Conception of a prototype to validate a maintenance expert system

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***Abstract*— Decision making is crucial for the life of many production plants. Good decision need the right information at the right time, and a deep knowledge of the system. This is especially true for older plants that are more prone to failures. Unfortunately, these systems are less rich of monitoring and diagnostics instrumentation, because of their seniority. When the maintenance service is carried out by a group of external companies, they suffer the consequences of backwardness of the equipment, having to deal with problems of poor coordination, delays in interventions and so on. Small and medium enterprises are often in trouble facing these issues so they need dedicated resources in order to offer a maintenance service compliant to the costumer requirements. In this context a research project was funded, aiming at aiding the birth of a virtual enterprise network of maintainers, which should provide a maintenance service of the highest level in the field of legacy industrial plants. One of the most difficult steps of the project, was to design a prototype capable of testing the architecture of the virtual network, the expert system and the overall goodness of the proposal for potential customers. In this paper we describe how it was possible to design, produce and operate a prototype which could fit a virtual enterprise network of maintainers. The method requires, among other things, to fulfil a preliminary *selective* Failure Modes and Effects Criticality Analysis (FMECA) to be properly used to implement the diagnostic system.**

Keyword- supporting tool, data collection and treatment, condition based maintenance, virtual enterprise, FMECA

I. INTRODUCTION

Any company has to deal with decision making activities which are a vital part of their functioning. In this ever-competitive world, it is increasingly important to facilitate the business of taking decision by managers. To facilitate this process, it is necessary to have the right information at the right time, in order to bridge the gap between the needs and the expectations. To facilitate a better flow of information, there is an increasing need for information management systems, more and more adapted to the needs. For this reason, it is very important to have a clear understanding of their mode of operation and how they are integrated into a company at all levels of management [1]. Only in this way you will understand how the decision support system can be useful for making appropriate decisions [2] [3]. An information management system collects and processes all data and provides a organized summary for managers who will use them to make decisions, plan, implement programs, and control. The information management systems can play many roles as decision support, performance monitoring, and functional support [4], necessary to manage the reliability [5] [6], safety [7] and maintenance management [8] [9] [10] issues, which are some of the most interesting issues of international scientific research and are among the topics studied by the authors.

If we wanted a broad definition of what the asset management is, we should refer to any system that monitors and keeps working things of value to a particular group. This definition would apply both to tangible assets, such as industrial plants and to intangible resources, such as services and intellectual property. The asset management is, therefore, a systematic process of operating, maintaining, improving and ultimately dismantle structures or services in an efficient way from the costs point of view [11]. Other interpretations of engineering asset management are: the ability to manage the assets in order to obtain the maximum benefit, or the process of monitoring and maintaining industrial plants, with the aim of providing the best possible service to users. While the first definition is particularly suitable for production systems such as facilities and plant equipment, the second is most suitable for public infrastructure. However, these two explanations are very related to each other and the pursuit of the first objective generally involves also to achieve the second.

The management of industrial systems is closely linked to business information systems. These latter, in fact, are increasingly necessary, given the extent and complexity of the companies, not just of large companies. Even small and medium-sized businesses, in fact, are investing in appropriate systems to manage economic, fiscal and logistical constraints. These same systems can be enhanced and expanded at last to be of help in the moment of decision. The reduced size of small businesses could be a limitation in the implementation of advanced information systems. This, in theory, would prevent smaller companies to enjoy the benefits that modern control technologies and monitoring and diagnostics would allow to have [12] [13].

The procedures which make up the maintenance service, ask for the interaction of internal resources - required to manage the core business - and external suppliers for the remaining activities. In this scenario, deeply transformed in recent years, it is necessary to also adapt the business functions of maintenance engineering. These latter play a role that becomes much more important: the collection, maintenance, transmission of the know-how, or, in other words, its enhancement.

Until a few years ago, was fairly widespread the tendency to rely upon a single subject, the main contractor, all the maintenance activities, through a contract of "global service". The excessive recourse to global service has proved negative in the medium term because it has caused the depletion of corporate knowledge on the fundamental process of maintenance. Indeed, although the practice of global service is very widespread nowadays, many companies turn to small operators, able to meet with their flexibility and expertise to the lack of organization and of technical skills that large service providers sometimes show. This is especially true when the small suppliers prove high professionalism and efficiency. Currently, the maintenance activity oriented to industrial assets is considered one of the most important business opportunities for many SMEs. The maintenance suppliers operate in a very competitive market: they have to resist not only the aggression of the great big service providers, but also the increasing requests of the final users in terms of reliability, availability and productivity of the assets.

The evolution we are seeing lately is the beginning of a new business model, namely the "collaborative networks" of small and medium-sized enterprises (SME) offering maintenance services. The strengths of this new model are the lean structure, typical of SMEs and the specialized skills that each actor can offer. In addition, structures of this type, guarantee response times shorter than more highly structured and, therefore, less reactive organizations. In this way the enterprise networks were born, which are formed through joint ventures, consortia, cooperatives and other forms of association. Patterns and processes of these particular organizational structures have been extensively studied in recent years [14], [15], [16].

Small and medium enterprises are often in trouble facing these issues, in particular when older plants are concerned, so they need dedicated resources in order to offer a maintenance service compliant to the costumer requirements. The same problem, but from a different perspective, affects the final users of the asset that would like to monitor and check the performance of their outsourced maintenance service, often managed by such SMEs.

In this context, in which you need to help small and medium-sized enterprises to develop innovative and full comprehensive control systems, Tuscany Region with the support of the European Union and in partnership with the University of Florence, funded a research project, called eMeccanica, in order to aid the birth of a Virtual Enterprise Network (VEN), formed by many SMEs, which should provide a maintenance service of the highest level in the field of industrial plants (power generation, chemical processing pants, manufacturing, and so on). The project involved two main phases. In the first part it was necessary to identify the architecture of the virtual network of enterprises in order to define the organizational, relational and operational necessities for the proper functioning of the virtual corporation. In this way, the foundation was laid for the next phase in which it was deemed necessary to develop a tool that would facilitate the interaction of so many different players.

To explain better, if some small and medium-sized enterprises decide to federate in order to offer an advanced maintenance service, they may meet many difficulties associated with the logistical organization and with the difficulties to set out the operational activities. The first consequence to be expected from a disorganization of the activities in the network, would definitely be the lack of cost effectiveness of the project. There would be, probably, many inefficiencies due to misunderstandings and discussions, lack of materials, double interventions and so forth. The modern technology of diagnosis and prognosis of production systems and of industrial applications might come in handy to a so advanced and complex structure like a VEN [17].

The purpose of this work is to propose a methodology capable to verify the real possibility of managing the maintenance of legacy systems through a VEN. To do this, a real thermodynamic system was designed and realized in order to reproduce, on a reduced scale, the reliability problems of a process plant. The scaled model was instrumented and an *ad-hoc* diagnostic system was developed for checking how the information system could be integrated with an evolved virtual network of maintainers [18], [19], [20].

In this paper we describe the second step of the eMeccanica project and, in particular, the development of an application prototype that could be useful for the growth of the CBM tool. In particular, we focused on how it was possible to design, produce and operate a prototype which could fit a virtual enterprise network of maintainers. The method requires, among other things, to fulfil a preliminary “selective” FMECA to be properly used to implement the diagnostic system.

The remainder of this paper is organized as follows: section 2 shows the case study, while and in section 3 the FMECA methodology is presented. Section 4 describes the experimental results and the fifth one presents a discussion of the results, the main conclusions and future developments.

II. CASE STUDY

A. Legacy plants management issues

Process plants are constituted by machines with very long life cycles. It is not uncommon to find old plants which have been working for decades, sometimes more than fifty years. This is the case, for example of portions of cement, steel and petrochemical plants and of many other cases in which such machines are very complex, have a high replacement cost and, on the other hand, are not obsolete: their productivity is still high enough that replacement with new installations is yet not economically profitable [21].

At the same time, advanced ages require expensive maintenance, given the criticality of these assets in the context of the company production. The relevance of the equipment is often so high that, in case of replacement, it might be appropriate to consider also the delocalization of the entire production site. To prevent this adverse event, it is necessary to make all the possible efforts to maintain, or even improve, the productivity of the existing systems. The preservation of high productivity passes through high qualitative and quantitative performance, among which are, and have primary importance, high maintainability and availability. In this framework the most suitable maintenance management, interacting with the information system through an expert system, plays a role of primary importance.

The maintenance service companies, compete in a market where the lower cost of service is a very important competitive advantage. At the same cost, however, comes the need to offer services with higher added value. In particular, nowadays are very much appreciated the potentials of condition based maintenance, supported by continuous monitoring systems, diagnostic and prognostic.

As regards the application of diagnostic and prognostic techniques and tools to existing industrial plants with several years of service behind them, the market does not offer low-cost solutions with a broad spectrum of implementation. The most frequent applications of these methods are found on machinery and equipment belonging to the last generation, already born with these support tools for managing both operation and maintenance.

These advanced diagnostic systems come with the product, being introduced already in the process of defining the technical specifications or, at the latest, in the design phase. The application of such systems to existing apparatuses, often involves considerable implementation costs, because of their inflexibility. In other cases there is a considerable specialization on certain degradation phenomena, at the expense of the flexibility of the scope. In further cases we have in-depth skills but these are of particular groups of machines or of specific technologies.

B. eMeccanica project

The eMeccanica project was created by a group of small size enterprises belonging to the territory of Piombino, in Tuscany, Italy. This is an area where you can feel the changes due to renovation and downsizing of heavy industries and ancillary companies. One of the most attractive businesses in such an area is maintenance, as an outsourcing activity. Through an enquiry in the district, there was the feeling of the need for innovation in Maintenance procedures, even if the basic needs for routine interventions didn't require particular skills but mostly manpower with low margins for companies. A tough competition among labour suppliers was constantly growing together with a decay of the demand for qualified workers and with lower prices for services. In such a scenario the group of SMEs involved in eMeccanica decided to merge in a team aiming at improving the quality of service, while maintaining competitive prices.

The idea behind was to offer some kind of revamping to chief assets, through online sensors and a platform that could communicate operational parameters to a data management system. Local industries appreciated the proposal, since they're based on machineries and technologies which are often belonging not to the "last generation" kind of equipment. The opportunity to revamp them, by means of some kind of condition based monitoring, with the same people, seemed a very attractive chance. The companies that joined the project would let eMeccanica group intervene into the plants, bringing its skills and knowledge. In this way the best experts of each service provider would be able to spend all of their skills and experience in predictive maintenance applications expressly for the customer.

Once found a significant number of companies willing to participate in the project, both as a supplier of maintenance, both as clients of the new type of service, it was still necessary to be able to show concretely how the integrated system would work.

III. METHODS

FMECA [22] is the acronym of 'Failure Modes Effects and Criticality Analysis' a procedure born in the military and then adopted by the major American manufacturing companies. FMECA has seen many applications in industrial environments [23] and always showed good performance [24].

The approach is bottom-up, is easy and allows you to highlight how failures of a system component, even the smallest and seemingly insignificant, could spread into the whole system and cause malfunctions and failures. In a FMECA analysis you've to break down the investigated system into its fundamental components or line replaceable units (LRU). In such a way, with a recursive approach, you can link each single failure of the components to the failure of the whole apparatus, detect all potential failure modes and their effects.

The first thing to do when you start FMECA analysis, is the decomposition of the system into subsystems and the definition of a hierarchical arrangement of the subsets. Then, you must analyse each failure mode of each element and evaluate the consequences of failure. These latter become the failure mode of the immediately higher level, and will again be evaluated analysing its consequences on such group. A schematic view of the FMECA structure is shown in Figure 1.

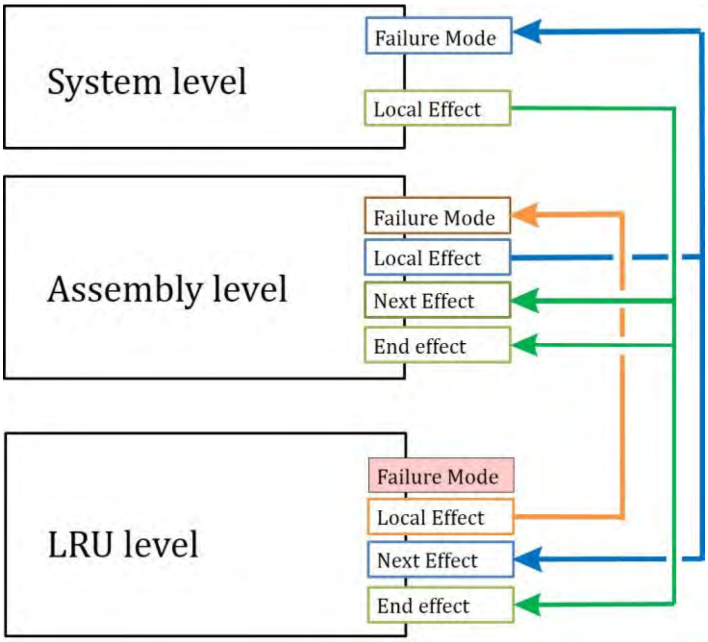

Fig. 1. FMECA structure. This illustration represents the diagram of an FMECA approach. After the subdivision of the system into groups, subgroups and LRUs, the analysis of the failure modes and consequences of each LRU takes place. The latter, at the immediately above level, become the failure modes of which will be identified the consequences later on in the analysis, precisely when such level will be analysed.

Once you have broken the system into sets and subsets, it is necessary, as said, to analyze the failure modes, identifying whether they are failures due to wear out, random failures, fatigue failures, corrosion failures and so forth.

Next, you will need to determine the effects of each failure and identify the failure criticality index (CI) or Risk Priority Number (RPN) [25]. This is obtained by multiplying a first factor, which represents the frequency of the fault, by a second factor, which represents the severity of the consequences, whether they are for the people or the environment. The value obtained is then multiplied by a third factor, which represents the ease with which the fault can be identified once it has occurred. Indeed, there are some types of failure that, when they occur, are not immediately identifiable by the plant operator. Before one can have certainty of failure occurred, you should wait until the effects of the failure propagate to the system and they are finally evident.

After calculating the criticality index of the fault, you can order the components of the system in an ascending order and get a ranking of the most critical elements. We should pay special attention to these, investigating the causes and symptoms of such failures. Thy may be, for example, problems of lubrication, of non-compliant materials, of under dimensioning, problems of shock and vibration. The symptoms are usually oil or fluid leaks, overheating, vibration, noise etc.

Once fulfilled the FMECA analysis, we can formulate the most appropriate maintenance plan, dividing the components basing on the most appropriate maintenance policy for each of them. It will be sufficient, for some of them, a maintenance action after the failure, others will instead request some preventive maintenance or even the proactive improving maintenance, if the element is particularly critical and can be enhanced. The process of the FMECA analysis just described is shown schematically in Figure 2.

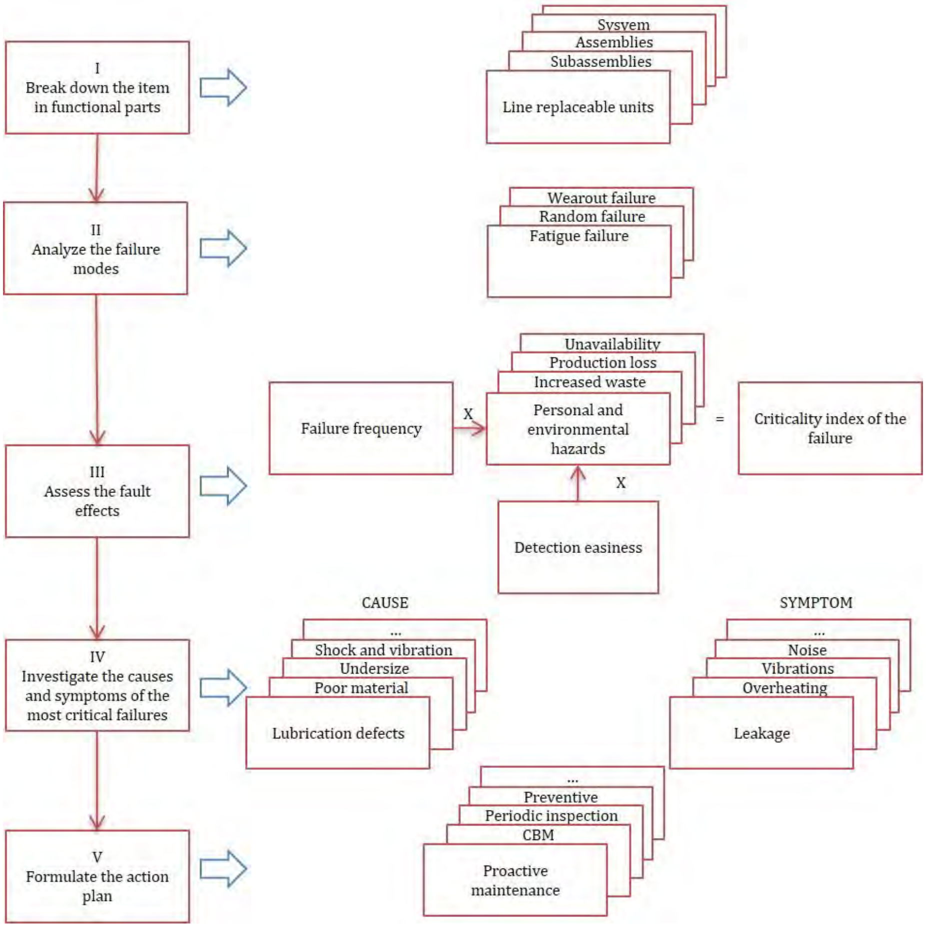

Fig. 2. FMECA steps. On the left side of the diagram, the five steps in which you can divide the FMECA methodology are shown. To each of them corresponds a detail diagram, shown on the right.

FMECA differs from the FMEA approach for the option of introducing the Criticality analysis (the C of FMECA), which ranks all failure modes in order of RPN. An proposed approach in literature [26] is to make first a first FMEA to identify the main causes for efficiency deficiency of a product followed by a second step Criticality Analysis, in order to assess the risk, in terms of occurrence severity and detection, involved in each failure mode previously identified.

IV. RESULTS

A. *Project steps*

The project was developed to seize a business opportunity in industrial plants maintenance and was particularly addressed to medium and big size enterprises dealing with chemical, oil&gas and energy assets.

The first step, at the very beginning, was a market analysis, carried out in order to identify and codify the plant user needs. Many talks were done with the potential customers with the aim of meeting their specific requirements in terms of reliability, availability and safety performances.

The second step was to investigate the finest solution for the VEN structure, capable of regulating the partner relationships, communications, roles and responsibilities. In this stage the reference business model was developed. This structure drove the later stages of the project. The last efforts were concentrated in the development of an integrated tool for condition based maintenance (CBM) [27] that was able to support maintenance service of the VEN [28].

The definition of the operating modes of the network, allowed us to define the technical specification of the expert system platform, opening the design step of the support tool and of the demo prototype.

As illustrated below, the software tool structure is composed by a database, where are stored the data and information, and by some intelligent modules, capable of interpreting the sensor data and to infer the state of the system.

For the development of a support system, it would be desirable to have a system on which doing some experimental work. So, the commercial partners of the VEN tried to find a case study that could represent a first industrial application and an opportunity to develop and test the expert system. As predictable, anyway, the critical project pursuit (facility maintenance) and its innovative approach, generated some concern in the potential customers and, unfortunately, there wasn't any prompt chance. So came the idea to create a prototype plant to be employed for the test and the final validation step.

The following paragraphs describe the main activities settled for the prototype development, starting from the cooling circuit technical design and coming up to the reliability analysis performed on the test bench.

B. The choice of the prototype

As described in the previous sections, it was requested to the authors of this article to create a prototype of a process plant for testing the VEN potential. The prototype had to be equipped with appropriate instrumentation, which should detect the operational parameters, and with a remote control monitoring system. This latter should have been able to decode the signals coming from the machine failed and then should have been bright enough to identify the type of fault and alert the best placed member of the VEN for an intervention.

Another benefit that would be achieved with the implementation of a prototype in place of a real industrial application, was that the operation of a prototype plant in a laboratory setting would have ensured a much simpler and more suitable environment for an expert system platform development.

A seemingly contradictory problem may arise: how is it possible to reconcile the objective of strengthening old plants with the creation of a brand new instrument? The answer to this question is that the new apparatus will have to show, in little, all the main issues of a real existing plant and for this reason it should be conceived and designed with the utmost care. We decided to realize a water chiller, the type used in air conditioning systems. It should be installed on a small skid with all the dynamic components linked to a custom data logger, expressly developed for this mission. This type of device should also be transportable in a van, so you could take it to interested companies and make them see the potential of the VEN proposal.

The choice of the type of plant fell upon a water chilling group, for the reasons summarized below:

- compact and easily transportable;
- widespread and common application;
- it works easily and the technological knowledge is consolidated;
- the maintenance activities include a broad spectrum of expertise;

Figure 3 shows the Piping & Instrumentation Diagram (P&ID) of the system:

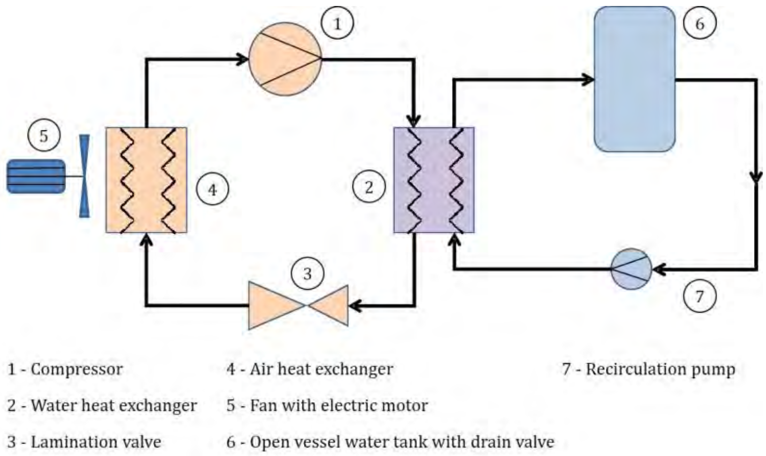

Fig. 3. Prototype P&ID. As visible in the scheme above, the system consists of two circuits. In the left part is visible the refrigerant circuit, with the typical four elements that compose it: the compressor, the evaporator, the expansion valve and the condenser. In the right side, the circuit to be cooled is shown, consisting of some typical elements of an open vessel hydraulic circuit.

C. The prototype design

The choice of the water chiller was crucial for the beginning of the prototype development, but a last problem, however, was still to be solved. It was how to get failures which should have two essential features: on the one hand they should be detectable by a diagnostic system and, on the other, they should not compromise the system so seriously to damage it irreversibly.

It was decided, therefore, to study the main failure modes of the chiller, developing first a FMECA done with a selective approach aiming to:

- avoid mistakes during the fault simulation, in particular it was necessary to preserve the system from enduring machine failures that could permanently stop the functioning;
- define which physical parameters should be acquired;
- outline all the sensors needed for feeding with the data the expert platform;
- ensure a design phase supported by an proper reliability assessment, as suggested by constructive good practices.

The FMEA approach was customized since it was made in a selective way, as shown in Table I. Instead of starting from all the LRU failure modes, we started from any failures that could be caused by a reversible modification of the chiller. Of all these failure modes, we evaluated the final effect on the overall system, and we selected only those in which this effect could be monitored by a sensor. The analysis was performed exclusively for the stage of normal operation and had a dual purpose. The first scope was the definition of the possible failure modes of the prototype, found during the simulation. The second was the identification of the type of sensors required for data acquisition and of their positioning.

TABLE I
Selective FMEA: In this analysis were identified those failure modes that can be created artificially and which have monitorable consequences on the overall system.

End Effect	Local Effect	Simulation	Measurement	Cause
Water in circuit 2 doesn't cool down	High pressure in circuit 1	Cover the gas/air heat exchanger	P2	Dirty radiator
		Power off the fan	P2+V2	Broken Fan
	Low pressure circuit 1	Partial closing of interception valve circuit 1	P2	Leakage circuit 1
		Power off the fan	P2+V1	Broken compressor
	Little flow in heat exchanger circuit 2	Partial closing of interception valve circuit 2	P3+ΔT3	Bad working of water pump
	No flow circuit 2	Power off the water pump	P3+ΔT3+V3	Broken water pump
Non water in circuit 2	Water level in tank of circuit 2 goes down	Open the tap of circuit 2 tank	L	

The analysis proceeded with a following Fault Tree Analysis (FTA) developed on the basis of the results of the previous FMEA. In fact, we selected the final effects and we put them as starting points (top events) for the development of the FTA. In this way, it was possible to check more thoroughly and with a top-down approach in which way the faults selected afflicted the system. This procedure allowed the setting of the expert system for the processing and interpretation of data from sensors, following one of the approaches proposed in the literature [29], [30].

Following the steps described above, the final draft of the prototype project was delivered. The last building stage was thus initiated. The chiller was built and only at the end of the implementation it was completed with sensors. This subsequent implementation was done and documented because, it should be always remembered, the ultimate goal of the project was to recondition existing plants and not to design new ones. A couple of photos of the prototype are shown in Figure 4.

Fig. 4. Prototype images. The two photos show the appearance of the prototype.

V. . DISCUSSION AND CONCLUSION

The objective of this research was to develop an experimental prototype to test the potential of a virtual enterprise network. The activity was fulfilled but the effectiveness of the result could be assessed only by testing its capabilities. So, we installed on the prototype an electronic system called Online Machine Tutor, developed within the eMeccanica research project, to create an integration through all the procedures, collecting all the most important feedbacks and functions from the strategic plant machineries. All records, feeding a single data manager, made it capable to take real time decisions on how and when an intervention by the supervisors is really needed. That was accomplished by means of an expert system for data interpretation. This tool represents an expert platform able to play the role of a decision support system for the VEN maintenance service. A synthetic view of the expert system architecture is visible in Figure 5.

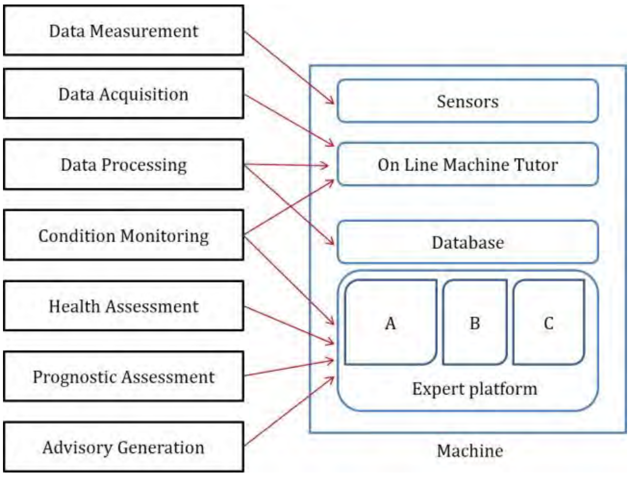

Fig. 5. Expert system structure. On the left side is presented the sequence of steps needed to accomplish a prognostic analysis. Each one is linked to the system element shown on the right side.

The prototype was installed in the IBIS Lab of the Department of Industrial Engineering of University of Florence. It was connected to a computer on which the expert platform was previously installed, developed in Microsoft Visual Studio. The verification of the proper functioning of the whole apparatus, through a series of tests and trials, gave good results, as shown in Figure 5.

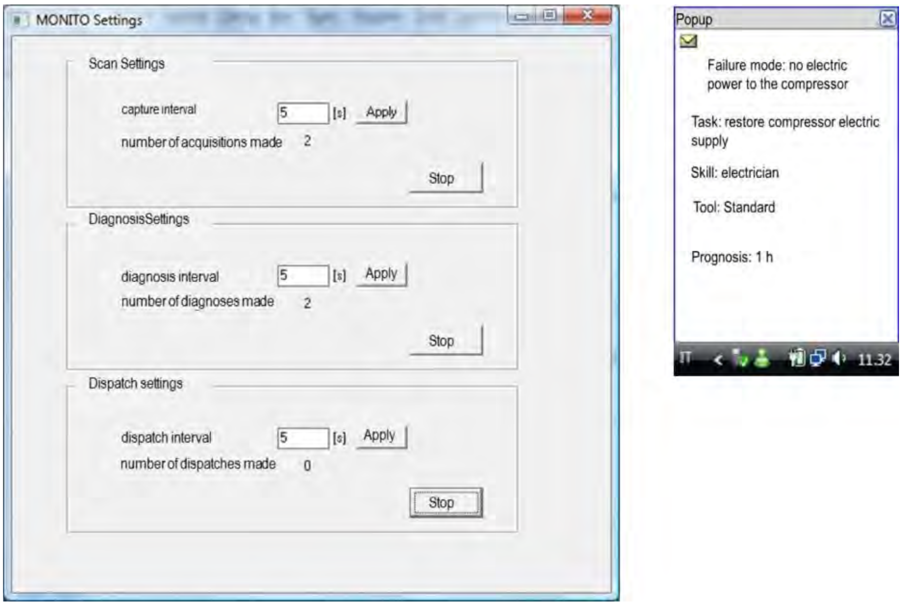

Fig. 6. Expert system interface. The expert system, continuously monitoring the prototype was able to detect a voltage drop induced artificially in the laboratory. So a warn, with all the details, was sent to the most suitable person of the network concerned with the maintenance, in this case the electrician.

Given the satisfactory results of the interaction between the prototype and the expert system, which was able to apply a “predict and prevent” strategy, a wider testing phase could start in order to improve the decision support system and to focus the possible weakness of the architecture. At the present time, the last step of the project is still in progress and the development of the decision support system is still going on. However the benefits of the prototype availability improvement are clear and they will confidently assure a reliability management improvement.

The opportunities for the application of an instrument of this type are very wide. Surely all the legacy critical machines of a production plant, would gain a great benefit in adopting this kind of systems. If we also consider a perspective where maintenance activities are handled by a network of operators who have complementary skills, then this architecture would find its ideal application and it would be able to generate a significant added value in effectiveness and efficiency of the service provided.

Considering the good results of the working prototype, we could say that, from the perspective of a company that follows the ideas of lean manufacturing, this pervasive ability to control the system would be very well accepted, because it allows to optimize the maintenance operations without creating any type of waste: real time maintenance operation upon real maintenance demand.

Focusing, in conclusion, on the constraints of the expert platform, we can remark how the main problem is the continuous online remote monitoring and the automatic and autonomous decision taking in terms of maintenance activities for industrial machines as compressors, boilers, and so on, which require a deep expertise and a significant processing power. Future works will try to focus this issue and to propose possible solutions.

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