

JADE was used for the control of the communication and behaviour of the agents. This environment is linked to the SEASALT architecture. JADE (jade.tilab.com) is probably the most widespread agent-oriented middleware in use today. This framework facilitates the development of complete agent-based applications by means of a run-time environment, implementing the lifecycle support features required by agents, the core logic of agents themselves, and a rich suite of graphical tools.

The last development tool was AML Studio. This is part of the software installation package of Aras Innovator. It supports the connection with the server of Aras to interchange messages using the AML language. Clients submit AML documents to the Aras Innovator server via HTTP, and the server returns an AML document containing the requested information.

Based on the information model created for the PLM system [9], staff from production and engineering, located in the selected German plant of Exide, were interviewed to identify the characteristics of the wet filling reality that make different each product, machine, process, worker, or environment from each other. These differences are the key to distinguish problems from each other in the similarity calculation executed by the CBR system. The steps followed in the interviews were:

- Identification of key elements.
- Identification of their relationships.
- Identification of the relevant attributes.

All the elements, relationships and attributes were mapped into the created model and then incorporated into the PLM system by using the creation and modification functionalities available in Aras.

A similar customisation step was conducted with myCBR. For the defined two case studies, the different case bases in the prototype application were populated with a total of 226 cases. These cases were collected from the existing PFMEA documents, and from problems solved at the production lines. The latter were recorded during the implementation time of the developed prototype.

The user manages the system through the GUI. The GUI represents a Problem-Solving Sheet (PSS) divided into the corresponding areas of the 8D method. The user inputs the description of the problem through the GUI. The user must provide an answer to the questions 'What?' (a brief description of the problem), 'When?' (date and time), 'How often?' (frequency), 'Where?' (this question is divided into three different fields related to the line and station where the problem happens and the product that is being produced), 'Who?' (operator name), and 'Why?' (a brief description of why it is a problem). Based on the input from the user, a GUI Agent sends a query to the PLM system to receive the contextual information related to it. Then, a comprehensive query, comprising both the user's input data plus the retrieved context data, is sent to the Coordination Agent. This agent needs to collect a set of possible solved cases from the available CBR systems. The Coordination Agent communicates with the different topic agents to request proposals for similar problems. The case base of each topic agent needs to be populated with an initial set of cases (i.e., already solved problems). To do so, the company's PFMEAs were taken as the initial set of cases. The case base can be continuously extended with new solved problems. The decision to include a new solved case is taken by an expert. Based on the received responses, the Coordination Agent is configured to send only the ten most similar cases to the GUI Agent. The information is then shown to the user through the GUI. Figure 2 shows the communication model [9].

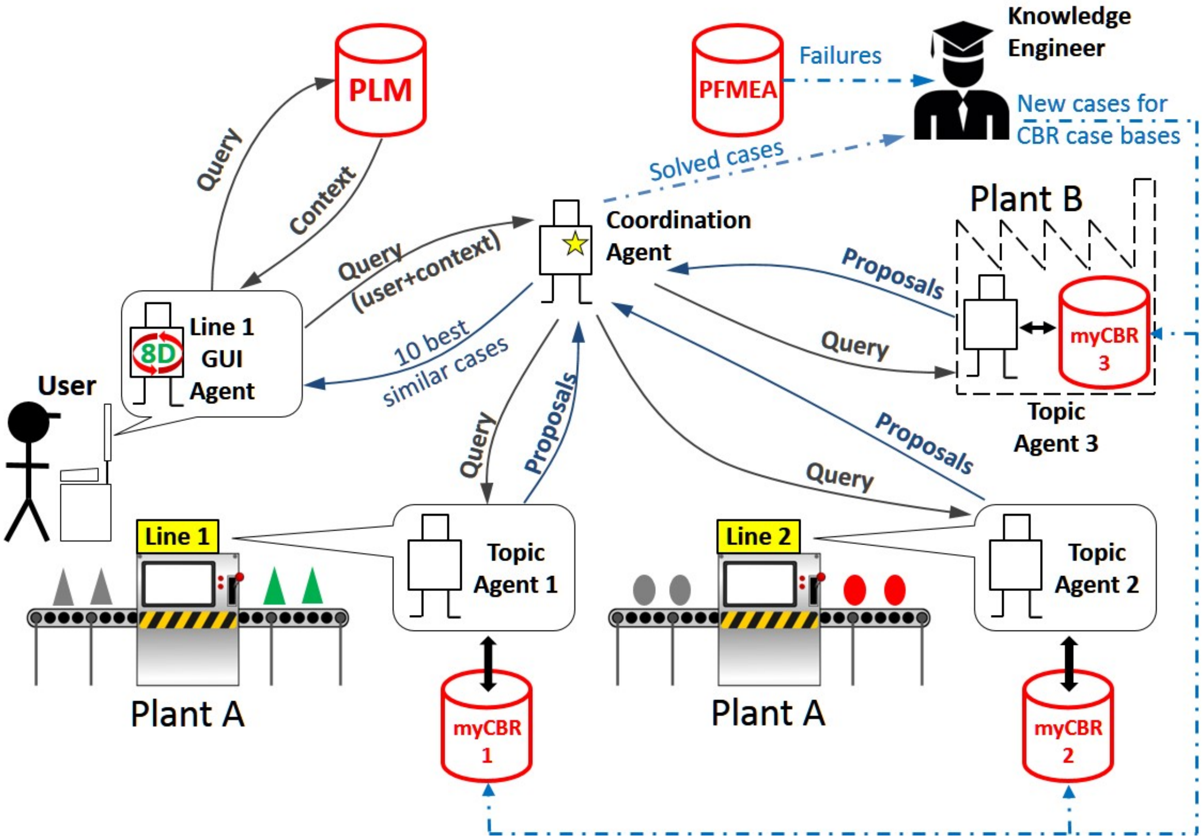

Figure 2: Communication model of the prototype system [9]

Results

The prototype system was tested and validated in three main steps. For the first validation step, the Wet Filling production area in Plant A, located in Germany, was selected (Case A). Case A represents the lowest level of complexity for the system, since the cases were all collected in this process and plant. The Wet Filling production area in Plant B, located in Spain, was selected for the second validation step of the prototype system (Case B). Case B represents a higher level of complexity for the system, since it occurs in a different manufacturing context (plant) from where the knowledge was collected. The types of problems in both plants can be quite different (e.g., machines can be different, some materials are bought from local suppliers, and personnel have different levels of training and experience). Finally, for the third validation step, the Casting production area in Plant A, located in Germany, was selected (Case C). This Case C represents the highest level of complexity for the system, because the case base did not contain any kind of problem from this area and the PLM system was not set up with data about this area either. The objective was to evaluate the response of the system to a situation where a problem arises in a manufacturing process that is not included in the prototype system. In the three cases, the corresponding group leaders were trained and used the prototype system to solve ten problems that arose during their shifts. Queries, results, and real solutions were all recorded for a detailed analysis and evaluation afterwards [8]. Figure 3 shows an example of the developed GUI with input data and results proposed by the system.

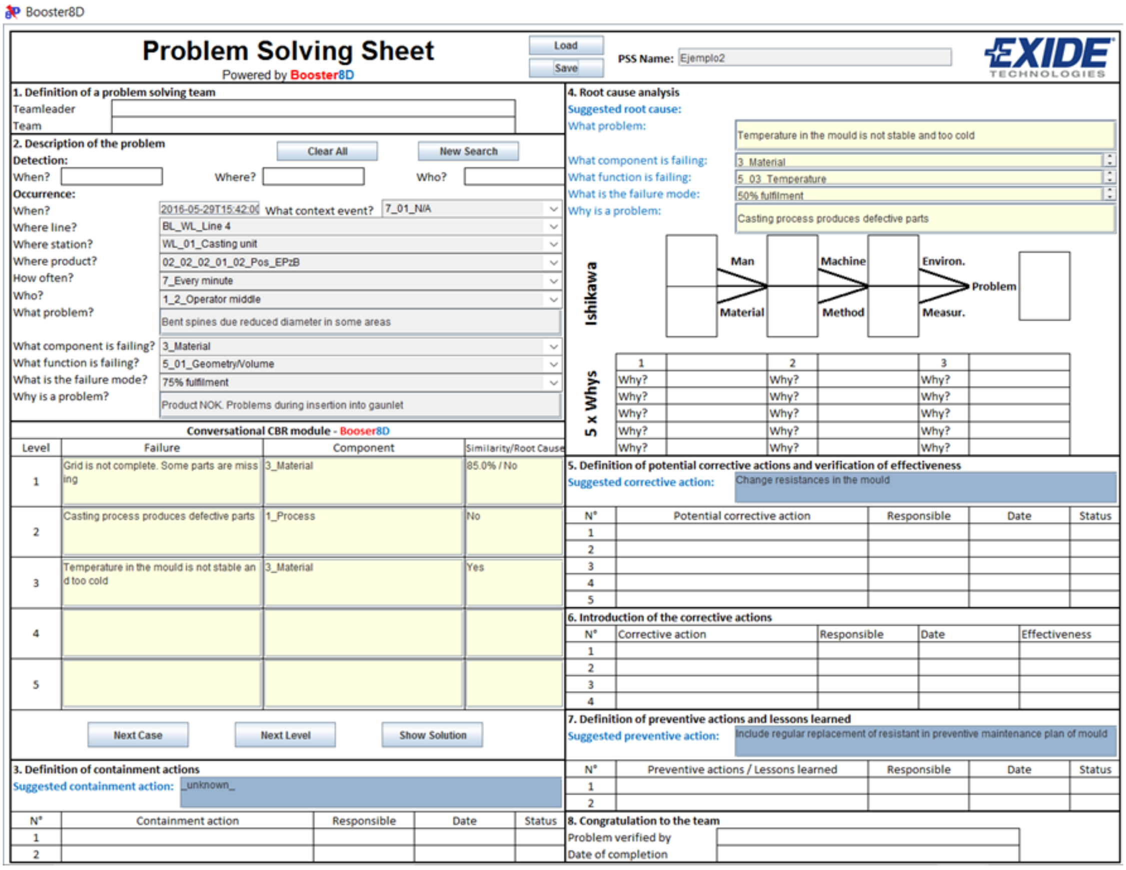

Figure 3: Developed GUI with data

The execution of the cases using the developed prototype demonstrated the feasibility of the adopted approach. Depending on the case, the suitability percentages of the proposed solutions were different. The overall values were: 90% for problems in Case A, 80% for problems in Case B, and 20% for problems in Case C [8]. The suitability percentages reflect how close was the testing environment to the cases stored in the case-base. The overall conclusion was that the approach fulfils the aim of assisting shop floor manufacturing employees, such as operators or quality inspectors, in the execution of MPS processes, which are characterised by knowledge intensive activities heavily based on prior experiences. The main benefits of the conducted work can be summarised as follows:

- It allows capturing knowledge at shop floor level of any type of manufacturing process and in any location with Internet access. Problems from different manufacturing processes collected in different countries and companies were represented without issues in the developed prototype system. The clarity and simplicity of the created model was illustrated by the profile of the person who collected problems at the production lines for two weeks. The person did not have any previous industrial background, and after an introduction to the model for about 30 minutes, was able to collect information concerning many problems properly, and also in the right format to be directly inserted into the case base of the prototype system.

- It allows reusing the captured knowledge. The prototype was able to provide solutions to the presented issues with significant percentage of success in two different manufacturing plants located in two different countries, and in two different manufacturing processes [8].
- It provides blue-collar personnel with a low time-consuming problem-solving tool, which can be used even by personnel with very low knowledge about the manufacturing process in which they work. With a short training, it is possible to fill the user query fields in the GUI in around one minute. The requested information about the problem under analysis requires a low level of knowledge. It just requires knowing the product name that is under production, and the structure of stations and substations of the line. The rest of the context information is provided automatically by the PLM system.
- It supports knowledge sharing across different manufacturing processes and locations. The flexibility of the agent architecture of SEASALT allows use of the system by many different users at the same time and in multiple locations. This was successfully tested in two manufacturing plants located in Germany and Spain.

Next steps

The developed system is a prototype, which means that work is still necessary to have it fully ready for its usage as a daily support CIP tool at the industrial level. There are quite a few lines that we consider to be worth investigating as future works. They can be summarised as follows:

- The development of the Knowledge Source and the Knowledge Formalization modules, which are part of the SEASALT architecture, to extract automatically knowledge from a PFMEA document. Currently, a PFMEA document is created on a semi-structured format and specific knowledge is introduced using natural language. This requires the intervention of humans to transform it into a structured format, to make it processable by a software application. In that direction, some research works propose the use of SysML to create a system model where artefacts contain FMEA information, and the use of a Prolog engine to query the created model to derive FMEA results [16].
- The use of semantic methods to collect information directly from free text describing a manufacturing problem.
- Adding a functionality to connect the proposed system with the Manufacturing Execution System (MES) used at the shop floor to integrate data from it. This connection should allow extracting automatically context event information like changeovers, starts of shifts, or change of operators at the line.
- An application test of the proposed approach integrating suppliers, manufacturers and customers, to achieve a collaborative CIP.
- The development of the adaptation container in myCBR to have automatic adaptation of the solutions proposed by the prototype system to the specific context of the user query.
- The display of visual media content in the GUI of the developed prototype would help to understand the problems and the proposed solutions. It would also help to remove the language barriers. As negative effect, it would demand more work to prepare the documentation.
- The systematic recording of manufacturing problems opens the door to the development of additional functionalities to process the stored data. For instance, a dashboard showing

statistics data and predictive analytics about: failures, components, suppliers, machine components, etc. This leads to analysing the use of machine learning techniques to make predictions and assist in decision making tasks.

- Development of a multi-language dictionary with all technical terminology to support the parallel use of the system by different users in different countries. With such a dictionary the system could translate automatically issues captured in a native language A into a different native language B.

Lessons Learned

The lessons learned along the execution of this work can be grouped into two main sets. One set relates to the knowledge collection process and a second set relates to the usage of the prototype system.

<u>Conclusions about the defined process to collect knowledge:</u>

- During this first phase of the project several peculiar behaviours, which can hinder the collection of knowledge related to problems, were observed in the operators. For instance, when operators or technicians try to explain how they have solved a problem, very often they give a list of different things that they did or changed in the machines, but they do not know which of them had real impact in the solution of the problem. It was also often observed that, even when operators fill in the Problem-Solving Sheet (PSS), following the eight steps of the method, in reality, they have figured out a solution previously. Then, they follow the MPS method from the beginning, but just looking for the arguments that justify their initial assumptions and solutions. This hampers completely the application of a CIP.
- PFMEA was considered as the initial source of information for the system. Nevertheless, a PFMEA document needs to have a certain depth of detail to be useful. A very generic document that focuses only on processes and does not take the analysis down to other components (e.g. machine or human resources), will be of very little help. The same consideration can be applied to other documents, from which problems and solutions could be extracted. For example, 8D documents with very poor problem descriptions or generic corrective actions do not add value.
- For the representation of a problem, it is recommended to start filling the information about “What problem” and “Why it is a problem”. This helps to settle down the reasoning about the problem. Then proceed to fill in the rest of the parameters.
- In a chain of problems, until a root cause is identified, it is possible to go from one step into the next one in a very detailed way (e.g. the machine tool is stopped> there is not enough coolant> valves do not operate properly> valves are dirty), or to jump quickly to the root cause (e.g. the machine tool is stopped, the coolant valves do not operate properly because they are dirty). The more defined steps, the easier it will be to reuse them in the future. More specific and detailed steps give the possibility to reuse any of the levels included in the case by a bigger variety of problems under analysis. A good practice, to ensure this during the representation of a case, is to observe which element is selected at the first level. It is recommended to select “Material” as the component of the first level, if the problem was identified as a quality issue in a product, and to select “Process” for any other case. In industry, problems are identified rather in products with poor quality (i.e. Material) or in

processes performing wrongly (i.e. Process). Then, in the following lower levels of analysis, the rest of the types of components can be selected. In this way, it is avoided to jump directly into conclusions and facilitates generating at least two or three levels of problem analysis in each case.

- When the name of the user of the system is explicitly recorded in the digital PSS, there is a clear possible rejection, or even blockage, from the operators or work council to use the proposed system and to share knowledge. There is a belief that this kind of tools can be used by the company as a personnel performance control tool.
- The context event information comprises, among others, the options: “New operator” or “New shift”. These two options create a conflict of interest. The context event information could not be always properly filled, because for an operator selecting as relevant event “New operator” or “New shift” means recognising his/her own guilt.

<u>Conclusions about the use of the prototype system:</u>

- The application of this model to unstable or very new processes, where their technical parameters are either not well defined or with extremely large tolerances, is very difficult. The difficulty derives from the definition of the similarity rules when there is a significant overlap in parameter values. This situation could arise when a process is used to manufacture more than one type of a product.
- In the developed prototype, the PLM system Aras Innovator was populated through its application user interface, which is extremely time consuming and a possible source of errors. It is recommended to develop macros to upload data automatically from Excel or csv files.
- The prototype system was developed to prove the theoretical concepts of this work. The PLM system was only configured to support until the level of the workstation. Therefore, data about lower level components were not included. At the maintenance level, searches are performed at lower level, therefore, data should be available in the PLM system to calculate the cases’ similarity properly. This shows that the implementation of a PLM system should be part of the highest-level company strategy.
- The proposed framework requires the pre-existence of computers at the shop floor level and a PLM system containing the PRR data of the company. This is a barrier to apply the proposed approach when that is not the case. Nevertheless, the current trend of digitalization in the industry [17] shows that the access to digital content from the shop floor will be more and more common in the near future.
- Another expected barrier is that the system requires incorporating, as much as possible, company existing data to create a significant set of cases. This implies incorporating data from existing documents (e.g. PFMEA, paper PSS, 8Ds, minutes of meetings) into the new data structure, and this process could consume many resources and much time at system set-up. For example, in the installation of a new CAD system in a company all old designs remain in the original format and they are only brought to the new format when they are involved either in a modification or used in a new project. However, in the presented system, if the PLM system of the company is not adapted to incorporate the defined data structure, and the data of existing documented manufacturing problems are not incorporated into the system, the system will not be able to provide the users with any solution proposal.

Advice

When considering the implementation of a similar system, there are a few recommendations that can be extracted from this case study. Some of them are common to any other industrial software system implementation, but perhaps it is worthwhile to emphasise them. The advice can be summarised as follows:

- Ensure proper support from management for the project. This will ensure both resources and enough time for the implementation.
- Start the project in a single manufacturing area that has enough relevance for the company. This will allow having impact after a successful implementation of the first prototype and will open the door for an easy spread of the project across other areas.
- The selected area for the first prototype should also have PFMEA documents with a good level of detail to populate the initial set of the case-base.
- This selected area should have enough performance troubles to give the system the possibility to show improvements quickly, but a too deteriorated area may put too much pressure on the project, not letting enough time for showing positive results.
- For the context information, it is important to select a reduced set of parameters. They should be the ones that allow differentiating strongly one case from another. Too many context parameters create issues in the similarity calculation, because the weight of each one becomes quite irrelevant.
- Provide support and early access to the system to the personnel at the shop floor. Spend enough time with them working with the new system. Make minor adjustments to fulfil their suggestions, then they will feel relevant and part of the project, and they will become motivated to use it.
- For the development of the software, it is critical to engage the IT department. They should provide the support needed to incorporate modifications into the PLM system, otherwise it may end in a never-ending bureaucratic process. Also, a lack of proper programming expertise in the project may cause the consumption of too much implementation time and deviate the focus onto software issues that add no value.

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Authors' Background

Alvaro Camarillo earned his Industrial Engineering degree in 2003 at the Universidad Politécnica de Madrid in Spain, where he is currently finalising his doctoral studies. Alvaro is Operations Director at Exide Technologies, and responsible for the coordination of the European manufacturing plants within the automotive business unit. He has fifteen years of experience in several technical and managerial roles in production plants. He is a strong believer of Lean Manufacturing and Continuous Improvement Process (CIP) as basic tools to ensure the sustainability and future of any business. He researches on Manufacturing Problem Solving (key activity within CIP) and how it can be supported with existing information available in the company. At this point, PLM arises as the logical and main source of true information about Products, Processes and Resources at any company.

José Ríos is Associate Professor in the Department of Mechanical Engineering at the Universidad Politécnica de Madrid, where he earned his doctoral degree in Mechanical Engineering in 1997. He has focused his work on the digital manufacturing area, and on techniques, standards and software systems involved. He has participated in projects related to digital manufacturing, CAD/CAM/PLM, information modelling, KBE and design integration, mainly in collaboration with companies from the aeronautical, automotive, and die and mould-making sectors. Along his professional career, he held a senior research fellow position at Cranfield University (UK) and he was the Spain representative to the ISO TC 184/SC4 for two years. He is a member of the IFIP TC5 WG5.1 Global product development for the whole lifecycle. Currently, he is a visiting researcher in the DiK Department at TU Darmstadt.

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