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Proactive maintenance strategy for harbour crane operation improvement

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SUMMARY
Quay cranes are particular transportation devices for which operation's safety and CRAMP parameters (Cost, Reliability, Availability, Maintainability, and Productivity) should be fulfilled with regard to a harbor maintenance strategy. The maintenance process is first considered within a holistic modeling framework in order to cope with the current practices of treating strategic, operational and engineering maintenance issues independently without taking into account their interactions within an entire Enterprise System. Proactive maintenance is then highlighted as a new model aiming to globally optimize the components operation parameters throughout three interacting prognosis, diagnosis and monitoring processes. Technical issues related to Intelligent Maintenance System are finally proposed in order to support proactive maintenance operations at the enterprise field level and applied to quay cranes in a particular site within the frame of the European Eureka 'Robcrane' project.

KEYWORDS: Proactive maintenance; Enterprise modeling; Cost-oriented automation; Quay crane; Intelligent maintenance platform.

1. INTRODUCTION

For the optimization of harbor operations, quay cranes are the group of transportation devices for which operation's safety[1] and CRAMP parameters fulfillment are the key issues (problems of wire rope, of component fatigue, . . .).[2,3]

Control techniques used by operators, intensity and influence of environmental conditions in device's workplaces, variability of devices coming from different suppliers, relatively long operation period with stochastic functioning modes, customized production are particularly important.

Decision-making processes related to qualifying the technical state of a device are most often executed by the operators and maintenance staffs during routine overhauls, and only in small degree it is automatically generated by monitoring of selected CRAMP parameters during operation.[4]

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Automation of decision-making processes within safety control of quay cranes as well as shaping their efficiency[5] requires working out an integrated system based on Information and Communication Technologies. Automatic analysis and synthesis play a vital role in such techniques for performance improvement from both on-line real-time operation and off-line proactive strategy.

This paper aims at underlining the main aspects of the definition, the development and the deployment of a proactive maintenance system applied to quay cranes operation within a harbor enterprise as one demonstration site of the Eureka Robcrane project.

2. EUREKA ROBCRANE PROJECT

Launched in July 1999, the EUREKA ROBCRANE project E!1968 (http://www.eureka.be/) aims at developing an intelligent system integrating both control and maintenance processes of heavy transportation (e.g. crane, overhead crane, quay crane, . . .) in industrial domains such as metallurgical industry, harbor exploitation. Indeed, the technical intelligence to the control-maintenance system has to be sensitive to both device and transportation track conditions, while taking into consideration environmental influences (mechanical, control, maintenance, environmental factors), to face many issues such as a large number of operating "cranes" are rather old and need retrofitting to adapt to new manufacturing conditions before their eventual replacement; the "crane" device is old technologically (resulting today in high operating costs) based mostly on traditional solutions and rather poor electronic equipment; the devices' monitoring and controlling activities are mostly manual based on human knowledge; all undesirable influences cannot be eliminated. This intelligent system will bring some solutions to:

- monitor, diagnose and forecast the selected exploitation parameters,
- correct and optimize crane bridge movement trajectory,
- stop the device when its action would be dangerous,
- improve quality of device (safety, reliability, accuracy) by optimizing (a) the maintenance operation time (better scheduling, teleoperation), and (b) the device availability (instantaneous availability, maintainability),
- reduction in operation and maintenance costs.

The implementation of these solutions will allow to better master the compromise between productivity and dependability of these transportation systems in order to fulfil the socio-economic needs required by the exploitation context (Enterprise strategy).

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In that way, the French partners of the consortium have to develop a platform (called MILOS) dedicated to cranes' (and tested on quay cranes) safety and dependability (intelligent proactive maintenance system); it also enables one to integrate the intelligent crane control part developed by the other partners.

To be generic and reusable, the development of this maintenance system will not be based on a traditional approach mainly related to knowledge discovery, but both first on a holistic approach to consider a maintenance process as a Enterprise process,[6] and second on a particular approach to consider proactive maintenance as a new model aiming to globally optimize the components operation parameters (mainly cost) throughout three interacting prognosis, diagnosis and monitoring processes.

3. PROACTIVE STRATEGY: A MAIN PROCESS IN QUAY CRANE EXPLOITATION TO REDUCE DIRECT AND INDIRECT MAINTENANCE COSTS

Quay cranes are transportation systems able to carry containers from ship to quay and *vice-versa*. Quay cranes allow translating containers from at least 3 axes (Figure 1).

Today one of the major challenges in the exploitation of quay crane, is to guarantee their optimal and operational "availability" all the time to allow the ship unloading as soon as they arrive at the harbor. Indeed, ships prefer to move to another quay, even to another harbor, rather than to wait in the quay if the quay crane is not instantaneously operational. This type of decision implies a important loss of money for the person who manages the quay crane operation and has to be fought by implementing a better maintenance strategy on the quay crane components and system to reduce non availability (and its impacts).

Fundamentally, there are three different maintenance strategies:[7]

- corrective maintenance {XE "Breakdown Maintenance"}: maintenance is undertaken in response to a failure that has been detected during the use of equipment,
- scheduled maintenance {XE "Preventative Maintenance"}: maintenance is undertaken at routine intervals; elapsed time or time of in-service use of equipment may determine these intervals (Mean Time To Failure (MTTF) and Mean Time Between Failure (MTBF)),

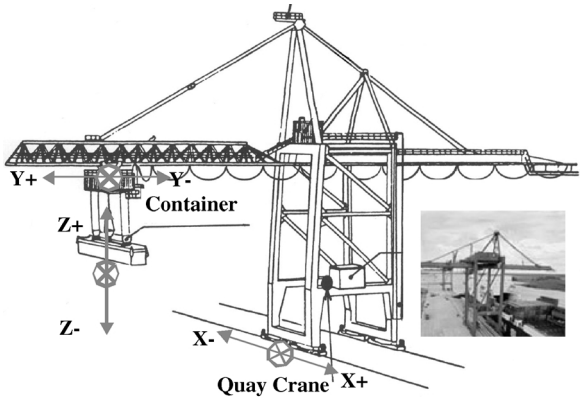


Fig. 1. Quay crane.

- predictive *vs*. proactive maintenance {XE "Predictive Maintenance"}: in this case equipment is continuously monitored and the future state is forecast. Based on this inspection, maintenance activities can be planned just in time and initiated.

In general, for the two first strategies an important part of the company budget is devoted to inspecting, repairing and modifying components, all this being done often too early or too late according to the system performance. For example, at the shop floor level, the maintenance processes which mainly focus on repairing and breakdown services, are sometimes started in a non co-ordinated way, even in contradiction to the business objectives, and without a real estimate of different effectiveness factors other than the availability impact. Moreover, the scheduled maintenance based on the experience and the vendor recommendations, is "blind" because the equipment could be in a perfect operating condition when it has to be changed or it could generate unavailability of the manufacturing system when it failed before its theoretical lifetime. Therefore, this not only greatly increases the costs of enterprise operation, but also decreases the lifetime due to the damage to the equipment done by the maintenance action itself. So, the non-production or unavailability cost of complex systems such as quay crane (indirect cost) is also important even more than the repairing cost (direct cost). Consequently, these type of systems are now considering or implementing **proactive maintenance** (Figure 2) to replace the scheduled maintenance, in order to greatly decrease the maintenance expenses and to improve the global performance of the operational systems[8] by taking the right maintenance decision, at the right time and in the right place.

Proactive maintenance[9] is based on the forecasting of the system degradations through a prognosis process, which aims at propagating forward the degradation causes. The cause identification determines the origins of the degradation from the symptom observation through a diagnosis process. The degradation identification represents the system's malfunctioning states from the property deviations of system flows identified through a monitoring process. The implementation of these three processes leads to a **just-in-time** mastering of the system degradation and failure to decrease direct and indirect maintenance costs because:

- they allow, after degradation observation, directly to intervene on the right component in a minimum of time (reducing the intervention time by adequate aids) and without additional operation after the maintenance action. Indeed, for example, from the degradation cause information (diagnosis process), the operator intervenes, if necessary, as soon as possible with a higher probability (a) to be on the component at the origin of the degradation (to anticipate the failure) and (b) to master the degradation impact (prognosis process) on the production cost (to anticipate the non-production).
- they allow to avoid unnecessary maintenance intervention leading to system stops by following, in a continuous way, the state and status of the system.

Nevertheless, as this maintenance strategy has a additional cost in relation to the new type of field instrumentation to be

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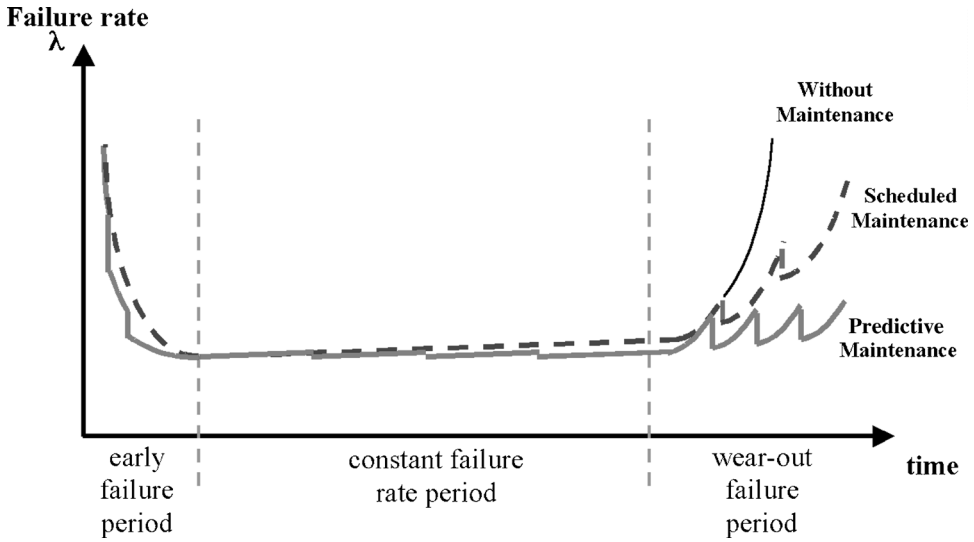


Fig. 2. Decreasing of failure rate (and cost) by means of proactive maintenance.

implemented, new information processing has to be used and a new maintenance operator to be trained, . . . it is well adapted for "**strategic components of the industrial systems**" related to CRAMP parameters (to justify a fast return on investment).

In this case, the proactive maintenance allows (a) improving the maintenance action (mean availability), to follow the degradation tendency (quality of service), to avoid the occurrence of a dangerous situation (safety) and to support the operator with knowledge oriented to the degradation cause and effect (maintainability) and (b) decreasing not just the direct costs, but also the indirect costs of production loss (cost-oriented automation).

The implementation of the proactive maintenance strategy to support the previous objectives, requires the design of a global solution to integrate a set of shop-floor processes (prognosis, diagnosis, monitoring, . . .) to better master the manufacturing (quay crane) system degradation, or as well as a set of enterprise (harbor operation) processes (cost, management, policy, . . .) to better master the capability of the whole enterprise system (to make a profit).

But today the design of this global proactive maintenance system is not yet efficient due to the inconsistent set of heterogeneous models[10] used by the different designers of partial maintenance processes. Indeed, Maintenance strategies result from a sum of isolated and compartmentalizing processes (fault diagnosis, cost management, spare parts management, . . .) without considering them as a complete Enterprise process interworking with other shop-floor and business processes. Existing models,[11–13] dedicated to the integration of maintenance points are focused more on the organization of the maintenance tasks (static aspect of information) than on the dynamic aspect and its holistic context. These several more or less partial maintenance models can be really efficient only when integrated into a more global maintenance process. This leads us to build the maintenance process by favouring the discourse universe as an original factor of the integration, by proposing an enterprise (holistic) modeling-based formal framework[14] as a common model of understanding between all the actors involved in a proactive maintenance strategy implementation (to define what Maintenance is in relation to the what the Enterprise goal is).[15] It allows one to cope with the current practices of treating strategic, operational and engineering maintenance issues independently without taking into account their interactions as a complete Enterprise System.

This enterprise holistic framework is based on and extends the GERAM[16] and CIMOSA[17] normative modeling framework to integrate, from the shop floor level to the business one, the three basic process of prognosis, diagnosis and monitoring which make up a proactive maintenance system (to better master the manufacturing system degradation and to better master the capability of the whole enterprise system).

This allows an integration into a continuum of information and knowledge, the domains of engineering, manufacturing and maintenance to reorder holistic approaches into practice.

This formal framework integrates first a three-axis **reference architecture**. One of this axis refers to the integration of the three basic manufacturing islands (Control, Maintenance and Technical Management) as formalized by Iung *et al.*[18] A second axis refers to the manufacturing system life cycle as proposed in GERAM. A third axis refers to the system point of views on information, communication and processing according to the systemic paradigm. Second, to assist the maintenance system designer all along the modeling phase, a **engineering methodology** is defined according to Amice[17] by taking into account modularity and system theory principles. Finally, to be fully compliant with the proactive maintenance objectives and to guide more precisely the designer[19] the GERAM-based framework integrates some **generic concepts** and **reference models** described with the CIMOSA formal **modeling language**. For example, the maintenance domain in accordance with the ISA-dS95[20] is described as a set of 11 domain processes (Figure 3) allowing to satisfy the whole of the maintenance objectives (Maintenance philosophy, maintenance management, monitoring, diagnosis,

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prognosis, compensation, decision, execution, quality assurance, evaluation, correction) in a holistic approach.

In this framework, the proactive maintenance process is formalized as an integrated maintenance process with its interactions as a complete Enterprise System (harbor operation).

But the proactive maintenance process is not yet really operational on site from a socio-economic points of view because the formalization of these three sub-processes (prognosis, diagnosis, monitoring) implies a development of models, which integrate all the failures and degraded states of the system, to be efficient in terms of improving the mean availability, the quality of service and safety.

In that way of formalization, the maintenance agents cannot use, at this moment, a complete guide (model, method, tool) to help them for the modeling and the understanding of such a type of system. It leads, from an industrial point of view, to a prognostic process, which is often not implemented or primarily based on empirical knowledge and real experiments. Then the current monitoring processes are mainly based on threshold detection (drift) of a quantitative variable but without taking into account the exhaustivity of the system-degraded states. Finally, the diagnosis is mostly applied to the failure and not to the degradation, and the identification procedure of the failure or degradation causes is commonly developed on a functional point of view, on expert empirical knowledge requiring the use of subjective methods such as FMECA (Failure Modes Effects and Criticality Analysis; IEC 812-1985), or HAZOP (Hazard and Operability Studies).

4. PROACTIVE MAINTENANCE PROCESS MODELLING

A first step towards a real formalization of the three processes has to consist in integrating the model of the global malfunctioning description of the system (deviation, degradation behavior and causality) with its functioning representation. Indeed, the functioning and malfunctioning of the system are dual[21] and must be studied together to control each system variable (control and degradation variable). The transition between these two modes is directly linked to the relation between the normal and abnormal system states. The normal states correspond with, among other things, to the functioning modes and the abnormal states with the possible system degradations.

Hence the need to focus first on the system functioning (to produce) to identify the resources and their relations with other resources in terms of products, materials, information, energies, . . .

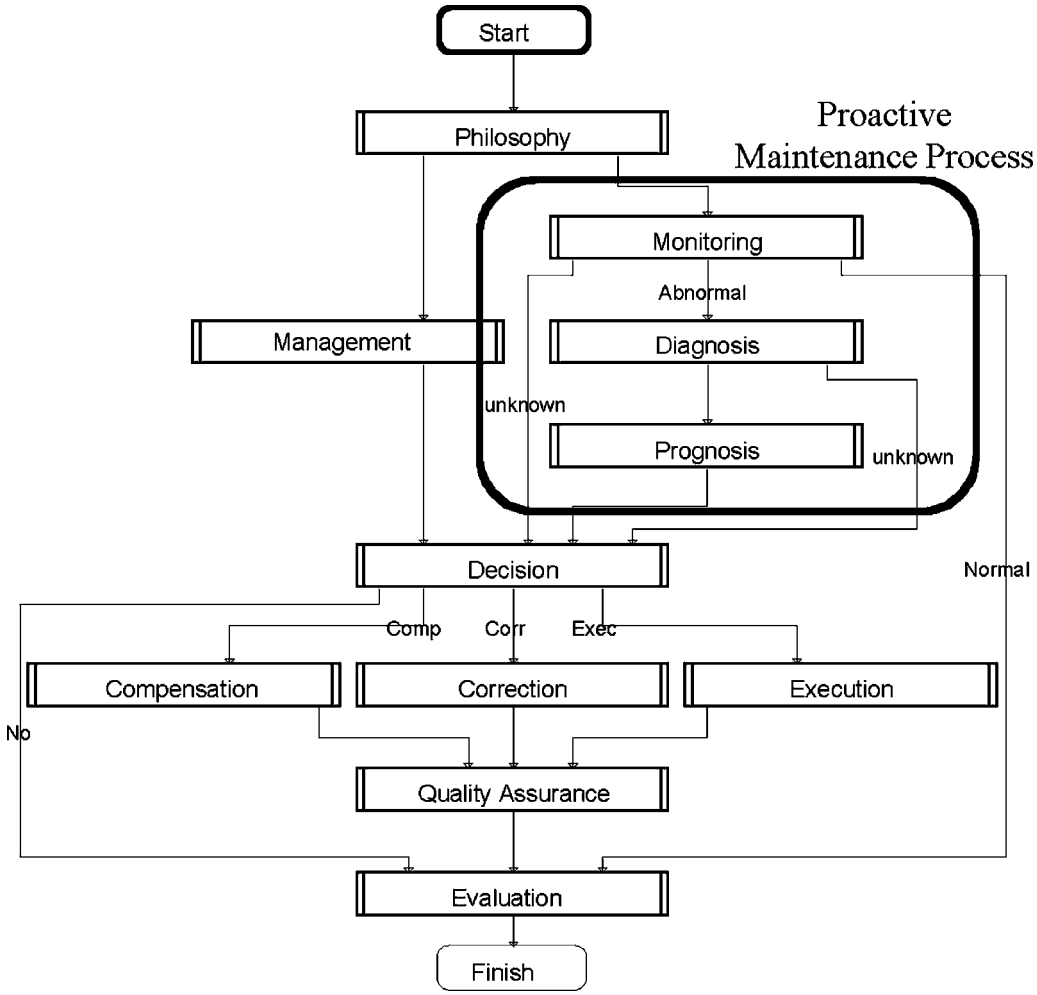


Fig. 3. Maintenance domain processes – proactive maintenance process.

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This action can be made through a **manufacturing system functioning modelling**[22] based on the principle of:

- **finality** (Obj_{DP}) associated to each process of the system whose purpose is to modify the space, time or shape attributes of the "product" realized by the system (container moving).
- **function** (Def_{DP}) of the system. Each function has to be broken-up to proceed from the functional abstraction level to the technological one by leading to the definition of a set of **activities**. According to the CIMOSA language the higher-level process is named a Domain Process (DP) triggered by an event.
- **flows** (FI_{DP}, FO_{DP}, CI_{DP}, CO_{DP}, RI_{DP}, RO_{DP}) consumed or produced by the function and also the activity. One flow is composed of objects (objects per time unit) and each flow or object is characterized by a set of shape, time and spatial properties. The different flows are:
  - the **"Having To Do" flow** which represents the finality flow (**HTD**),
  - the **"Knowing How To Do" flow** which represents the knowledge on the manufacturing process (**KHTD**),
  - the **"Being Able To Do" flow** which represents the flows required to realise the process (**BATD**). One specific **BATD** flow is the resource, which supports the activity (e.g. component).
  - and finally, the **"Wanting To Do" flow**, which represents the flow, triggering the process (**WTD**).

In the context of the Eureka project, this functioning modeling has been realized on a "generic" quay crane by using the SADT (Structured Analysis and Design Technique) graphical representation, where the main level (A-0) is called "To move containers" (Figure 4) and its first decomposition is composed of 5 main functions :

- to control all the operations
- to move the quay crane on the X axis (supported by the translation unit),
- to move the quay crane on the Y axis (supported by the **direction unit**),
- to move the quay crane on the Z axis (supported by the lifting unit),
- to operate the container moving.

Each function is broken up since elementary levels allow the link to be made through a "physical support mechanism" (resource of the **BATD**) with the real components of the quay crane (motors, breaking system, cable, jack, . . .).

On this basis, in a second step of the methodology, it is then possible to induce malfunctioning modeling by defining the failure and degradation (in relation to the activities), in general, and by studying its causes, effects and the means to observe them (in relation to the flows, objects and properties).

In the Eureka project, two complementary ways have been explored to model the global malfunctioning of the quay crane:

- An analytical model-based approach to formalize at the lower levels of the decomposition, a degradation model for each component such as motors. The normal behavior is learned and modeled through temporal and frequential analysis (speed/time).[25] Each abnormal behavior is then constructed during experimentation by modifying the properties of the flows linked to the activity supported by the component and by observing the impact of this modification on the normal behavior. A bad functioning is therefore identified (monitoring) as a deviation between a reference (normal analysis) and a current value (speed). Each deviation is associated to a cause (diagnostic) and a effect (prognosis) according to the experimentation context. Thus, the pertinence of the malfunctioning modeling depends of the exhaustive identification of the degradation modes and causes. This approach is well adapted at the component level (minor complexity) to develop degradation models for each component and reusable in different applications.
- A knowledge model-based approach to formalize at the middle and higher levels of the decomposition, the degradation models integrating the degradation of the function or component itself but also the degradation propagation issued from other functions or components. This approach is well adapted when the complexity is high in terms of relationships between components,

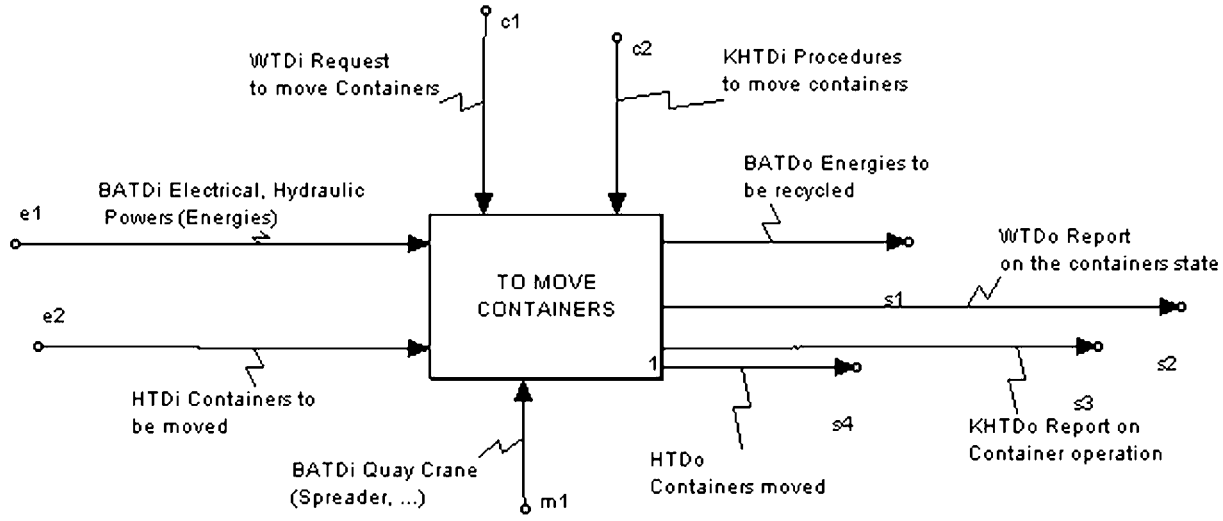


Fig. 4. Main finality of the quay crane (A-0).

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Table I. First order predicate.

negation (NO)	
A	¬A
F	T
T	F

disjunction (OR)		
A	B	A∨B
F	F	F
F	T	T
T	F	T
T	T	T

conjunction (AND)		
A	B	A∧B
F	F	F
F	T	F
T	F	F
T	T	T

implication		
A	B	A→B
F	F	T
F	T	T
T	F	F
T	T	T

functions, and environment. In this case, it is impossible to develop, in a cheaper way, an analytical model.

The first approach is referred to *System Theory and Automatic Control*, while the second one is referred to as *Systems Engineering and Systemics*.[23] The first approach more dedicated to develop a precise and complete model based on mathematical foundations that has to lead to integrate into MILOS (§5) a library of degradation models for generic components, such as motors, pumps, valves, etc. The second approach more dedicated to develop functioning models based on system finality and complexity has to lead to implement into MILOS, on the basis of the generic component models, a network of degradation relationships (based on the propagation or abstraction of the flow or activity degradations) for the specific system (e.g. quay crane), as well to the technological level (e.g. to operate the motor rotation) as the function level (e.g. to move the quay crane on the Z axis) or as the product level (e.g. to move containers): It is therefore possible to implement a pro-activity for the quay crane operation to evaluate from a component degradation, its "cost" impact on the component itself, on the components in relation with it through the flows exchanged, on the function supported partially by it, etc.

In this last case, the knowledge-based approach can be automatically performed from the functional analysis by identifying the failures and the degradation (drift behavior), by studying their relations with the consumed or produced flows through HAZOP principles and then by defining their causes, effects and criticality through FMECA principles.

Using these principles, this phase is rendered consistent with the **M**odel **B**ased **D**iagnosis (MBD) theories[27,28] which define relations between failure cause and component abnormal behavior, bearing in mind that the improvement we proposed is (a) to take into account external cause of system failure, and (b) the concept of relation with cause for diagnosis has been extended to the relation with effects for prognosis. In that way, the three monitoring, diagnoses and prognosis can be formalized from functional analysis.

4.1. Prognosis process modeling

The prognosis process modeling is constructed using the principle of **degradation** in relation to the influence of the component degradation development on itself (to go deeper: breaking up principle) and on the flows produced by the activity (upstream and downstream consequences: propagation principle).

The degradation modeling is based on the S5 modal operators allowing one to distinguish the activity functioning at different consecutive times. The modality □ represents the Necessity, of depth n, implying that the hypothesis is true under all the times before. The modality ■ is the same but for depth n+1. This modeling is also founded on the first order predicate calculus (Table I) used in Artificial Intelligence.

For example, the characterization of an irregular functioning of a activity is expressed by:

Activity (Irregular Functioning) ∧ WTDi (On) ⟶ System (internal degradation)
□ Activity (Irregular Functioning) ∧ □ WTDi (On) ⟶ □ HTDo (nominal)
■ Activity (Irregular Functioning) ∧ ■ WTDi (On) ⟶ ■ ¬HTDo (nominal)

The degradation prognosis process can be therefore formalized by redefining the triplet of the MBD to propose a triplet {{*BM*, *COMP*}, *CXT*, *OBS*}, where:

- BM corresponds to the abnormal description {$Defabn_{DP}$} linked to causality and degradation behavior,
- COMP is the system structural description {$Employs_{DP}$} such as the components,
- CXT (context) is an empty set because all the output objects and the output flows of the activity are considered as potential consequences {*CXT*} = ∅
- OBS represents the observations to be made to implement the prognosis. {*OBS*} = {*OBS prognosis*}

These observations are the degradations from which it is possible to calculate the effects on the output objects or flows and therefore on the closed activities. They are composed of factual and measured observations. The facts are constituted by the degradations occurring on the activity, while the measures are made on the properties of the output objects and flows but also on the properties of the resources supporting the activity, in order to minimize the solution hypothesis.

Indeed, in relation to a degradation, first if the properties of the output objects or flows are identified as abnormal then the effect is seemingly propagated outside the activity. Second, in the case where the properties of the output objects and flows are identified as normal, there is no external consequence. Finally, if some properties of the resources are identified as abnormal, the effect is apparently propagated inside the activity.

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Table II. Part of the direction unit degradation behavior.

□ move_in_Y (Irregular Functioning) ∧ □ Y_moving_order (On) → □ mov_speed (nominal)
■ move_in_Y (Irregular Functioning) ∧ ■ Y_moving_order (On) → ■ ¬mov_speed (nominal)
move_in_Y (Decreas_Functioning) ∧ Y_moving_order (On) → mov_speed (decreasing)
move_in_Y (Intermittent_Functioning) ∧ Y_moving_order (On) → mov_speed (no)

The set of the prognostic observable variables is therefore defined as the set of the activity degradations, of the properties of the output flows and objects, and of the properties of the resource supporting the activity.

4.2. Prognosis process related to "to move the quay crane on the Y axis" function

On the basis of prognosis process modeling principles and from the functional analysis of the quay crane, it is possible to develop one prognosis process for each function. In this case, the prognosis process of the function "To move the quay crane on the Y axis" (move_in_Y) at the level A0 (supported by the direction unit) is described by the BM of Table II, its structural description COMP (motor, cable, braking system, . . .), its factual observations (irregular functioning, no functioning, . . .), its measure observation (Y moving speed) and its context CXT (empty set).

For example, the irregular functioning of the direction unit is characterized through the model $\{Def_{abnDP}\}$ of $\{BM\}$ by the alternation between a nominal and non nominal value of the Y moving speed bearing in mind that the Y moving order (WTDi) is on.

These equations allow one to identify by a deductive reasoning and from the degradations, the **effects** on the activity output flows such as the HTDo flow (decreasing of the moving speed, non-moving speed, moving speed value less than nominal expected one, . . .), or the BATDo flow (vibration, noise, fatigue, . . . related to the Direction Unit BATDo).

The observable facts are therefore the activity degradation:

{OBS prog_fact} ⊆ {move_in_Y (Irregu_funct), move_in_Y (Decrea_Funct), move_in_Y (Interm_Funct)}

while the observable measures concern some properties of the activity output flows (moving speed, noise, fatigue).

Mov_speed ∈ $\{\text{Proper}_{\text{HTDo}}\}$, Noise_cable ∈ $\{\text{Proper}_{\text{BATDo}}\}$, Fatigue_structure ∈ $\{\text{Proper}_{\text{BATDo}}\}$, . . .

4.3. Diagnosis process modeling

The diagnosis process modeling is constructed on the principle of **causality** allowing one to represent from the functioning modeling, each cause degradation as a relation between the activity degradation and the system (resource) malfunctioning (internal cause), or between the activity degradation and the deviations of the input object or flow properties (external cause).

So, the possible transitions between the normal and degraded states of the system are expressed either as the influence of a deviation of an input object property $Prop_{EOi}$ or of input object flow property $Prop_{Fli}$ (product, energy, . . .), or as the influence of an internal activity degradation on the system.

This causality between the normal and abnormal states is modeled with S5 modal operators allowing one to distinguish the chronological relations between these states.

Relation 1 (internal cause):
□ Activity (normal) ∧ System (degraded) → ■ Activity (degradation)

Relation 2 (external cause):
□ Activity (normal) ∧ Proper_HTDi (deviation) → ■ Activity (degradation)
□ Activity (normal) ∧ Proper_BATDi (deviation) → ■ Activity (degradation)
□ Activity (normal) ∧ Proper_KHTDi (deviation) → ■ Activity (degradation)
□ Activity (normal) ∧ Proper_WTDi (deviation) → ■ Activity (degradation)

The degradation diagnosis process can be therefore formalized by redefining the triplet of the MBD to propose a triplet $\{\{BM, COMP\}, CXT, OBS\}$, where:

- BM corresponds to the description $\{Def_{DP}\}$, that is to say the gathering of the normal description $\{Defn_{DP}\}$ and the abnormal one $\{Defabn_{DP}\}$ related to the causality.
- COMP is the system structural description $\{Employs_{DP}\}$,
- CXT is an empty set because all the input objects and the input flows of the activity are considered as potential causes $\{CXT\} = \varnothing$,
- OBS represents the observations to be made to implement the diagnosis. $\{OBS\} = \{OBS_{diag}\}$

$\{BM\} \subseteq \{Defn_{DP}\} = \{Defn_{DP}\} \cup \{Defabn_{DP}\}$ with:

$\{Defabn_{DP}\} \subseteq \bigcup_{1}^{n} \{Causalityn_{DP}\}$ n: causality relationship number

Among these observations, the factual ones are made up of the degradations occurring on the activity, while the measure observations are made on the properties of the input objects and flows and on the properties of the resources in order to minimize the solution hypothesis.

Indeed, in relation to a degradation, first if the properties of the input objects and flows are identified as abnormal then the cause is seemingly external to the activity. Secondly, in the case where the properties of the input objects and flows are identified as normal, there is no external cause. Finally, if some properties of the resources are identified as abnormal, the cause is apparently internal to the activity. The set of the diagnosis observable variables is defined as the set of the activity degradations, of the properties of the input flows and objects, and of the properties of the resource supporting the activity.

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Therefore, the identification of the potential cause has to be made on the basis of the possible observations on which our proposition is to apply the abduction principle (reasoning associated to the logical operator "implication") allowing one to find the fact from the observations. The abduction model for the degradation diagnosis, in relation to the reference one developed by Bylander[30] is a quadruplet <Dall, Hall, e, pl> where:

Dall: set of the degradations, of the observations on the properties of the input objects and flows, and on the properties of the resource supporting the activity (data to be explained)
Hall: set of the input objects and flows, and the physical resource (the system) supporting the activity (**individual hypothesis**) $Hall \subseteq \{System, HTDi, KHTi, BATDi, WTDi\}$
$e(H)$: functioning and malfunctioning relationships (way from Hall to Dall)
$pl(H)$: H has as plausibility pl(H)).

The diagnosis consists in "abducting" from the degradations *Dall*, the hypothesis *Hall* allowing one to determine the system potential causes.

4.4. Diagnosis process related to "to move the quay crane on the Y axis" function

The application of these previous formal definitions to the diagnosis process of the direction unit (supporting the "To move the quay crane on the Y axis" function) led to the BM causalities modeling, its structural description COMP (motor, cable, braking system, . . .), its factual observations (irregular functioning, no functioning, . . .), its measure observations (electrical power flow, moving order flow, containers to be moved on Y axis flow, . . .), and its context (empty set).

For example, the transition between the normal state and the dysfunctional one (no functioning, decreasing, . . .) of the direction unit is modelled by :

□ move_in_Y (normal) ∧ Direction_Unit (vibration) → ■ move_in_Y (Irregular)
□ move_in_Y (normal) ∧ Direction_Unit (flexion) → ■ move_in_Y (Irregular)
. . .
□ move_in_Y (normal) ∧ Frequ_Electrical_Power (lessthan) → ■ move_in_Y (Decrease)
□ move_in_Y (normal) ∧ Frequ_Electrical_Power (morethan) → ■ move_in_Y (Increase)
. . .

This model enables one to identify the internal causes such as : crack in the direction unit structure, fatigue of the direction unit structure, bad configuration of the direction unit components, . . . or the external ones such as bad Frequency or voltage of the Electrical Power, Non nominal properties of the containers to be moved on Y axis (container is too heavy), Non nominal properties of the moving_order (too late, too soon).

In this model the factual observations are related to the activity degradations realized by the Direction Unit: move_in_Y (irregular, decreasing, no functioning, . . .), . . . , while the measure observations are linked to the intrinsic properties of the Direction Unit *BATDo*.

4.5. Monitoring process modeling

The monitoring process modeling is constructed on the principle of **deviations**, which correspond to a qualitative or quantitative variation of the object properties or of the flow properties.[26] The deviation is defined as an attribute integrated with the object or flow properties and is modeled with S5 modal operators allowing to differentiate the property at chronological times.

Proper_objects (deviation) ∈ {No, MoreThan, LessThan, PartOf, SupPart, OtherThan, Inverse},
Proper_flow (deviation) ∈ {No, MoreThan, LessThan, Inverse}.
Prop_obj = 0 ⇒ Prop_obj (No), ■ Prop_obj – □ Prop_obj > ε ⇒ Prop_obj (MoreThan),
□ Prop_obj – ■ Prop_obj > ε ⇒ Prop_obj (LessThan),),
□ Prop_obj ⊃ ■ Prop_obj ⇒ Prop_obj (PartOf),
□ Prop_ob ⊂ ■Prop_obj ⇒ Prop_obj (SupPart), □ Prop_obj ⊄ ■ Prop_obj ⇒ Prop_obj (OtherThan),
□ Prop_obj ≈ – ■ Prop_obj ⇒ Prop_obj (Inverse)

In that way, the degradation monitoring process consists in observing a deviation (untimely flow, irregular flow) representative of the symptoms (threshold exceeding), first, on a resource property (activity support flow) or, second, on activity output flows. It can be formalized by redefining the triplet of the MBD to propose a triplet {{*BM*, *COMP*}, *CXT*, *OBS*}, where:

- BM corresponds to the description $\{Def_{DP}\}$, that is to say the gathering of the normal description $\{Defn_{DP}\}$ and the abnormal one $\{Defabn_{DP}\}$ related to the degradation behaviour.
- COMP is the system structural description $\{Employs_{DP}\}$, $\{COMP\} \subseteq \{Employs_{DP}\}$
- CXT corresponds to the description of the context defined as activity input or as using the activity. $\{CXT\} = \{CXT_{Inp}\} \subseteq \{FI_{DP}) \cup \{CI_{DP}\} \cup \{RI_{DP}\} \cup \{Where - Used_{DP}\}$
- OBS represents the observations to be made to implement the monitoring. $\{OBS\} = \{OBS_{Monitoring}\}$, $\{OBSMonit\} \subseteq \{PropHTDo\} \cup \{PropKHTDo\} \cup \{PropBATDo\} \cup \{PropWTDo\}$ $\{BM\} \subseteq \{DEF_{DP}\} = \{Defn_{DP}\} \cup \{Defabn_{DP}\}$ with:

  $\{Defabn_{DP} \subseteq \bigcup_{1}^{n} \{Behn_{DegDP}\}$ *n*: system degradations number

Therefore the degradation identification is made on the available observations on which it is possible to apply the abduction principle allowing one to determine the facts from symptoms and hypothesis. Our abduction model for the degradation monitoring is a quadruplet <Dall, Hall, e, pl> where :

Dall $\{OBS_{monitor}\}$
Hall set of the degradation hypothesis $Hall \subseteq \{NonFonc, FoncTard, FoncPrem, FoncDim, FoncAug \ldots\}$
$e(H)$ abnormal behavior

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$pl(H)$ plausibility value for each hypothesis

The monitoring consists in "abducting" from symptoms *Dall*, the hypothesis *Hall* allowing one to determine in which degradation mode the system is.

4.6. Monitoring process related to "To move the quay crane on the Y axis" function

The application of these previous formal definitions to the monitoring process of the direction unit (supporting the "To move the quay crane on the Y axis" function) led to degradation behavior modeling, its structural description (motor, cable, braking system, . . .), its observations (moving speed, noise, vibration, . . .), and its context (electrical power, . . .).

For example, the model $\{Def_{abnDP}\}$ applied to the direction unit supporting the function "to move the quay crane on the Y axis", identifies mainly the degradation behavior such as:

□ move_in_Y (Intermittent_Functioning) ∧ □ Y_moving_order (On) → □ mov_speed (nominal)
■ move_in_Y (Intermittent_Functioning) ∧ ■ Y_moving_order (On) → ■ mov_speed (No)
□ move_in_Y (Irregular Functioning) ∧ □ Y_moving_order (On) → □ mov_speed (nominal)
■ move_in_Y (Irregular Functioning) ∧ ■ Y_moving_order (On) → ■ ¬mov_speed (nominal)
□ move_in_Y (Increasing Functioning) ∧ □ Y_moving_order (On) → □ mov_speed (nominal)
□ move_in_Y (Increasing Functioning) ∧ □ Y_moving_order (On) → □ direction_vibration (nominal)
□ move_in_Y (Increasing Functioning) ∧ □ Y_moving_order (On) → □ direction_noise (nominal)
■ move_in_Y (Increasing Functioning) ∧ ■ Y_moving_order (On) → ■ mov_speed (MoreThan)
■ move_in_Y (Increasing Functioning) ∧ ■ Y_moving_order (On) → ■ direction_noise (MoreThan)
■ move_in_Y (Increasing Functioning) ∧ ■ Y_moving_order (On) → ■ direction_vibration (MoreThan)
. . .

These equations enable one to determine the degradations: Irregular Functioning, Intermittent Functioning, Functioning in Increasing, . . ., from observable symptoms on the finality flow (Moving Speed of the quay crane on the Y axis) which results from the activity fulfilment but also on the Vibration, Noise, . . . properties which are internal to the Direction Unit Resource.

5. MILOS: A INTELLIGENT MAINTENANCE PLATFORM TO SUPPORT PROACTIVE MAINTENANCE OF QUAY CRANES

The deployment, on the quay crane, of the monitoring, diagnosis and prognosis processes previously formalized by means of complementary knowledge and analytical approaches is made with the computer aided safety software CASIP of the company PREDICT to lead to the MILOS product (distributed software platform making it possible to implement a remote monitoring, diagnosis and maintenance for multi-sites harbor and quays).

The CASIP suite is a formal framework integrating a set of methods and tools to implement the different processes on the quay crane site (a) from the **engineering** phase to transform the formalization of the processes into a practicable form (modules) directly "computerizable" and executable, (b) to **operation** phase where all the modules are active to follow and master the degradation on site.

For example, the engineering phase consists for the monitoring process of one moving speed degradation (mov_speed) of the direction unit (e.g. to detect one degradation (no nominal value) on the performance property of the finality flow "moving speed" in terms of trend analysis):

- in declaring the input variables to be monitored (the speed in the 2 ways of direction). These variables (the process interfaces) (Figure 5a) result from sensors in that case (it could result from the operators observations if instrumentation is not available or from other calculations) and are acquired in real through the network.
- in defining in $C++$, from the monitored variables, (a) the algorithm (part of the behavior process) to calculate the variable which will be the basic element for this degradation detection (performance of the moving speed) (Figure 5b), (b) the algorithm to calculate the moving average (Figure 5b) and (c) the algorithm to calculate the trend analysis on this average (Figure 5d). This last result is the input of one diagnosis and prognosis process to fulfil proactivity if necessary and therefore to be just in time for the maintenance actions in order to master the direct and indirect cost (link with CMMS). The parameters which are used in the different algorithms, are retrieved directly in other data bases more specialized and managed by the right actors (maintenance, control, technical management, safety, . . .) and the results of the different processes can be available also in form of synoptic (different colors to represent the degradation state, . . .).

To make active all the different processes, MILOS (Figure 6) integrates (a) in link with the shop floor components of the quay crane, a real-time database allowing to acquire the real-time instrumentation information, the operator observation, . . . and (b) in link with the environmental indicators, a communication with other Information System of the Harbor (e.g. to retrieve parameters, to be consistent with business strategy, . . .).

In that way, MILOS is structured in 3 levels:

- a local level connected to the communication networks for the acquisition, the processing and the storing in real-time of the data,
- a networked level for the more global safety processing based on exploitation data, treatment, expert algorithms, their displaying and the storing of the information within a data base (e.g. ORACLE, SQL Server, Sybase, . . .),
- a remote level for distant access from anywhere and through the Internet.

The integration, first, of the TCP/IP protocol allows MILOS to communicate with the Harbor Management level (ERP) and the Operational level (MES), and second, of the OPC (OLE for Process Control) standard warrants the commu-

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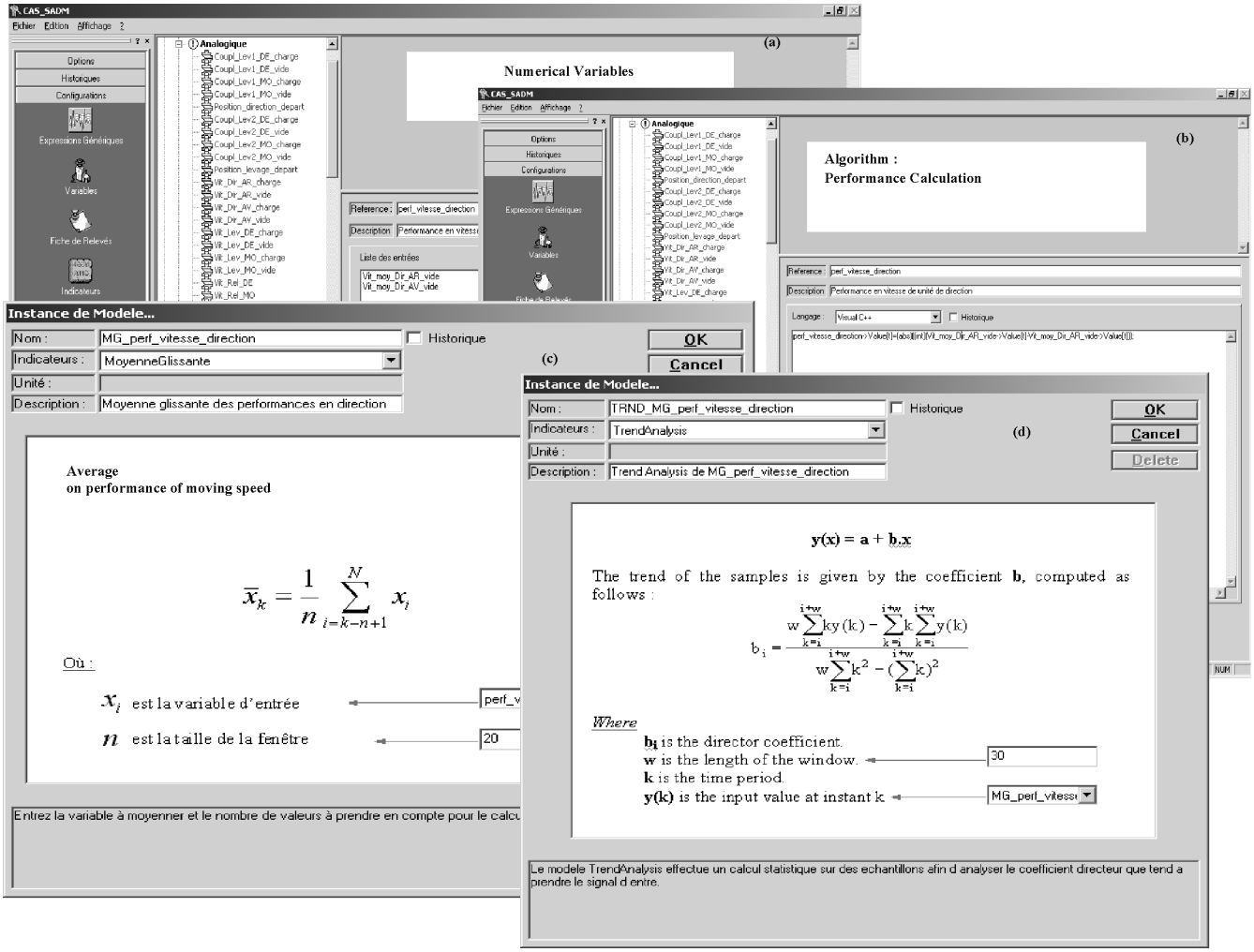


Fig. 5. Deployment of the processes on the CASIP-MILOS platform (with courtesy of PREDICT).

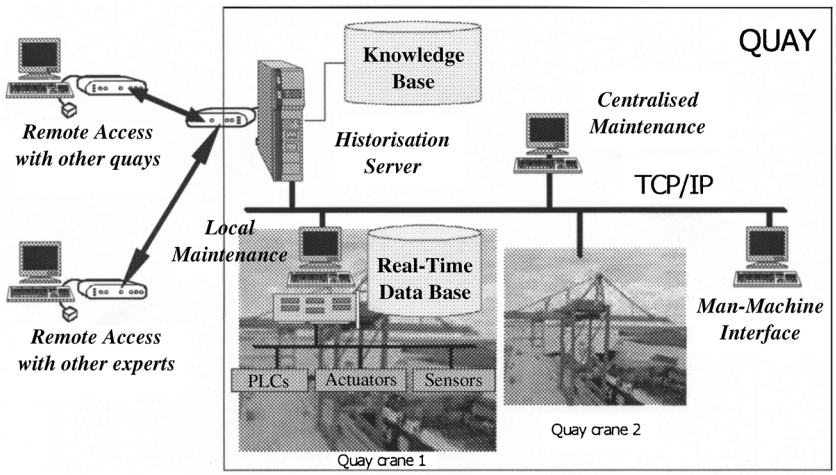


Fig. 6. Integration of CASIP-MILOS in the harbour (with courtesy of PREDICT).

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nication with the industrial process components through fieldbuses. This communication confers a large range of possibilities to communicate as well as with the PLCs, the sensors and distributed Input/Output (to acquire the real-time instrumentation information, the operator observation). An independent communication also ensures a robustness and an autonomy in particular in the event of failure of the Supervisory Control.

Inside the database of MILOS, the results of the process activation are formalized in terms of knowledge to make it more synthetic and shareable between users (experts, technicians, operators). The knowledge database system uses trade patterns[29] and case based reasoning[30] techniques. MILOS integrates also *XML* (eXtended Markup Language)[31] in order to get an ergonomic Man Machine Interface and a wide portability.

The Operational Safety based to the continuous measurement and indicators evaluation, makes it possible to observe degradations being able to have an catalectic impact and dangerous phenomena on the Human Being and Environment.

6. CONCLUSION

MILOS is a first pro-active intelligent maintenance platform contributing to cost-oriented automation by allowing a optimization of the operation's safety and CRAMP parameters of the quay crane with regard to the harbor maintenance strategy (decreasing operational and maintenance costs) to support:

- the interactions of the proactive maintenance process with the complete harbor exploitation system to be holistic compliant, as formalized in our enterprise modeling framework based and extending the GERAM and CIMOSA normative modeling framework,
- the modeling of the monitoring, diagnosis and prognosis processes to form the proactive maintenance process and issued from an analytical model-based approach and a knowledge model-based approach by using Model Based Diagnosis concepts (development also of library of processes for generic components more reliable),
- the deployment on site and in operation of the monitoring, diagnosis and prognosis processes in the harbor context.

The platform development and tests are in progress on a quay crane example in France (Le Havre). Even if this platform is a first step toward stable functioning for a maintenance optimization of a quay crane in a Tele-service context while solving on-line reactivity, it is not sufficient to fulfil the maintenance optimization in regards to internal and external quay crane changes in order to meet, for example, the dynamic requirements of Agile Manufacturing/Fractal Factory (metamorphic changes).[32] It implies a need to evolve towards maintenance processes, which should be both self-controlling and self-executing (autonomy) while co-operating with other processes via communication and negotiation abilities (co-operation) to fully optimize the dynamical Maintenance efficiency.[33] Such an improvement requires also an evolution towards engineering processes related to Distributed Artificial Intelligence based on emerging trends, such as the Multi-Agent System (MAS) modeling technique.

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