Experience report: Deriving Architecture Specifications from KAOS Specifications

Divya Jani
Damien Vanderveken

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Contents

List of Figures

Chapter 1

Introduction

The most difficult step in the design process of a system is clearly the transition from the requirements to the architecture. Requirements obtained from the various stakeholders are transformed to an architecture that can be understood by developers. There are several different ways to derive an architecture and two of those ways are explored here.

The system we used throughout this report was a power plant that was obtained from [4, 5]. Our first step was to create a goal-oriented requirement specifications from the information available. The KAOS requirement specification language is used [9, 7, 6]. The power plant description was not complete so we often had to do with inadequate data.

The first method used was developed by Axel van Lamsweerde (University of Louvain - Belgium) and is described in [10]. The various steps are explained in detail in one of the following sections of this report. We have also described some of the problems encountered during the derivation process.

The second method results from the work of Dewayne Perry and Manuel Brandozzi (University of Texas at Austin). Their work is presented in [2, 3, 1]. The resulting architecture and some of the derivation issues are described in the report.

After obtaining both architectures we have attempted to compare them and suggest some further work.

Chapter 2

Requirements derivation using the KAOS method

2.1 Goal Model

2.1.1 Goal model elaboration

Given the fact KAOS is a goal-oriented requirement specification method we logically began by trying to extract the goals of the system. A definition of the system was implicitly given in [4]. However the description of the powerplant monitoring system provided was partial and lacked details. So, throughout the requirement extraction process, we had to rely on our engineering skills, on professor Perry's advices and on our common sense in order to gather requirements as realistic as possible.

The following steps were followed in order to build the goal model. First of all, the informal definition of goals that are mentioned in [4] were carefully written down. From that, a first goal refinement tree was built. This first draft was all but complete. This tree was completed thanks to a refinement/abstraction process. The version we obtained at that point was still totally informal. Temporal first-order logic [8] was then used to remove this weakness. It enabled us to ensure our refinement tree was correct, complete and coherent. The use of refinement patterns as described in [9] served as a guidance. The milestone-driven pattern in particular was applied numerous times. It prescribes that some milestone states are mandatory in order to reach the final one. This pattern is presented in fig 2.1. The patterns were a great help to track and correct incompleteness and incoherence. Furthermore they enabled us to save a huge amount of time by freeing us to do the tedious proof work.

Because of the iterative nature of the requirements gathering process, the goal model underwent subsequent changes. The reasons for that were various,e.g., coherence between the different models forming the KAOS specifications, enhancements, simplifications,etc.

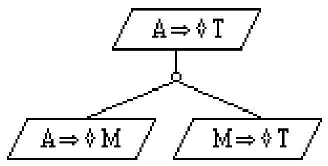


Figure 2.1: Milestone refinement pattern

2.1.2 Goal model characteristics

The goal refinement tree is globally structured in two parts. This shape reflects the two main goals the system has to ensure to monitor the powerplant. The occuring faults have to be detected and the alarms resulting from those faults have to be managed. The roots of the two resulting subtrees are respectively *FaultDetected* and *AlarmCorrecltyManaged*. They are subsequently refined using the various patterns until the leaf goals are assignable to a single agent - from the environment or part of the software.

As an illustration of the use of the milestone refinement pattern – the most widely used – the following example will be developed. Let's consider the goal *AlarmRaisedIfFaultDetected* with its formal definition

$$\big(\forall f : Fault, \exists ! l : Location, \exists ! a : Alarm\big)\big(Detected(f,l) \Rightarrow \Diamond Raise(f,a)\big) \quad (2.1)$$

This goal is refined using the milestone refinement pattern presented in fig 2.1 by instanciating the parameters as follows:

$$A \ : \ \big(\forall f : Fault, \exists ! l : Location\big)\big(Detected(f,l)\big) \quad (2.2)$$

$$M \ : \ \big(\exists fi : FaultInformation\big)\big(f \equiv fi \wedge Transmitted(fi, PRECON, ALARM)\big) \quad (2.3)$$

$$T \ : \ \big(\forall fi : FaultInformation, \exists ! a : Alarm\big)\big(Raised(fi,a)\big) \quad (2.4)$$

The application of that pattern in particular results here from the fact that the information concerning the detected faults has to be transmitted to the ALARM to enable it to raise the proper alarm. This intermediate state is a necessary step to reach the final state, i.e., the raising of the alarm.

In order to have a system as robust as possible various goals have been added to the goal diagram. Among these a first class takes care of the correct working of all the sensors and ensures the data provided is consistent and coherent. The goals *SanityCheckPerformed* and *ConsistencyCheckPerformed* belong to this class. The second category – represented by the goal *DataCorrectlyUpdata* – makes sure the updates are well performed by the database. The purpose of some goals is to maintain the powerplant in a consistent state (e.g., *FaultStatusUpdated*, *AlarmStatusUpdated*). The communication has also been constrained in order to prevent any transmission problems.

The refinement of the goal *DataTransmittedToDB* is the result of that policy. The goal was refined as shown in Fig. 2.2

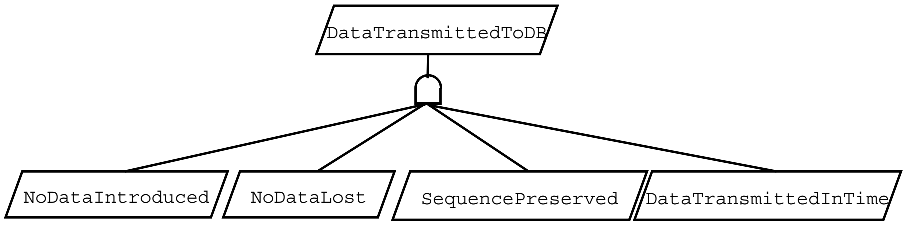


Figure 2.2: Communication refinement subtree

The three first subgoals ensure the corectness of the transmission while the last one sets a time limit. This constraint varies througout the system depending on the importance of the communication channel. The *FaultInformation* has to be transmitted from PRECON to ALARM within 1 second while answer a request can take a little longer – 5 seconds. The three first subgoals have been formally refined as followed [1]:

$$NoDataIntroduced : \big(\forall x : Data\big)\big(Transmitted(X,\_,\_) \wedge x \in Transmitted(\_) \Rightarrow x \in X\big) \quad (2.5)$$

$$NoDataLost : \big(\forall x : Data\big)\big(x \in X \wedge Transmitted(X,\_,\_) \Rightarrow x \in Transmitted(\_)\big) \quad (2.6)$$

$$SequencePreserved : \big(\forall x, y : Data, \exists u, v : Data\big)\big(x, y \in X \wedge Transmitted(X,\_,\_) \wedge Before(x, y, X) \quad (2.7)$$

$$\Rightarrow u, v \in Transmitted(X) \wedge Before(u, v, Transmitted(X)) \wedge x = u \wedge y = v\big) \quad (2.8)$$

They prescribe that no alteration has occured on the data transmitted,i.e., no data has been introduced or lost and the sequential order has been preserved.

The formal definition of the last subgoal depends on the time constraint. If we consider for example the transmission of a *FaultInformation* – which has the strongest time constraint – the formalization is:

$$DataTransmittedWithinTimeConstraint : \neg Transmitted(fi, PRECON, ALARM) \quad (2.9)$$

$$\Rightarrow \Diamond_{\leq 1s} Transmitted(fi, PRECON, ALARM) \quad (2.10)$$

[1]X stands for *SensorInformation*, *FaultInformation*, *AlarmInformation*, *FaultDiagnosis* and *AlarmDiagnosis*

2.2 Object Model

2.2.1 Object Model Elicitation

Entities present in the objects were first derived from the informal definition of the goals. All the concepts of importance were modelized either under the form of an object or of a relationship. Attributes were then added to the different entities in order to characterize them. Some of the attributes were extracted from the problem definition but most of them just reflect a necessity. This necessity arises from two main reasons.

First certain goal definitions need the presence of specific attributes. For example the attribute *WorkCorrectly* of *Sensor* was needed by the goal *Sanity-CheckPerformed*.

Second the definition of the properties of the various entities – expressed by invariants – requires specific attributes. As an illustration consider the following invariant of the object *Alarm* which expresses that all the alarms still active cannot have a deactivation time:

$$Activated = true \Rightarrow DeactivationTime = null \tag{2.11}$$

The purpose of certain attributes is to prepare for change. The reconfiguration function was finally not taken into account in the elaboration of the different models due to lack of time. However we believe that basically the only effect will be to modify the allowed range of temperature and pressure. Attributes representing the minimum, the maximum and desired value of both pressure and temperature were consequently added to the objects *SteamCondenser* and *CoolingCircuit*.

Last, a few attributes were just added in order to build a more complete model. The justification was just common sense. Among these are the attributes *Type* and *Power* of the object *PowerPlant*.

The last step of the elaboration of the goal model was the formalization of the domain invariants characterizing the differents entities. The model was refined many times due to the iterative nature of the requirement extraction process.

2.2.2 Object Model Characteristics

The main characteristic of the model is the presence of two different levels of representations for the concepts *Sensor*, *Fault* and *Alarm*. The first level refers to the object in itself while the second one refers to its representation in the software. This distinction was introduced for robustness reasons. In fact it enables us to manage the case where the representation of the object is not correct which would be unfortunate but can happen. The two levels are constrained by an invariant prescribing that all the attributes have to be identical.

The representation of the three main concepts – Sensor, Fault and Alarm – are linked together by a diagnosis relationship. The information provided by the sensor permits the detection of the faults and the description of a fault is the rationale for the raising of an alarm. Consequently the relationship *Fault-Diagnosis* links *SensorInformation* and *FaultInformation* while *AlarmDiagnosis* links *FaultInformation* and *AlarmInformation*. Those two relationships are one-one. It is a modelization choice. We chose that a fault is the result of one and only one error detected by one sensor and that each fault raises one and only one alarm. The reason for that is the resulting simplicity and the easiness of traceability.

2.3 Agent Model

2.3.1 Agent Model Elaboration

The definition of the agents was extracted mostly from [4, 5]. We drew inspiration from the existing agents. Each leaf goal from the Goal Model was assigned to one of the agents. We made sure that every agent has the capacity to assume the responsibility of the goal. By capacity we mean that every agent could monitor or control, depending on the case, every single variable appearing in the formal definition of a goal the agent has to ensure. For further details please refer to [6].

However a new agent was introduced : the `MANAGEMENT UNIT`. Its purpose is to ensure that all the sensors are working properly. It was added in a robustness concern.

Finally the operations needed to operationalize the differents goals were assigned to the responsible agent. This step will be explained later in the Operation Model section.

2.3.2 Agent Model characteristics

As it was already said, most of the agents come from the existing system. This is the case for `PRECON`, `ALARM`, `COMM`, `DB` and `Sensor`. The name used in [4] may be different but basically the functions performed are the same.

`PRECON` is in charge of the detection of all the faults that might occur either in the cooling circuit or in the steam condenser. `ALARM` takes care of the alarm management. `COMM` ensures the reliability and the performance of all the communcication throughout the system. `DB` stores all the data persistently and answers all the request concerning current values of the sensors, faults and alarms. The `Sensor` agent acquires the data from the field.

The additional agent – `MANAGEMENT UNIT` – has to check the sensors to see if they work properly.

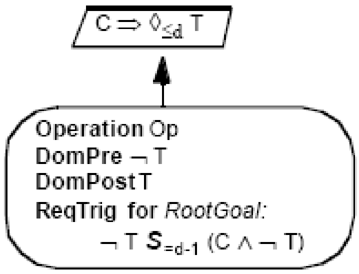
The agents belong to two different categories; they can be either part of the sofware-to-be or part of the environment. For example, `PRECON` belongs to the first class while `Sensor` belongs to the second one. This distinction in agents results also in a goal differentiation. In fact the goals assigned to environment agent are expectations while the others are requirements. This leads us to the introduction of the `MANAGEMENT UNIT` agent. `Sensor` is an environment agent and so all the goals assigned to it are expectations. But obviously we canot assume that the goals `SanityCheckPerformed` and `ConsistencyCheckPerformed` will be true without the intervention of a reliable software device. Moreover those kind of tests should not be the responsibitlity of the `Sensor` from a conceptual point of view.

2.4 Operation Model

2.4.1 Operation Model Elaboration

The operation model was the the last one to be constructed because it relies on a precise formal definition of the goals in order to be derived automatically. The operations contained in the model were derived in such a way that they operationalize some goal present in the goal model. A complete operationalization of a goal is a set of operations (described by their pre-, trigger- and postconditions) that guarantee the satisfaction of that goal if the operations are applied. That is where all the difficulty lies: finding complete operationalizations. We did an extensive use of the operationalization patterns described in [7] in order to derive complete operation specifications. It enabled us to save a lot of time on proofs. It is even more true than for the goal refinement pattern because we found the application of the operationalization very systematic.

Two patterns were in particular useful and we used them numerous times. The first one is the bounded achieve pattern described in Fig. 2.3. Its applicabilty condition (i.e., $C \Rightarrow \lozenge_{\leq d} T$) makes it very popular. In fact most of our system's goals have that form. The operation specification prescribes that $\neg T$ becomes T as soon as $C \wedge \neg T$ holds for $d-1$ time units. It is then straightforward to see that such a specification operationalizes the goal $C \Rightarrow \lozenge_{\leq d} T$.



$C \Rightarrow \lozenge_{\leq d}\ T$
Operation Op
DomPre $\neg$ T
DomPost T
ReqTrig for *RootGoal:*
$\neg T\ \mathbf{S}_{=d-1}\ (C \wedge \neg T)$

Figure 2.3: Bounded achieve operationalization pattern

The second most useful pattern was the immediate achieve pattern described in Fig. 2.4. Its applicability condition prescribes here that the final state T has to be reached as soon as C becomes true. In this case it is a bit more difficult to see why the satisfaction of the two operations guarantee the satisfaction of the goal. We will give a short intuition explaining why but the interested reader can find a complete proof in [7]. The first operation prescribes that as soon C becomes true the operation *must* be applied if $\neg T$ holds in order to reach the final state T. The second operation *may* be applied when C does not hold if the precondition T is true, making the postcondition $\neg T$ true.

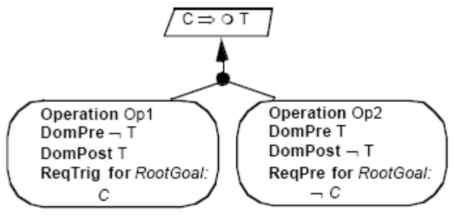


Figure 2.4: Immediate achieve operationalization pattern

Once all the operations were derived the were assigned to the agent responsible for the goal operationalized by those operations.

2.4.2 Operation Model Characteristics

We will presented in this section an illustration of the two operationalization patterns mentionned in the previous section.

For the first pattern, we will examine the operationalization of the goal `FaultInformationTransmittedWhenFaultDetected`. Its formal defintion is given by

$$\big(\forall f : Fault, \exists! l : Location, \exists! fi : FaultInformation\big)$$
$$\big(Detected(f,l) \wedge f.ID = fi.ID \Rightarrow \Diamond_{\leq 1s} Transmitted(fi, PRECON, ALARM)\big)$$

We can instantiate the pattern presented in Fig 2.3 with the following parameters.

$$C \; : \; Detected(f,l) \wedge f.ID = fi.ID \tag{2.12}$$
$$T \; : \; Transmitted(fi, PRECON, ALARM) \tag{2.13}$$

The operation resulting from the application of the pattern is:

Operation TransmitFaultInformation

DomPre ¬ Transmitted(fi,PRECON,ALARM)

DomPost Transmitted(fi,PRECON,ALARM)

ReqTrig for FaultInformationTransmittedWhenFaultDetected
¬ Transmitted(fi,PRECON,ALARM) $\mathbf{S}_{\mathbf{=1ms}}$ Detected(f,l) ∧ f.ID=fi.ID ∧
¬ Transmitted(fi,PRECON,ALARM)

Note that as $d-1$ time units makes here zero we simply took a smaller time unit.

To illustrate the second pattern consider the goal `SanityCheckPerformed` whose formal defintion is given by

$$\big(\forall s : Sensor\big)$$
$$\big(\neg s.workingProperly \wedge s.status =' on' \Rightarrow \circ s.status =' off'\big)$$

The instantiation of the immediate achieve pattern presented in Fig. 2.4 is straightforward.

$$C \quad : \quad \neg s.workingProperly \wedge s.status =' on' \tag{2.14}$$
$$T \quad : \quad s.status =' off' \tag{2.15}$$

The first operation derived thanks to application of the pattern is

Operation SwitchSensorOff

DomPre s.status='on'

DomPost s.status='off'

ReqTrig for SanityCheckPerformed
¬ s.workingProperly

and the second one is

Operation SwitchSensorOn

DomPre s.status='off'

DomPost s.status='on'

ReqPre for SanityCheckPerformed
s.workingProperly

Chapter 3

Architecture derivation

3.1 First method: Axel van Lamsweerde

The architecture derived in this section will be derived using the method developped by Axel van Lamsweerde in [10]. The method prescribes the use of three different steps. The first step consists of the derivation of a abstract dataflow architecture from the KAOS specifications. This first draft is next refined using style in order to meet architecturals constraints. The architecture obtained is finally refined using design patterns so as to achieve non-functional requirements. One section will be devoted to each step. After that the issues encountered will be discussed.

3.1.1 Step 1: From software specifications to abstract dataflow architectures

The first architecture is obtained from data dependencies between the different agents. The agents become software components while the data dependencies are modelized via dataflow connector. The procedure followed is divided into two sub-steps.

1. Each agent that assumes the responsibility of a goal assigned to the software-to-be becomes a software component together with its operations.

2. For each pair of components C1 and C2, drive a dataflow connector between C1 and C2 if

$$DataFlow(d, C1, C2) \Leftrightarrow Controls(C1, d) \wedge Monitors(C2, d) \qquad (3.1)$$

This step is very systematic. The result is shown in Fig. B.1.

One can note certain features. Due to the fact that the `COMM` agent does not control any variables no arrow comes from it. In fact `COMM` carries all the data among the different components but does not do any modifications. Moreover there is a dataflow connector between PRECON and ALARM while the real dataflow goes through COMM. This situation also happen between Sensor and Precon. The real dataflow pass through DB but there is no dataflow derived.

We believe that the underlying cause is the presence of low-level agents – DB and COMM – performing low-level functionalities – storage and transmission of data respectively – in the requirements. They were however needed to achieve certain goals. It results from that a strange architecture.

3.1.2 Step 2: Style-based architectural refinement to meet architectural constraints

In this step, the architectural draft obtained from step 1 is refine by imposing a “suitable” style, that is, a style whose underlying goal match the architectural constraint. The main architectural constraint of our system [4], [5] is that all the components should be distributed. In fact, in the real system, only PRECON had to be built and it has to integrate in a pre-existing architecture characterized by centralized communications and by distributed components.

The only transformation rule mentionned in [10] did not match our architectectural constraints so we had to design a new one considering what we thought we should obtain. The resulting transformations rule is shown in Fig. 3.1.

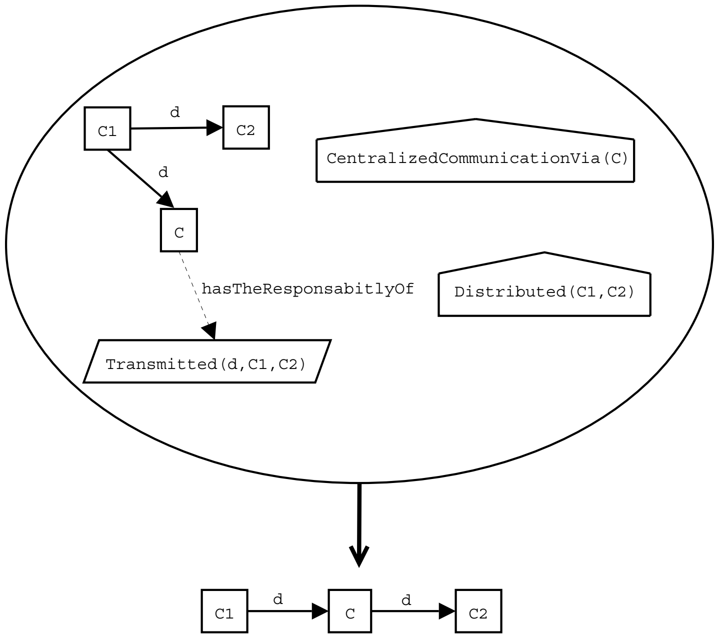


Figure 3.1: Centralized communication architectural style

This style was applied on our architectural draft and the result is shown in

Fig. B.2

As you can see, the architecture looks now closer to what we expected. Every single communication is achieved in a centralized way through the communication module. The architectural constraints are now met.

3.1.3 Step 3: Pattern-based architecture refinement to achieve non-functional requirements

Th purpose of this last step is to refine further the architecture in order to achieve the non-functionnal requirements. Those can belong to two different categories; they can be either quality-of-service or developemnt goals. Quality-of-service goals include, among others, security, accuracy an usability. Development goals encompass desirable qualities of software such as *MinimumCoupling*, *MaximumCohesion* and *reusabilty*.

This step refines the architecture in a more local way than the previous one. Patterns are used instead of styles. The procedure to follow could be divided further into two intermediary steps.

1. for each NFG G, identify all the connectors and components G may constrain and, if necessary, instantiate G to those connectors and constraints.
2. apply the refinement pattern matching the NFG to the constrained components. If more than one is applicable, select one using some qualitative technique (e.g., NFG prioritization).

Two refinement patterns were used on our system. The first one is presented in Fig. 3.5. We wanted to have a fault-tolerant communication between `PRECON` and `ALARM` because it is the core of the system. The most critical functions (i.e., the fault detection and the alarm managemnet) are performed in those two component. That's why we wanted to make those modules as resistant as possible to any kinds of failure. One could note than the pattern was not applied exactly like it is defined in Fig. 3.5. The presence of the component `COMM` between `PRECON` and `ALARM` was however ignored because we believed it has no influence on the capacity of the pattern to achieve its goal.

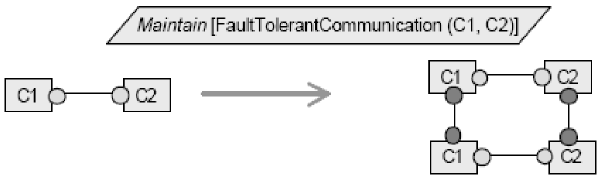


Figure 3.2: Fault-tolerant refinement pattern

The second refinement pattern we used is shown in Fig. 3.3. It was introduced because both `Sensor` and `Management Unit` access and modify the same data – `SensorInformation`. We wanted to make sure that all the modifications made from both sides are consistent.

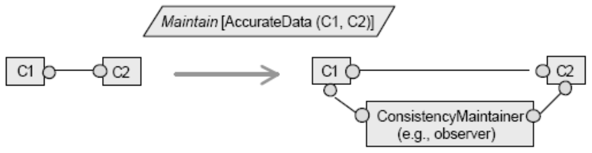

Maintain [AccurateData (C1, C2)]
C1
C2
C1
C2
ConsistencyMaintainer (e.g., observer)

Figure 3.3: Consistency maintainer refinement pattern

The final architecture is presented in Fig. B.3.

3.2 Second method: Dewayne Perry and Manuel Brandozzi

The second method converts the goal oriented requirement specifications of KAOS into architectural prescriptions.

The components in an architecture prescription can be of three different types - process, data or connector. Processing components perform transformation the data components. The data components contain the necessary information. The connector components, which can be implemented by data or processing components, hold the system together. All components are characterized by goals that they are responsible for. The interactions and restrictions of these components characterize the system. The following is a sample component -

Component PRECON

Type Processing

Constraints FaultDetected
RemedyActionSuggested
PeriodicalChecksPerformed&ReportWritten

Composed of FaultDetectionEngine
FaultInformation
FaultDiagnosis
SensorInformation
SensorConnect

Uses /

This example shows a component called PRECON. Type denotes that the component is a processing type component. The constraints are the various goals realized by PRECON. It thereby defines the constraints on the component. Composed of illustrates the sub components that implement PRECON in the next refinement layer. The last attribute Uses, indicated what are the components used by this component. It also specifies the connectors used for the interaction.

There are well defined steps to go from KAOS entities to APL entities. The following table illustrates this relationship

KAOS entities	APL entities
Agent	Process component / Connector component
Event	-
Entity	Data component
Relationship	Data component
Goal	Constraint on the system / on a subset of the system
	One or more additional processing, data or connector components.

In this method we create a component refinement tree for the architecture prescription from the goal refinement tree of KAOS. This is a three step process and may be iterated.

3.2.1 First step

In the first step we derive the basic prescription from the root goal of the system and the knowledge of the other systems that it has to interact with. In this case the software system is responsible for monitoring the power plant. Thus the root goal is defined as "PowerPlantMonitoringSystem".

This goal is then refined into PRECON, ALARM, DataBase and Communication components. These refinements are obtained by selecting a specific level of the goal refinement tree. If we only take the root of the goal refinement tree, the prescription would end up being too vague. On the other hand if we pick the leaves, we may end up with a prescription that is too constrained. Therefore we pick a certain level of the tree which we feel allows us to create a very well defined prescription while preventing a specification that constrains the lower level designs.

3.2.2 Second step

Once the basic architecture is in place, we obtain potential sub components of the basic architecture. These are obtained from the objects in KAOS specification. We derive data, processing and connector components that can implement PRECON, ALARM, DataBase and Communication components. If in the third step we don't assign any constraints to these components, they won't be a part of the system's prescription.

The following are Preskriptor specifications of some candidate objects from the requirement specifications.

Component Fault

Type Data

Constraints ...

Composed of ...

Component FaultInformation

Type Data

Constraints ...

Composed of ...

Component SensorConnect

Type Connector

Constraints ...

Composed of ...

Component QueryManager

Type Processing

Constraints ...

Composed of ...

Since all the components derived from KAOS' specification are data, we need to define various processing and connector components at this stage. At the next step we decide which of these components would be a part of the final prescription.

3.2.3 Third step

In this step we determine which of the sub goals are achieved by the system and assign them to the previously defined components. With the goal refinement tree as our reference, we decide which of the potential components of step two would take responsibilities of the various goals. Note that this is a design decision made by the architect based on the way he chooses to realize the system. The components with no constraints are discarded, and we end up with the first complete prescription of the system.

Components like Fault were discarded from the prescription because they were not necessary to achieve the sub goals of the system. Instead of the Fault component we chose to keep FaultInformation. Different architects may use different approaches.

It is interesting to note that in our first iteration of the prescription Communication was a leaf connector with no subcomponents. It was responsible for realizing the necessary communication of the system. However the power plant communication was not uniform throughout the system. Different goals had different time, connection and security constraints for communication. In our first iteration we assumed that Communication component could handle these varying types of requirements on it. However then we realized that creating sub components for Communication component was a step that helped illustrate these differences. Therefore we created the sub components - UpdateDBConnect, FaultDetectionEngineAlarmManagerConnect and QueryDBConnect. As the names suggest, each of these were responsible for the communication in different parts of the system. Therefore it was easier to illustrate the different time and security constraints needed for each of these.

The following are the prescriptions for the sub components

Component UpdateDBConnect

Type Connector

Constraints Secure
TimeConstraint = 2 s

Composed of /

Uses /

Component QueryDBConnect

Type Connector

Constraints TimeConstraint = 5 s

Composed of /

Uses /

Component FaultDetectionEngineAlarmManagerConnect

Type Connector

Constraints Fault Tolerant
Secure
TimeConstraint = 1 s

Composed of /

Uses /

3.2.4 achieving non-functional requirements

An additional fourth step in the prescription design process focuses on the non functional requirements. Goals like reusability, reliability etc can be achieved by refining the prescription. This step is iterated till all the non domain goals are achieved.

For this system we introduced additional constraints on the Database and the connector between Alarm and Precon (FaultDetectionEngineAlarmManagerConnect).

In case of Database an additional copy of the Database was introduced to ensure fault tolerance. With the introduction of a copy additional issues arise. For example, we need to ensure that if the main database recovers from a failure, all the changes made on the second database since the failure should now be made on the main database. Once that's done the control should be shifted to the main database. This an several other additional constraints were thus defined.

As a second step, we also defined two copies of Alarm and Precon. This again created additional constraints. For example, each time one copy of Precon fails, the other one should take over without affecting the functioning of Alarm.

A comprehensive list of additional constraints can be found with the prescription of the system.

3.2.5 Box diagram

Once the architecture was created we also added a box diagram illustrating the various components and connectors. The component tree created as a result of the three steps did not show how the various components are linked through the connectors. The box diagram helps in visualizing this and thus gives a more complete view of the architecture.

3.3 Problems and Issues

The following section provides an overview of some of the problems encountered while working on the architecture.

There were some issues common to both architectures. Firstly neither architecture has means of addressing fault tolerance, reliability etc as architectural constraints. The architectures are derived only from the goal oriented requirements, and there is a possibility that for some cases fault tolerance etc may be introduced for architectural reasons. Neither method has a well defined way of dealing with this. Secondly, we often had to work with inadequate information on the functioning of the power plant. We were unable to find any information on certain requirements like performance. Therefore performance was not included. However in a real world power plant system performance is very critical to the functioning.

Next we describe the problems encountered specific to each architecture.

3.3.1 Architecture 1

Once the requirements are finalized, the first step is to obtain an abstract dataflow architecture. Dataflow architecture is obtained by using functional goals assigned to software agents. The agents become architectural components and then dataflow connectors are derived from input/output dependencies.

In the next stage architectural styles are applied. At this point there were only a few sample styles to look at. The power plant architecture was relatively small and we were unable to apply many of these styles to the architecture.

The third step requires the use of patterns to achieve non functional requirements. There were various sample patterns given, however the small size of the power plant architecture limited the choice of patterns to apply.

An other issue with the architecture was the creation of new components during the course of the derivation that had no operations. We also had to create some new connectors that did not have a complete definition.

In some cases the patterns were not well documented so it was difficult to understand their application.

On the other hand there were cases where it was required to apply two or more patterns to the same components. It was difficult to decide how to combine the patterns to realize this.

The following two figures show how to apply patterns to achieve interoperability and fault tolerance between components. However it is difficult to see how the patterns would be applied if say components C1 and C2 needed to achieve both interoperability and fault tolerance. An other consideration would be if the order in wich we apply these patterns to achieve a combination matters. There were no clear guidelines provided to realize this.

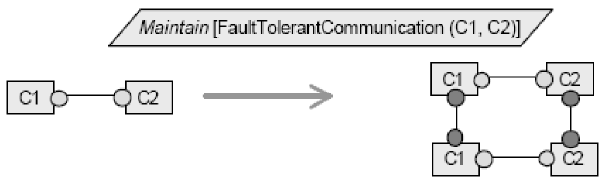


Figure 3.4: Interoperability refinement pattern

We were unable to find suitable patterns for some other non functional requirements. The power plant architecture required certain time constraints on different functions, however it was not possible to illustrate these time constraints with the architecture.

In order to achieve fault tolerance some components were made redundant as illustrated in the pattern. It was difficult to determine which and how many components should be redundant. There wasn't enough information available on the functioning of the power plant to assign higher priority to some compo-

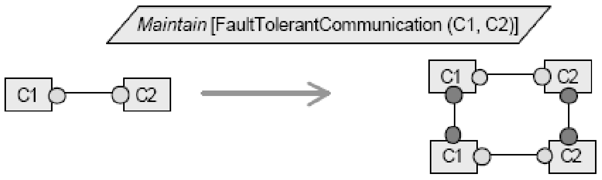


Figure 3.5: Fault-tolerant refinement pattern

nents and lower to others. The final decision was made based on the limited information provided.

An additional problem was illustrating the need to ensure consistency between the two redundant components. The communication between the components would change with the introduction of redundant components however it was difficult to explain how.

Alarm component was made redundant since it was critical to ensure smooth functioning of the power plant. However we could not define the method of communication between the two copies of alarm, and the method used to ensure consistency. It was also difficult to determine how the communication between Alarm-Operator, Alarm-Communication would change with the presence of an additional component and how this would change the current connector.

We could not determine the need for interoperability due to the lack of detailed system information.

The final architecture obtained used a communication component to facilitate all communication for the system. However the communication between components often had different features and constraints. There were hardware connections, software connections, redundant components, different time constraints and different reliability constraints. It was not possible to illustrate these differences in communication with the architecture. One possibility discussed was to define communication as a connector instead of a component.

Alternative
One alternative discussed was to obtain the dataflow architecture using objects instead of agents.

3.3.2 Architecture 2

This method takes as input the requirement specifications in KAOS and provides as output an architecture specification in an architectural prescription language (APL) - Preskriptor. Creating the architecture is a three step process where in the first step the basic prescription is derived from the root goal for the system and the knowledge of the other systems it has to interact with. In the second step objects in the KAOS specification are used to are used to derive components that are potential sub components of the basic architecture. In the third step an appropriate degree of refinement of the goal refinement tree is selected. At this point the sub goals that are achieved by the system are assigned to the sub components created in step two. This defines the basic architecture of the system. Further refinement can then be done to achieve various non functional properties. We were unable to find sufficient guidance on the various steps in the process. There was no example where we could find both the complete goal tree and the complete component tree. This would have allowed us to compare the trees and understand better the progression required to create the architecture. Therefore our first hurdle was the very first step. It was difficult to determine how to start and how much to try to do in the first step. It was also difficult to realize how much leeway was allowed for each of the steps. Some of the questions that came up were -

- What decisions regarding the architecture are made at step 1. Do we simply assign a root goal or do we need to anticipate the next steps and have a basic structure thought out?
- Is it possible to have refinement where the tree had more than three levels?
- If all the sub goals (of a root goal) are realized by a component, does the root goal (for those sub goals) still need to be assigned to a component?
- Ideally in the second step KAOS objects are used to create sub components. However was it possible to use agents in this step also? Sensor Management Unit was an agent that we though could be made a subcomponent. However finally we used SensorInformation (which was an object) instead.
- Is it possible for a goal (and thus constraints) to be shared between sub components

Once the architecture was created we also added a box diagram illustrating the various components and connectors. The component tree created as a result of the three steps did not show how the various components are linked through the connectors. The box diagram helps in visualizing this and thus gives a more complete view of the architecture.

Once we obtained the component tree and the box diagram it provided us with different views. The tree seems to indicate a hierarchy whereas the actual structure is quite different. The box diagram helps us realize the architecture as a network. Therefore there were different views of the system and structure based on the way we chose to look at it.

Additionally there were some components in the architecture that had no connectors. For example the AlarmInformation component under Alarm is a data component with various constraints on it, however it does not have a connector.

In the component tree and the resulting architecture there is no way to tell the data that is being passed through a connector. This makes the architecture more difficult to understand. This information is particularly critical to describing the connectors. An alternative discussed for this problem was the possibility of having data as a constraint for a connector.

We also considered ways to explore the richness of connectors. Connectors can have different responsibilities like mediation, transformation and coordination. It would lead to a better design if we could portray this in the architecture.

3.4 Comparison between the two methods

In this section we compare the two architecture derivation methods and the resulting architectures . The most significant difference is that the first architecture is more low level. The components are described together with the operations that they have to perform creating a more rigid design. The second method uses a architecture prescription language which tends to be more high level. This allows the designer to pick a better solution at a low level. However at the same time it provides less guidance in getting to the solution.

The first method provides a more 'network type' view showing the various relationships and interactions between the components. The second method resulted in a component tree which was more hierarchical in nature. We needed an additional box diagram to better explain the component interaction. However both views though different were useful.

The first method was more systematic in the beginning. There was a clearly laid out approach for going from requirements to an architecture. The initial steps were simple enough to consider the possibility of automation in the future. However in the second method one of our biggest hurdles was getting past the first step. It was difficult to determine the basic composition with which to start. This was probably due to the high level nature of this method.

As we continued with the architecture derivation the first method got a little more confusing. We had problems choosing the appropriate patterns, and applying combination of patterns. There was inadequate documentation on them to help in the process. On the other hand the second method became more manageable once we decided on an initial design.

An interesting difference was that in the first method there were no constraints on the various connectors. Instead the focus was on the data that is passed through those connectors. On the other hand, in the second method we were able to specify various constraints for each of the connector, however there was no way of specifying the data that is passed through. In both cases we were unable to specify the differences possible in the nature of various types of connectors. For example, connectors fault tolerant components may have mediation type connectors. There was no way to specify this in either case.

As concerns non functional requirements, in the first method we applied them by choosing the appropriate pattern. However in the second method we created additional constraints on the components for the same.

Chapter 4

Conclusion

In this report we have taken a real world example of a power plant system and systematically obtained goal-oriented requirement specifications. We have then created two different architectures that satisfy the requirements. We analyzed and compared the results. Both architectures provide us with different but nonetheless useful views of the system. We hope our example contributes to creating further well defined derivation methods making this critical step of the system design process easier.

Some of the possible further work in the area includes using data flow and constraints as a basis for logical description on connectors. The connectors were not defined adequately in both architecture approaches, therefore this would be a useful enhancement. We can also look at the kinds of non functional constraints that might apply to data flow elements. We can further explore methods to apply non functional requirements, and study how these requirements affect the architecture. Non functional requirements constitute an important part of a system and this would benefit both designs. For the first method the patterns need to be documented better. It would also be useful to study ways to apply combinations of patterns. For the second method it is still unclear how the non functional requirements would transform the architecture.

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Appendix A

KAOS specifications

A.1 Goal specifications

The goals are listed following a breadth-first traversal of the goal graph shown in Fig. A.1.

- *PerformanceOfThePlantMonitored*

  Def The system must continuously monitor the performance of the plant in order to detect faults in the steam condenser or in the cooling circuit. Moreover, it supports the operators suggesting remedy actions.

  Concerns PowerPlant, SteamCondensor, CoolingCircuit

  RefinedTo FaultDetected, RemedyActionSuggestedWhenFaultDetected, AlarmCorrectlyManaged

- *FaultDetected*

  Def Faults in the steam condenser and in the cooling circuit must be detected

  Concerns SteamCondensor, CoolingCircuit, Fault

  AndRefines PerformanceOfThePlantMonitored

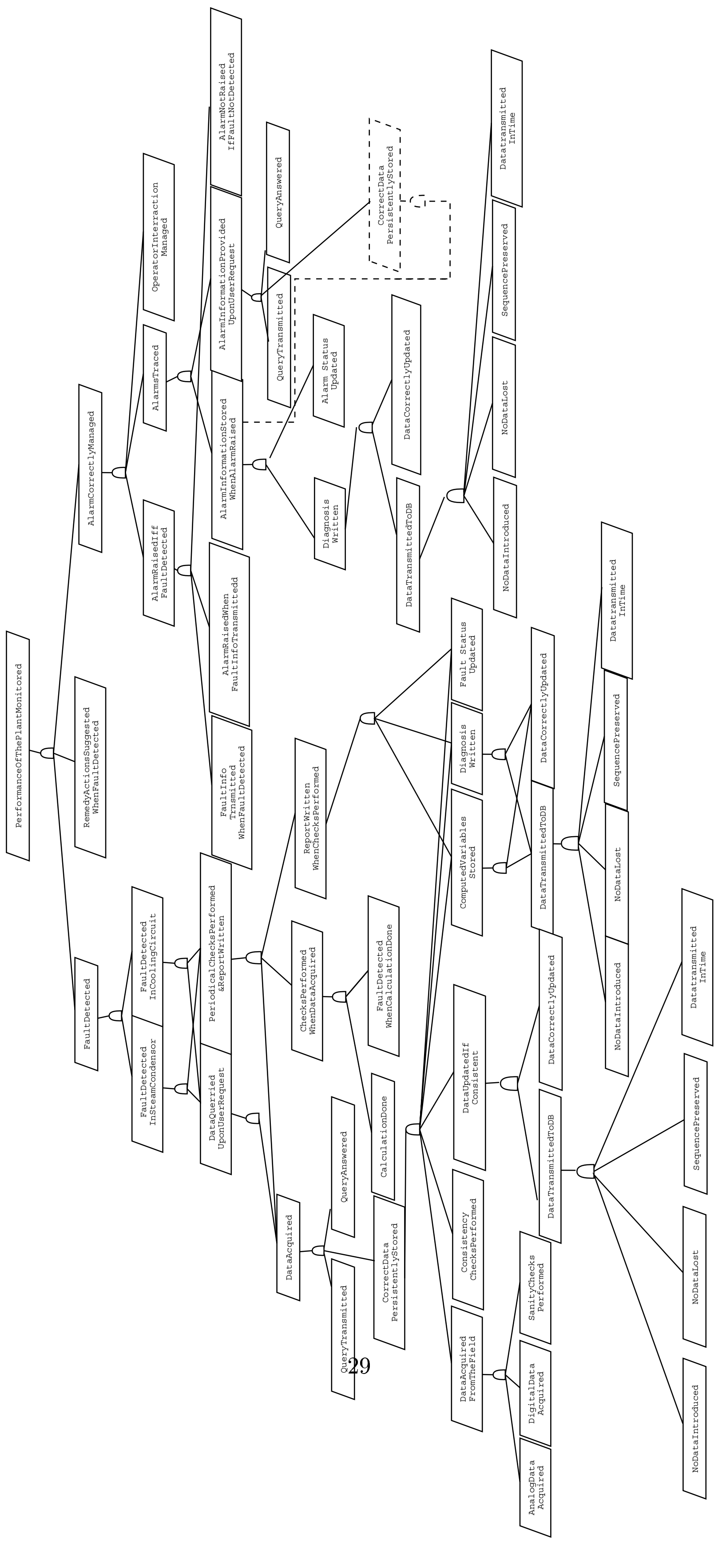
  RefinedTo FaultDetectedInSteamCondensor, FaultDetectedInCooling-Circuit

  FormalDef $\forall f : Fault, \exists! l : Location$
  $Occurs(f, l) \Rightarrow \Diamond Detected(f, l)$

- *RemedyActionsSuggestedWhenFaultDetected*

  Def Remedy actions must be suggested to the operators each time a fault is detected.

  Concerns SteamCondensor, CoolingCircuit, Fault



PerformanceOfThePlantMonitored
RemedyActionsSuggested WhenFaultDetected
AlarmCorrectlyManaged
FaultDetected
AlarmRaisedIff FaultDetected
AlarmsTraced
OperatorInteraction Managed
AlarmInformationStored WhenAlarmRaised
AlarmInformationProvided UponUserRequest
AlarmNotRaised IfFaultNotDetected
QueryTransmitted
QueryAnswered
CorrectData PersistentlyStored
Alarm Status Updated
Diagnosis Written
DataCorrectlyUpdated
DataTransmittedToDB
NoDataIntroduced
NoDataLost
SequencePreserved
Datatransmitted InTime
AlarmRaisedWhen FaultInfoTransmittedd
FaultInfo Trnsmitted WhenFaultDetected
FaultDetected InCoolingCircuit
FaultDetected InSteamCondensor
PeriodicalChecksPerformed &ReportWritten
DataQuerried UponUserRequest
ReportWritten WhenChecksPerformed
ChecksPerformed WhenDataAcquired
FaultDetected WhenCalculationDone
CalculationDone
QueryAnswered
DataAcquired
CorrectData PersistentlyStored
QueryTransmitted
Fault Status Updated
Diagnosis Written
ComputedVariables Stored
DataCorrectlyUpdated
DataTransmittedToDB
Datatransmited InTime
SequencePreserved
NoDataLost
NoDataIntroduced
DataUpdatedIff Consistent
DataCorrectlyUpdated
DataTransmittedToDB
Consistency ChecksPerformed
DataAcquired FromTheField
SanityChecks Performed
DigitalData Acquired
AnalogData Acquired
Datatransmitted InTime
SequencePreserved
NoDataLost
NoDataIntroduced

Figure A.1: Goal diagram

AndRefines PerformanceOfThePlantMonitored

UnderResponsabilityOf PRECON

- *AlarmCorrectlyManaged*

  Def The system must raised an alarm each time a fault is detected. In addition, it must trace and keep the state of all the alarms previously raised.

  Concerns Alarm, Fault

  AndRefines PerformanceOfThePlantMonitored

  RefinedTo AlarmRaisedIffFaultDetected, AlarmTraced, OperatorInteractionManaged

- *FaultDetectedInSteamCondenser*

  Def Faults in the steam condenser must be detected

  Concerns SteamCondenser, Fault

  AndRefines FaultDetected

  RefinedTo DataQuerriedUpondUserRequest, PeriodicalChecksPerformed&RepportsWritten

  FormalDef $\forall f : Fault$
  $Occurs(f, SteamCondenser) \Rightarrow \Diamond Detected(f, SteamCondenser)$

- *FaultDetectedInCoolingCircuit*

  Def Faults in the cooling circuit must be detected

  Concerns CoolingCircuit, Fault

  AndRefines FaultDetected

  RefinedTo DataQuerriedUpondUserRequest, PeriodicalChecksPerformed&RepportsWritten

  FormalDef $\forall f : Fault$
  $Occurs(f, CoolingCircuit) \Rightarrow \Diamond Detected(f, CoolingCircuit)$

- *AlarmRaisedIffFaultDetected*

  Def The alarm has to be raised if and only if a fault has been detected

  Concerns Alarm

  AndRefines AlarmCorrectlyManaged

  RefinedTo FaultInformationTransmittedWhenFaultDetected, AlarmRaisedWhenFaultInformationTransmitted, AlarmNotRaisedIfFaultNotDetected

  FormalDef $\forall f : Fault, \exists! l : Location, \exists! a : Alarm$
  $Detected(f, l) \Rightarrow \Diamond Raise(f, a)$
  $\wedge \forall a : Alarm, \exists! f : Fault, \exists! l : Location$
  $Raise(f, a) \Rightarrow \blacklozenge Detected(f, l)$

- *AlarmTraced*

Def Informations on alarms previously raised can be retrieved

Concerns Alarm

AndRefines AlarmCorrectlyManaged

RefinedTo AlarmInformationStoredWhenAlarmRaised, AlarmInformationProvidedUponUserRequest

- *DataQuerriedUponUserRequest*

Def All the data concerning the state of the Power Plant must be provided upon operators request

Concerns

AndRefines FaultDetectedInSteamCondensor, FaultDetectedInCoolingCircuit

RefinedTo CorrectDataPersistentlyStored, QuerryTransmitted, QuerryAnswered

FormalDef $\forall s : Sensor, \exists ! si : SensorInformation$
$Querry(s) \Rightarrow \Diamond Answer(si) \wedge s \equiv si$

- *PeriodicalChecksPerformed&ReportWritten*

Def A check must be carried out every 5 minutes in order to detect faults and a report must be written.

Concerns

AndRefines FaultDetectedInSteamCondensor, FaultDetectedInCoolingCircuit

RefinedTo DataAcquired, ChecksPerformedWhenDataAcquired, ReportWrittenWhenChecksPerformed

FormalDef $\forall f : Fault, \exists ! l : Location$
$Occurs(f, l) \Rightarrow \Diamond_{\leq 5min} Detected(f, l)$

- *FaultInformationTransmittedWhenFaultDetected*

Def Each time a Fault is detected, information on that fault has to be transmitted to the ALARM unit

Concerns Alarm

AndRefines AlarmRaisedIffFaultDetected

UnderResponsabilityOf COMMUNICATION

FormalDef $\forall f : Fault, \exists ! l : Location, \exists ! fi : FaultInformation$
$Detected(f, l) \wedge f \equiv fi \Rightarrow \Diamond Transmitted(fi, PRECON, ALARM)$

- *AlarmRaisedWhenFaultInformationTransmitted*

Def Each time the ALARM unit receive information on a fault, an alarm has to be raised

Concerns Alarm, FaultInformation

AndRefines AlarmRaisedIffFaultDetected

UnderResponsabilityOf ALARM

FormalDef $\forall fi : FaultInformation, \exists ! a : Alarm$
$Transmitted(fi, PRECON, ALARM) \Rightarrow \Diamond Raise(fi, a)$

- *AlarmNotRaisedIfFaultNotDetected*

Def If no fault is detected no alarm can be raised

Concerns Alarm, Fault

AndRefines AlarmRaisedIffFaultDetected

UnderResponsabilityOf ALARM

FormalDef $\forall a : Alarm, \exists ! f : Fault, \exists ! l : Location$
$Raise(f, a) \Rightarrow \blacklozenge Detected(f, l)$

- *AlarmInformationStoredWhenAlarmRaised*

Def Each time an alarm is raised, information on that alarm must be kept in the DataBase.

Concerns Alarm, AlarmInformation, PowerPlant/AlarmStatus

AndRefines AlarmTraced

RefinedTo AlarmDiagnosisWritten, AlarmStatusUpdated

FormalDef $\forall a : Alarm, \exists ! fi : FaultInformation, \exists ! ai : AlarmInformation, \exists ! fd : FaultDiagnosis$
$Raise(fi, a) \wedge a \equiv ai \Rightarrow \Diamond Stored(ai, DB) \wedge Stored(fd, DB) \wedge Concerns(fd, fi, ai) \wedge PowerPlant.AlarmStatus =' on'$

- *AlarmInformationProvidedUponUserRequest*

Def Operators should be able to retrieve informations about all the alarms previously raised

Concerns Alarm, AlarmInformation

AndRefines AlarmTraced

RefinedTo CorrectDataPersistentlyStored, QuerryTransmitted, QuerryAnswered

FormalDef $\forall a : Alarm, \exists ! ai : AlarmInformation$
$Querry(a) \Rightarrow \Diamond Answer(ai) \wedge a \equiv ai$

- *DataAcquired*

Def All the data needed are acquired from the field

Concerns Sensor, SensorInformation

AndRefines DataQuerriedUponUserRequest, PeriodicalChecksPerformed

RefinedTo CorrectDataPersistentlyStored, QuerryTransmitted, QuerryAnswered

FormalDef $\forall s : Sensor, \exists! si : SensorInformation$
$Querry(s) \Rightarrow \lozenge_{\leq 2s} Transmitted(si, DB, PRECON) \wedge s \equiv si$

- *ChecksPerformedWhenDataAcquired*

  Def Checks must be performed when all the data needed is available in order to detect faults in the Steam Condenser or in the Cooling Circuit

  Concerns SensorInformation, Fault

  AndRefines PeriodicalChecksPerformed

  RefinedTo CalculationDone, FaultDetectedWhenCalculationDone

  FormalDef $\forall f : Fault, si : SensorInformation, l : Location$
  $Occurs(f,l) \wedge Transmitted(si, DB, PRECON) \Rightarrow \lozenge_{\leq 5min} Detected(f,l)$
  $\wedge \neg Occurs(f,l) \wedge Transmitted(si, DB, PRECON) \Rightarrow \lozenge \neg Detected(f,l)$

- *ReportWrittenWhenChecksPerformed*

  Def Whether a fault is detected or not, all the results of the check must be stored.

  Concerns SensorInformation, Fault, FaultInformation

  AndRefines PeriodicalChecksPerformed

  RefinedTo ComputedVariablesStored, DiagnosisWritten, FaultStatusUpdated

  FormalDef $\forall f : Fault, \exists! fi : FaultInformation, \exists! l : Location\ \exists! fd : FaultDiagnosis, \exists! si : SensorInformation\ Detected(f,l) \Rightarrow \lozenge Stored(fi, DB) \wedge f \equiv fi \wedge Stored(fd, DB) \wedge Concerns(fd, si, fi)$

- *AlarmDiagnosisWritten*

  Def Each time an alarm is raised, information on that alarm must be kept in the DataBase.

  Concerns Alarm, AlarmInformation, FaultInformation

  AndRefines AlarmInformationStoredWhenAlarmRaised

  RefinedTo AlarmDataTransmittedToDB, DataCorrectlyUpdated

  FormalDef $\forall a : Alarm, \exists! fi : FaultInformation, \exists! ai : AlarmInformation, \exists! ad : AlarmDiagnosis$
  $Raise(fi, a) \Rightarrow \lozenge Stored(ai, DB) \wedge a \equiv ai \wedge Concerns(ad, fi, ai) \wedge Stored(ad, DB)$

- *AlarmStatusUpdated*

  Def If there is at least one alarm raised, the AlarmStatus must be set to on, otherwise it must be set to off.

Concerns Alarm, Fault, PowerPlant/AlarmStatus

AndRefines AlarmInformationStoredWhenAlarmRaised

UnderResponsabilityOf ALARM

FormalDef $\forall a : Alarm, \exists! fi : FaultInformation$
$Raise(fi, a) \Rightarrow \circ PowerPlant.AlarmStatus =' on'$

- *DataTransmittedToDB*

Def Each time an alarm is raised, corresponding information must be transmitted to the DataBase

Concerns Alarm, AlarmInformation, FaultInformation

AndRefines AlarmInformationStoredWhenAlarmRaised

RefinedTo NoDataLost, NoDataIntroduce, SequencePreserved, DataTransmittedWithinTimeConstraints

UnderResponsabilityOf COMMUNICATION

FormalDef $\forall a : Alarm, \exists! fi : FaultInformation, \exists! ai : AlarmInformation, \exists! ad : AlarmDiagnosis$
$Raise(fi, a) \wedge a \equiv ai \Rightarrow \Diamond Transmitted(ai, ALARM, DB) \wedge Transmitted(ad, ALARM, DB) \wedge Concerns(ad, fi, ai)$

- *DataCorrectlyUpdated*

Def Each time alarm information is transmitted to the DataBase, this information has to be stored

Concerns AlarmInformation, DataBase

AndRefines AlarmInformationStoredWhenAlarmRaised

UnderResponsabilityOf DB

FormalDef $\forall ai : AlarmInformation, ad : AlarmDiagnosis$
$Transmitted(ai, ALARM, DB) \Rightarrow \Diamond Stored(ai, DB)$
$Transmitted(ad, ALARM, DB) \Rightarrow \Diamond Stored(ad, DB)$

- *QueryTransmitted*

Def Each time the operator queries informations on an alarm, the query has to be transmitted to the DataBase

Concerns Alarm, AlarmInformation

AndRefines AlarmInformationProvidedUponUserRequest

UnderResponsabilityOf COMMUNICATION

FormalDef $\forall a : Alarm$
$Querry(a) \Rightarrow Transmitted(a, ALARM, DB)$

- *CorrectDataPersistentlyStored*

Def All the data of the system (reports resulting from checks, alarm information, status of the I/O devices, values of the sensors,etc.) must be stored persistently)

Concerns AlarmInformation, FaultInformation, SensorInformation

AndRefines DataAcquired, AlarmInformationProvidedUponUserRequest

RefinedTo DataAcquiredFromTheField, ConsistencyCheckPerformed, DataUpdatedWhenAcquired, ComputedVariablesStored, DiagnosisWritten, I/OStatusUpdated, AlarmInformationStoredWhenAlarmRaised

FormalDef $\forall si : SensorInformation, fi : FaultInformation, ai : AlarmInformation, fd : FaultDiagnosis, ad : AlarmDiagnosis$
$Stored(si, DB) \wedge Stored(fi, DB) \wedge Stored(ai, DB) \wedge Stored(fd, DB \wedge$
$Stored(ad, DB$

- *CalculationDone*

Def All the calculations needed to detect fault in the PowerPlant are done

Concerns SensorInformation

AndRefines ChecksPerformedWhenDataAcquired

UnderResponsabilityOf PRECON

FormalDef $\forall si : SensorInformation$
$Transmitted(si, DB, PRECON) \Rightarrow \Diamond CalculationDone$

- *FaultDetectedWhenCalculationDone*

Def When the calculations are done, all the faults present either in the cooling circuit or in the steam condenser must be detected

Concerns Fault, SteamCondenser, CoolingCircuit

AndRefines ChecksPerformedWhenDataAcquired

UnderResponsabilityOf PRECON

FormalDef $\forall f : Fault, l : Location$
$CalculationDone \wedge Occurs(f, l) \Rightarrow \Diamond Detected(f, l)$
$\wedge\ CalculationDone \wedge \neg Occurs(f, l) \Rightarrow \Diamond \neg Detected(f, l)$

- DataAcquiredFromTheField

Def Data concerning the state of the power plant must be acquired

Concerns Sensor

AndRefines CorrectDataPersistentlyStored

RefinedTo AnalogDataAcquired, DigitalDataAcquired, SanityCheckPerformed

FormalDef $\forall s : Sensor$
$s.type =' Digital' \vee s.type =' Analog' \Rightarrow \Diamond Acquired(s)$

- *ConsistencyCheckPerformed*

  Def Consistency checks are performed on all the acquired data in order to ensure consistency within all the sensor datas

  Concerns SensorInformation

  AndRefines CorrectDataPersistentlyStored

  UnderResponsabilityOf ACQUISITION UNIT

  FormalDef $\forall s : Sensor$
  $Acquired(s) \Rightarrow \Diamond Consistent(s)$

- DataUpdatedWhenAcquired

  Def When the data have been acquired, they must be stored correctly

  Concerns Sensor, SensorInformation

  AndRefines CorrectDataPersistentlyStored

  UnderResponsabilityOf DB

  FormalDef $\forall si : Sensor$
  $Acquired(s) \wedge Consistent(s) \Rightarrow \Diamond Stored(si, DB) \wedge s \equiv si$

- *ComputedVariablesStored*

  Def

  Concerns

  AndRefines

  RefinedTo

  FormalDef

- *FAultDiagnosisWritten*

  Def Each time a fault is detected, informations concerning the fault and the diagnosis must be written

  Concerns SensorInformation, Fault

  AndRefines ReportWrittenWhenChecksPerformed

  RefinedTo DataTransmittedToDB, DataCorrectlyUpdated

  FormalDef $\forall f : Fault, \exists! l : Location, \exists! fi : FaultInformation, \exists si : SensorInformation, \exists! fd : FaultDiagnosis$
  $Detected(f, l) \Rightarrow \Diamond Store(fi, DB) \wedge f \equiv fi \wedge Stored(fd, DB) \wedge Concerns(ds, di, si)$

- *FaultStatusUpdated*

  Def If there is a least one fault detected, the FaultStatus must be set to on, otherwise it must be set to off

  Concerns Fault, PowerPlant/FaultStatus

AndRefines ReportWrittenWhenChecksPerformed

UnderResponsabilityOf PRECON

FormalDef $\forall f : Fault, \exists! l : Location$
$Detected(f, l) \Rightarrow \circ PowerPlant.FaultStatus =' on'$

- *DataTransmittedToDB*

Def Each time an fault is detected, corresponding information must be transmitted to the DataBase

Concerns Fault , FaultInformation, SensorInformation

AndRefines FaultDiagnosisWritten, ComputedVariablesStored

RefinedTo NoDataLost, NoDataIntroduce, SequencePreserved, DataTransmittedWithinTimeConstraints

UnderResponsabilityOf COMMUNICATION

FormalDef $\forall f : Fault, \exists l : Location, \exists! fi : FaultInformation, \exists! si : SensorInformation \exists! ad : FaultDiagnosis$
$Detected(f, l) \wedge f \equiv fi \Rightarrow \Diamond Transmitted(fi, PRECON, DB) \wedge Transmitted(fd, ALARM, DB) \wedge Concerns(ad, si, fi)$

- *DataCorrectlyUpdated*

Def Each time fault information is transmitted to the DataBase, this information has to be stored

Concerns FaultInformation, DataBase

AndRefines FaultDiagnosisWritten, ComputedVariablesStored

UnderResponsabilityOf DB

FormalDef $\forall fi : FaultInformation, fd : FaultDiagnosis$
$Transmitted(fi, ALARM, DB) \Rightarrow \Diamond Stored(fi, DB)$
$Transmitted(fd, ALARM, DB) \Rightarrow \Diamond Stored(fd, DB)$

- *AnalogDataAcquired*

Def All the data coming from working analog sensors are acquired

Concerns Sensor

AndRefines DataAcquiredFromTheField

FormalDef $\forall s : Sensor$
$s.type =' Analog' \wedge s.status =' on' \Rightarrow \Diamond Acquired(s)$

- *DigitalDataAcquired*

Def All the data coming from working digital sensors are acquired

Concerns Sensor

AndRefines DataAcquiredFromTheField

FormalDef $\forall s : Sensor$
$s.type =' Digital' \land s.status =' on' \Rightarrow \Diamond Acquired(s)$

- *SanityCheckPerformed*

  Def SanityChecks are performed in order to ensure that all working sensors work correctly

  Concerns Sensor

  AndRefines DataAcuiredFromTheField

  FormalDef $\forall s : Sensor$
  $s.workingProperly = false \land \bullet s.status =' on' \Rightarrow \circ s.status =' off'$
  $\land\, s.workingProperly = true \land \bullet s.status =' off' \Rightarrow \circ s.status =' on'$

- *NoDataLost*

  Def No data can be lost during the transmission

  Concerns SensorInformation, FaultInformation, AlarmInformation

  AndRefines DataTransmittedToDB

  UnderResponsabilityOf COMMUNICATION

  FormalDef $\forall si : SensorInformation, fi : FaultInformation, ai : AlarmInformation, fd : FaultDiagnosis, ad : AlarmDiagnosis, x : Data$
  $x \in si \land Transmitted(si, \_, \_) \Rightarrow x \in Transmitted(si)$
  $\land\, x \in fi \land Transmitted(fi, \_, \_) \Rightarrow x \in Transmitted(fi)$
  $\land\, x \in ai \land Transmitted(ai, \_, \_) \Rightarrow x \in Transmitted(ai)$
  $\land\, x \in fd \land Transmitted(fd, \_, \_) \Rightarrow x \in Transmitted(fd)$
  $\land\, x \in ad \land Transmitted(ad, \_, \_) \Rightarrow x \in Transmitted(ad)$

- *NoDataIntroduce*

  Def No data can be introcue during the transmission

  Concerns SensorInformation, FaultInformation, AlarmInformation

  AndRefines DataTransmittedToDB

  UnderResponsabilityOf COMMUNICATION

  FormalDef $\forall si : SensorInformation, fi : FaultInformation, ai : AlarmInformation, fd : FaultDiagnosis, ad : AlarmDiagnosis, x : Data$
  $Transmitted(si, \_, \_) \land x \in Transmitted(si) \Rightarrow x \in si$
  $\land\, Transmitted(fi, \_, \_) \land x \in Transmitted(fi) \Rightarrow x \in fi$
  $\land\, Transmitted(ai, \_, \_) \land x \in Transmitted(ai) \Rightarrow x \in ai$
  $\land\, Transmitted(fd, \_, \_) \land x \in Transmitted(fd) \Rightarrow x \in fd$
  $\land\, Transmitted(ad, \_, \_) \land x \in Transmitted(ad) \Rightarrow x \in ad$

- *SequencePreserved*

  Def The order of the data must be preserved during the transmission

  Concerns SensorInformation, FaultInformation, AlarmInformation

AndRefines DataTransmittedToDB

UnderResponsabilityOf COMMUNICATION

FormalDef $\forall si : SensorInformation, fi : FaultInformation, ai : AlarmInformation, fd : FaultDiagnosis, ad : AlarmDiagnosis, x, y : Data, \exists u, v : Data$
$x, y \in si \wedge Transmitted(si, \_, \_) \wedge Before(x, y, si) \Rightarrow u, v \in Transmitted(si) \wedge Before(u, v, si) \wedge x = u \wedge y = v$
$\wedge x, y \in fi \wedge Transmitted(fi, \_, \_) \wedge Before(x, y, fi) \Rightarrow u, v \in Transmitted(fi) \wedge Before(u, v, fi) \wedge x = u \wedge y = v$
$\wedge x, y \in ai \wedge Transmitted(ai, \_, \_) \wedge Before(x, y, ai) \Rightarrow u, v \in Transmitted(ai) \wedge Before(u, v, qi) \wedge x = u \wedge y = v$
$\wedge\ x, y \in fd \wedge Transmitted(fd, \_, \_) \wedge Before(x, y, fd) \Rightarrow u, v \in Transmitted(fd) \wedge Before(u, v, fd) \wedge x = u \wedge y = v$
$\wedge x, y \in ai \wedge Transmitted(ad, \_, \_) \wedge Before(x, y, ad) \Rightarrow u, v \in Transmitted(ad) \wedge Before(u, v, ad) \wedge x = u \wedge y = v$

- *DataTransmittedWithinTimeConstraints*

Def All the data that need to be transmittend are effectively transmitted to their destination within 2 s

Concerns SensorInformation, FaultInformation, AlarmInformation

AndRefines DataTransmittedToDB

UnderResponsabilityOf COMMUNICATION

FormalDef $\forall si : SensorInformation, fi : FaultInformation, ai : AlarmInformationm, fd : FaultDiagnosis, ad : AlarmDiagnosis$
$\Diamond_{\leq 2s} Transmitted(si, \_, \_)$
$\wedge \Diamond_{\leq 2s} Transmitted(fi, \_, \_)$
$\wedge \Diamond_{\leq 2s} Transmitted(ai, \_, \_)$
$\wedge \Diamond_{\leq 2s} Transmitted(fd, \_, \_)$
$\wedge \Diamond_{\leq 2s} Transmitted(ad, \_, \_)$

A.2 Object Specifications

- *PowerPlant*

Def Defines the power plant system. Its components include steam condenser and cooling circuit.

Has PowerPlantID: Integer
Type: Hydrolic, Nuclear, Petrol, Gas, Coal
Power: MegaWatt
Location: Address
FaultStatus: on,off
AlarmStatus: on,off

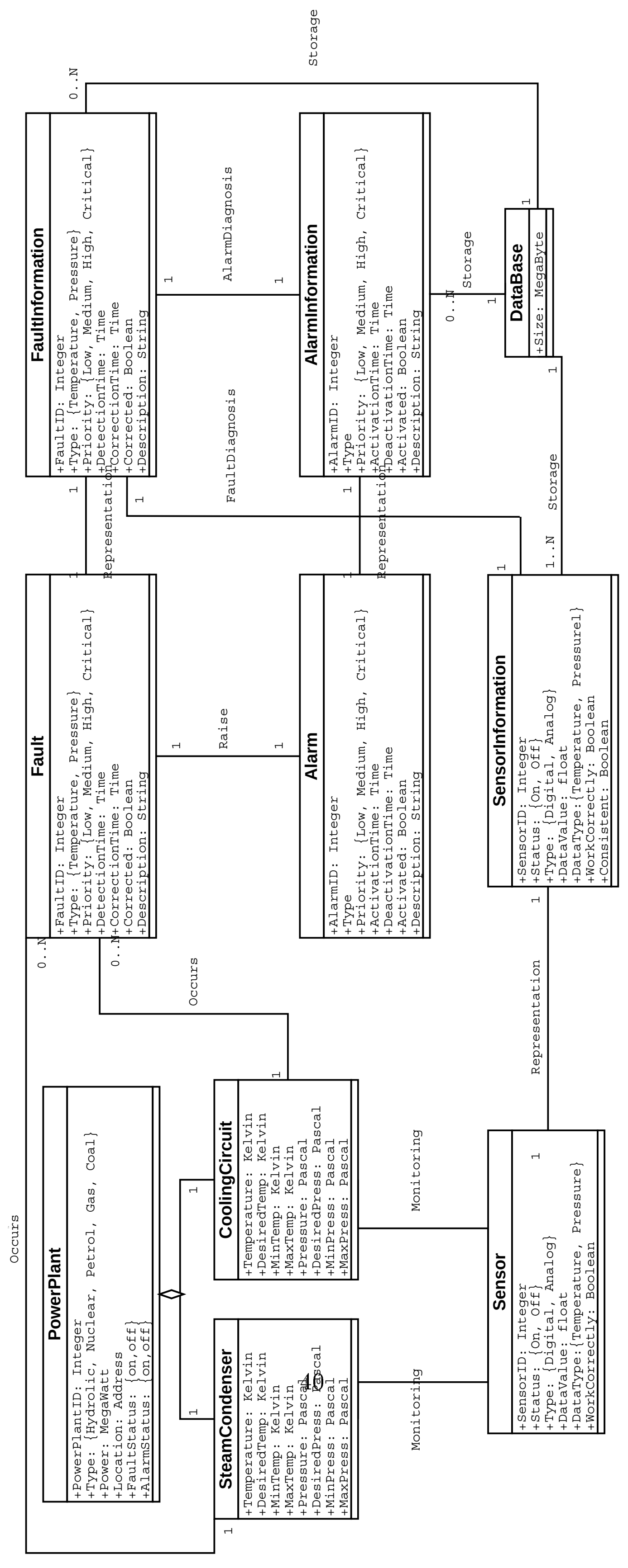


Figure A.2: Object diagram

DomInvar $\forall$ p:PowerPlant
p.faultStatus = on $\Leftrightarrow$ ($\exists$ f:Fault,$\exists$ l:Location)(Occurs(f,l) $\wedge$ PartOf(l,p)
$\wedge$ f.Corrected = false
p.alarmStatus = on $\Leftrightarrow$ ($\exists$ a:Alarm,$\exists$ l:Location,$\exists$ f:Fault)(Occurs(f,l)
$\wedge$ PartOf(l,p) $\wedge$ Raise(f,a) $\wedge$ f.Activated = true

DomInit FaultStatus = off
AlarmStatus = off

- *SteamCondenser*

Def condenses steam. It accounts for temperature, desired temperature and a range, similarly pressure, a desired pressure and a pressure range.

Has Temperature: Kelvin
DesiredTemp: Kelvin
MinTemp: Kelvin
MaxTemp: Kelvin
Pressure: Pascal
DesiredPress: Pascal
MinPress: Pascal
MaxPress: Pascal

DomInvar MinTemp $\leq$ Maxtemp
MinPress $\leq$ MaxPress

DomInit /

- *SteamCondenser*

Def cools the power plant. It is a component of the power plant. It accounts for temperature, desired temperature and a range, similarly pressure, a desired pressure and a pressure range.

Has Temperature: Kelvin
DesiredTemp: Kelvin
MinTemp: Kelvin
MaxTemp: Kelvin
Pressure: Pascal
DesiredPress: Pascal
MinPress: Pascal
MaxPress: Pascal

DomInvar MinTemp $\leq$ Maxtemp
MinPress $\leq$ MaxPress

DomInit /

- *Sensor*

Def it obtains information from the power plant using physically placed sensors. Informations obtained includes data type and its value. Sensors are also checked to ensure that they are working correctly

Has SensorID: Integer
Status: on,off
Type: Digital, Analog
DataValue: Float
DataType: Temperature, Pressure
WorkCorreclty: Boolean

DomInvar $forall$ s: Sensor
s.workingProperly = false $\wedge$ s.status = on $\Rightarrow \circ$ s.status = off
s.workingProperly = true $\wedge$ s.status = off $\Rightarrow \circ$ s.status = on

DomInit status = on
workingProperly = true

- *Fault*

Def Faults can occur in the cooling circuit or in the steam condenser. When each fault is detected, an ID, type, priority, description and detection time are associated with it. Measures are then taken ot correct the fault.

Has FaultID: Integer
Type: Temperature, Pressure
Priority: Low, Medium, High, Critical
DetectionTime: Time
CorrectionTime: Time
Corrected: Boolean
Description: String

DomInvar DetectionTime ¡ CorrectionTime
Corrected = true $\Rightarrow$ CorrectionTime $\neq$ null
Corrected = false $\Rightarrow$ CorrectionTime = null

DomInit DetectionTime = currentTime
Corrected = false
CorrectionTime = null

- *Alarm*

Def An alarm is raised when a fault is detected

Has AlarmID: Integer
Type:
Priority: Low, Medium, High, Critical
ActivationTime: Time
DeactivationTime: Time
Activated: Boolean
Description: String

DomInvar ActivationTime ¡ DeactivationTime
Activated = true $\Rightarrow$ DeactivationTime = null
Activated = false $\Rightarrow$ DeactivationTime $\neq$ null

DomInit Activated = true
DeactivationTime = null

- *SensorInformation*

Def representation of the sensor

Has SensorID: Integer
Status: on,off
Type: Digital, Analog
DataValue: Float
DataType: Temperature, Pressure
WorkCorreclty: Boolean
Consistent: Boolean

DomInvar $forall$ s: Sensor
s.workingProperly = false $\wedge$ s.status = on $\Rightarrow \circ$ s.status = off
s.workingProperly = true $\wedge$ s.status = off $\Rightarrow \circ$ s.status = on

DomInit status = on
workingProperly = true
Consistent = true

- *FaultInformation*

Def representation of the fault

Has FaultID: Integer
Type: Temperature, Pressure
Priority: Low, Medium, High, Critical
DetectionTime: Time
CorrectionTime: Time
Corrected: Boolean
Description: String

DomInvar DetectionTime ¡ CorrectionTime
Corrected = true $\Rightarrow$ CorrectionTime $\neq$ null
Corrected = false $\Rightarrow$ CorrectionTime = null

DomInit DetectionTime = currentTime
Corrected = false
CorrectionTime = null

- *AlarmInformation*

Def representation of the Alarm

Has AlarmID: Integer
Type:
Priority: Low, Medium, High, Critical
ActivationTime: Time

DeactivationTime: Time
Activated: Boolean
Description: String

DomInvar ActivationTime ¡ DeactivationTime
Activated = true ⇒ DeactivationTime = null
Activated = false ⇒ DeactivationTime ≠ null

DomInit Activated = true
DeactivationTime = null

- *DataBase*

Def A storage unit that hold SensorInformation, AlarmInformation and FaultInformation

Has Size: Megabytes

DomInvar /

DomInit Size = O

A.3 Agents Specifications

- `ALARM`

Def An agent that controls the status of the alarm

Has AlarmID, Type, Priority, ActivationTime, DeactivationTime, Activated, Description

Monitors FaultInformation/FaultID, FaultInformation/Type, FaultInformation/Priority, FaultInformation/DetectionTime, FaultInformation/CorrectionTime, FaultInformation/Corrected, FaultInformation/Description

Controls Alarm/AlarmID, Alarm/Type, Alarm/Priority, Alarm/ActivationTime, Alarm/DeactivationTime, Alarm/Activated, Alarm/Description

ResponsibleFor AlarmRaisedWhenFaultInfoTransmitted, AlarmNotRaisedIfFaultNotDetected, AlarmStatusUpdated

DependsOn PRECON

Perfoms Raise Alarm When Alarm Info Transmitted, Update alarm status, Not Raise Alarm if Fault Not Detected

- `OPERATOR`

Def Represents user who interacts with the system

Has /

Monitors Alarm/AlarmID, Alarm/Type, Alarm/Priority, Alarm/ActivationTime, Alarm/DeactivationTime, Alarm/Activated, Alarm/Description

Controls /

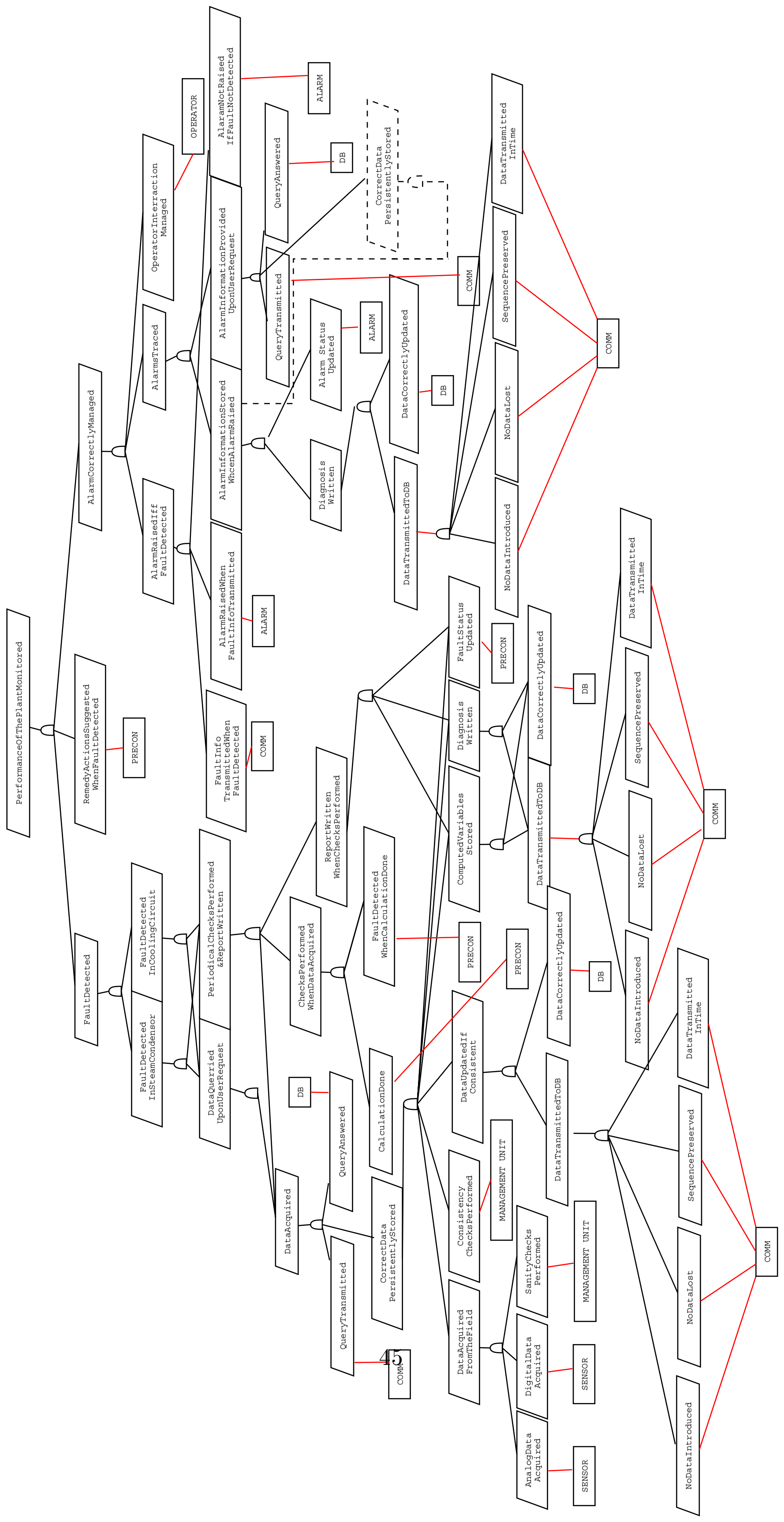

PerformanceOfThePlantMonitored
AlarmCorrectlyManaged
RemedyActionsSuggested WhenFaultDetected
PRECON
FaultDetected
FaultDetected InCoolingCircuit
FaultDetected InSteamCondensor
OperatorInteraction Managed
OPERATOR
AlarmsTraced
AlarmRaisedIff FaultDetected
AlaramNotRaised IfFaultNotDetected
ALARM
AlarmInformationProvided UponUserRequest
AlarmInformationStored WhenAlarmRaised
AlarmRaisedWhen FaultInfoTransmitted
FaultInfo TransmittedWhen FaultDetected
COMM
PeriodicalChecksPerformed &ReportWritten
DataQueried UponUserRequest
QueryAnswered
DB
QueryTransmitted
CorrectData PersistentlyStored
Alarm Status Updated
Diagnosis Written
DataCorrectlyUpdated
DataTransmittedToDB
DataTransmitted InTime
SequencePreserved
NoDataLost
NoDataIntroduced
ReportWritten WhenChecksPerformed
ChecksPerformed WhenDataAcquired
FaultDetected WhenCalculationDone
CalculationDone
FaultStatus Updated
ComputedVariables Stored
DataUpdatedIf Consistent
Consistency ChecksPerformed
MANAGEMENT UNIT
DataAcquired FromTheField
SanityChecks Performed
DigitalData Acquired
AnalogData Acquired
SENSOR
DataAcquired

Figure A.3: Agent diagram

ResponsibleFor OperatorInteractionsManaged

DependsOn /

Perfoms Manages Operator Interaction

- DB

  Def Stores, updates and returns queries on sensor, fault and alarm information

  Has Size

  Monitors FaultInformation/FaultID, FaultInformation/Type, FaultInformation/Priority, FaultInformation/DetectionTime, FaultInformation/CorrectionTime, FaultInformation/Corrected, FaultInformation/Description, AlarmInformation/AlarmID, AlarmInformation/Type, AlarmInformation/Priority, AlarmInformation/ActivationTime, AlarmInformation/DeactivationTime, AlarmInformation/Activated, AlarmInformation/Description, SensorInformation/SensorID, SensorInformation/Status, SensorInformation/Type, SensorInformation/DataValue, SensorInformation/DataType, SensorInformation/WorkProperly

  Controls Database/Size

  ResponsibleFor DataCorrectlyUpdated, QueryAnswered

  DependsOn Communication, PRECON, ALARM, Sensor

  Perfoms Update Data Correctly, Answer Query

- PRECON

  Def Detects faults from the data and handles fault status

  Has /

  Monitors SensorInformation/SensorID, SensorInformation/Status, SensorInformation/Type, SensorInformation/DataValue, SensorInformation/DataType, SensorInformation/WorkCorrectly, SensorInformation/Consistent

  Controls FaultInformation/FaultID, FaultInformation/Type, FaultInformation/Priority, FaultInformation/DetectionTime, FaultInformation/CorrectionTime, FaultInformation/Corrected, FaultInformation/Description

  ResponsibleFor CalculationDone, FaultDetectedWhenCalculationDone, RemedyActionSuggestedWhenFaultDetected, FaultStatusUpdated

  DependsOn DataBase

  Perfoms Do Calculation, Detect Fault When Calculation is Done, Suggest Remedy Action When Fault Detected, Update Fault Status

- COMM

  Def Handles communication between the different objects

Has /

Monitors FaultInformation/FaultID, FaultInformation/Type, FaultInformation/Priority, FaultInformation/DetectionTime, FaultInformation/CorrectionTime, FaultInformation/Corrected, FaultInformation/Description, AlarmInformation/AlarmID, AlarmInformation/Type, AlarmInformation/Priority, AlarmInformation/ActivationTime, AlarmInformation/DeactivationTime, AlarmInformation/Activated, AlarmInformation/Description, SensorInformation/SensorID, SensorInformation/Status, SensorInformation/Type, SensorInformation/DataValue, SensorInformation/DataType, SensorInformation/WorkCorrectly

Controls /

ResponsibleFor NoDataIntroduced, NoDataLost, SequencePreserved, DataTransmittedInTime, FaultInfoTransmittedWhenFaultDetected

DependsOn Sensor, PRECON, ALARM, Database

Perfoms Transmit Query, Transmit Data to DB, Transmit Fault Info When Fault Detected

- `Sensor`

Def Physical sensors provide plant information

Has SensorId, Status, Type, DataValue, DataType, WorkCorrectly

Monitors SteamCondensor/Temperature, SteamCondensor/DesiredTemp, SteamCondensor/MinTemp, SteamCondensor/MaxTemp, SteamCondensor/Pressure, SteamCondensor/DesiredPress, SteamCondensor/MinPress, SteamCondensor/MaxPress, CoolingCircuit/Temperature, CoolingCircuit /DesiredTemp, CoolingCircuit /MinTemp, CoolingCircuit /MaxTemp, CoolingCircuit /Pressure, CoolingCircuit /DesiredPress, CoolingCircuit /MinPress, CoolingCircuit /MaxPress, SensorInformation/Status,

Controls Sensor/SensorID, Sensor/Status, Sensor/Type, Sensor/DataValue, Sensor/DataType, SensorInformation/SensorID, SensorInformation/Type, SensorInformation/DataValue, SensorInformation/DataType, SensorInformation/WorkProperly

ResponsibleFor AnalogDataAcquired, DigitalDataAcquired

DependsOn /

Perfoms Acquire Analog Data, Acquire Digital Data

- `MANAGEMENT UNIT`

Def Ensures efficient working of the sensors, checks consistency in data obtained from the sensors

Has /

Monitors SensorInformation/SensorID, SensorInformation/Type, SensorInformation/DataValue, SensorInformation/DataType, SensorInformation/WorkProperly

Controls SensorInformation/Status, SensorInformation/Consistent

ResponsibleFor SanityChecksPerformed, ConsistencyChecksPerformed

DependsOn Sensor

Perfoms Perform Sanity Check, Perform Consistency Check

A.4 Operations specifications

- *AcquireAnalogData*

  Def Acquire the data coming from an analog device

  Input s:Sensor,si:SensorInformation

  Output si:SensorInformation/Value

  DomPre s.value $\neq$ si.value

  DomPost s.value = si.value

  ReqTrig for AnalogDataAcquired
  s.value $\neq$ si.value $\mathbf{S}_{=9s}$ s.Type = 'Analog' $\wedge$ s.ID=si.ID $\wedge$ s.Value $\neq$ si.Value

  PerformedBy Sensor

- *AcquireDigitalData*

  Def Acquire the data coming from an digital device

  Input s:Sensor,si:SensorInformation

  Output si:SensorInformation/Value

  DomPre s.value $\neq$ si.value

  DomPost s.value = si.value

  ReqTrig For DigitalDataAcquired
  s.value $\neq$ si.value $\mathbf{S}_{=9s}$ s.Type = 'Digital' $\wedge$ s.ID = si.ID $\wedge$ s.Value $\neq$ si.Value

  PerformedBy Sensor

- *SwitchSensorOff*

  Def Turn the sensor off

  Input s:Sensor

  Output s:Sensor/Status

  DomPre s.Status = 'on'

  DomPost s.Status = 'off'

ReqTrig For SanityCheckPerformed
$\neg$ s.WorkingProperly

PerformedBy ACQUISITION UNIT

- *SwitchSensorOn*

Def Turn the sensor on

Input s:Sensor

Output s:Sensor/Status

DomPre s.Status = 'off'

DomPost s.Status = 'on'

ReqPre For SanityCheckPerformed
s.WorkingProperly

Operationalizes SanityCheckPerformed

PerformedBy ACQUISITION UNIT

- *UnValidateData*

Def Unvalidate the sensor data if they are not considered plausible

Input si: SensorInformation

Output si: SensorInformation/Consistent

DomPre si.Consistent

DomPost $\neg$ si.Consistent

ReqTrig For ConsistencyChecksPerformed
$\big($si.DataType = 'Temperature' $\wedge$ (si.Value $<$ minTemp $\vee$ si.Value $>$ maxTemp)$\big)$
$\vee$ $\big($si.DataType = 'Pressure' $\wedge$ (si.Value $<$ minPres $\vee$ si.Value $>$ maxPres)$\big)$

PerformedBy ACQUISITION UNIT

- *ValidateData*

Def Validate the sensor data if they are considered plausible

Input si: SensorInformation

Output si: SensorInformation/Consistent

DomPre $\neg$ si.Consistent

DomPost si.Consistent

ReqPre For ConsistencyChecksPerformed
$\big($si.DataType = 'Temperature' $\wedge$ (minTemp $\leq$ si.Value $\leq$ maxTemp)$\big)$
$\vee$ $\big($si.DataType = 'Pressure' $\wedge$ minPres $\leq$ si.Value $\leq$ maxPres)$\big)$

PerformedBy ACQUISITION UNIT

- *TransmitSensorData*

  Def Transmit the data to the DataBase

  Input si: SensorInformation

  Output /

  DomPre $\neg$ Transmitted(si,ACQUISITION,DB)

  DomPost Transmitted(si,ACQUISITION,DB)

  ReqTrig For SensorDataTransmitted
  $\neg$ Transmitted(si,ACQUISITION,DB) $\mathbf{S}_{=1s}$ si.Consistent $\land$ $\neg$ Transmitted(si,ACQUISITION,DB)

  PerformedBy COMMUNICATION

- *UpdateSensorData*

  Def Update the data in the DataBase

  Input si: SensorInformation

  Output /

  DomPre $\neg$ Stored(si)

  DomPost Stored(si)

  ReqTrig For SensorDataUpdated
  $\neg$ Stored(si) $\mathbf{S}_{=1s}$ Transmitted(si,ACQUISITION,DB)$\land$ $\neg$ Stored(si)

  PerformedBy DB

- *TransmitSensorQuery*

  Def transmit a sensor query to the DataBase

  Input s: Sensor

  Output /

  DomPre $\neg$ Transmitted(s,PRECON,DB)

  DomPost Transmitted(s,PRECON,DB)

  ReqTrig For SensorQuerryTransmitted
  $\neg$ Transmitted(s,PRECON,DB) $\mathbf{S}_{=1s}$ Query(s) $\land$ $\neg$ Transmitted(s,PRECON,DB)

  PerformedBy COMMUNICATION

- *AnswerSensorQuery*

  Def Answer to a sensor query

  Input s: Sensor

  Output si: SensorInformation

  DomPre $\neg$ Transmitted(si,DB,PRECON)

  DomPost Transmitted(si,DB,PRECON)

ReqTrig For SensorQueryAnswered
$\neg$ Transmitted(si,DB,PRECON) $\mathbf{S}_{=1s}$ Transmitted(s,PRECON,DB)$\wedge$ Query(s)$\wedge$ Stored(si) $\wedge$ si.ID = s.ID $\wedge$ $\neg$ Transmitted(si,DB,PRECON)

PerformedBy DB

- *Calculate*

  Def calculate all needed things in order to detect faults

  Input si: SensorInformation

  Output /

  DomPre $\neg$ CalculationDone

  DomPost CalculationDone

  ReqTrig For CalculationDone
  $\neg$ CalculationDone $\mathbf{S}_{=1s}$ Transmitted(si,DB,PRECON) $\wedge$ $\neg$ CalculationDone

  PerformedBy PRECON

- *DetectFault*

  Def detect Fault

  Input f: Fault, l: Location

  Output /

  DomPre $\neg$ Detected(f,l)

  DomPost Detected(f,l)

  ReqTrig For FaultDetectedWhenCalculationDone
  $\neg$ Detected(f,l) $\mathbf{S}_{=1s}$ CalculationDone $\wedge$ Occurs(f,l) $\wedge$ $\neg$ Detected(f,l)

  PerformedBy PRECON

- *TransmitDiagnosisData*

  Def Transmit the data concerning the diagnosis of a fault to the DataBase

  Input f: Fault, l: Location, fi: FaultInformation, si: SensorInformation, fd: FaultDiagnosis

  Output /

  DomPre $\neg$ Transmitted(fi,PRECON,DB) $\vee$ $\neg$ Transmitted(ad,PRECON,DB) $\vee$ $\neg$ Concerns(ad,si,fi)

  DomPost Transmitted(fi,PRECON,DB) $\wedge$ Transmitted(ad,PRECON,DB) $\wedge$ Concerns(ad,si,fi)

  ReqTrig For DiagnosisDataTransmitted
  $\neg$ Transmitted(fi,PRECON,DB) $\vee$ $\neg$ Transmitted(ad,PRECON,DB) $\vee$ $\neg$ Concerns(ad,si,fi) $\mathbf{S}_{=1s}$ Detected(f,l) $\wedge$ f.ID = fi.ID $\wedge$ $\Big($ $\neg$ Transmitted(fi,PRECON,DB) $\vee$ $\neg$ Transmitted(ad,PRECON,DB) $\vee$ $\neg$ Concerns(ad,si,fi) $\Big)$

PerformedBy COMMUNICATION

- *UpdateDiagnosisData*

  Def Store the data concerning a detected fault in the DataBase

  Input fi: SensorInformation, fd: FaultDiagnosis

  Output /

  DomPre $\neg$ Stored(fi) $\vee$ $\neg$ Stored(fd)

  DomPost Stored(fi) $\wedge$ Stored(fd)

  ReqTrig For DiagnosisDataUpdated
  $\neg$ Stored(fi) $\vee$ $\neg$ Stored(fd) $\mathbf{S}_{=1s}$ Transmitted(fd,PRECON,DB) $\wedge$
  Transmitted(fi,PRECON,DB) $\wedge$ $\big(\neg$ Stored(fi) $\vee$ $\neg$ Stored(fd)$\big)$

  PerformedBy DB

- *SwitchFaultStatusOn*

  Def switch the Fault Status on

  Input f: Fault, l: Location, PowerPlant

  Output PowerPlant/FaultStatus

  DomPre PowerPlant.FaultStatus = off

  DomPost PowerPlant.FaultStatus =on$\neg$ Transmitted(fi,PRECON, ALARM)

  ReqTrig For FaultStatusUpdated
  Detected(f,l)

  PerformedBy PRECON

- *SwitchFaultStatusOff*

  Def switch the Fault Status off

  Input f: Fault, l: Location, PowerPlant

  Output PowerPlant/FaultStatus

  DomPre PowerPlant.FaultStatus = on

  DomPost PowerPlant.FaultStatus = off

  ReqPre For FaultStatusUpdated
  $\neg$ Detected(f,l)

  PerformedBy PRECON

- *TransmitFaultInformation*

  Def Transmit Fault Information to The ALARM Management unit

  Input f: Fault, l: Location, fi: FaultInformation

  Output /

  DomPre $\neg$ Transmitted(fi,PRECON, ALARM)

DomPost Transmitted(fi,PRECON, ALARM)

ReqTrig For FaultInformationTransmittedWhenFaultDetected
$\neg$ Transmitted(fi,PRECON, ALARM) $\mathbf{S}_{=1s}$ Detected(f,l) $\wedge$ f.ID = fi.ID $\wedge$ $\neg$ Transmitted(fi,PRECON, ALARM)

PerformedBy COMMUNICATION

- *RaiseAlarm*

Def Raise the alarm

Input fi: FaultInformation

Output a: Alarm

DomPre $\neg$ Raise(fi,a)

DomPost Raise(fi,a)

ReqTrig For AlarmRaisedWhenFaultInformationTransmitted
$\neg$ Raise(fi,a) $\mathbf{S}_{=1s}$ Transmitted(fi,PRECON, ALARM) $\wedge$ $\neg$ Raise(fi,a)

PerformedBy ALARM

- *TransmitAlarmData*

Def Transmit the alarm data to the DataBase

Input fi: FaultInformation, a: Alarm, ai: AlarmInformation, ad: AlarmDiagnososis

Output /

DomPre $\neg$ Transmitted(ai,ALARM,DB) $\vee$ $\neg$ Transmitted(ad,ALARM,DB) $\vee$ $\neg$ Concerns(ad,fi,ai)

DomPost Transmitted(ai,ALARM,DB) $\wedge$ Transmitted(ad,ALARM,DB) $\wedge$ Concerns(ad,fi,ai)

ReqTrig For AlarmDataTransmitted
$\neg$ Transmitted(ai,ALARM,DB) $\vee$ $\neg$ Transmitted(ad,ALARM,DB) $\vee$ $\neg$ Concerns(ad,fi,ai) $\mathbf{S}_{=1s}$ Raise(fi,a) $\wedge$ a.ID = ai.ID $\wedge$ $\Big($ $\neg$ Transmitted(ai,ALARM,DB) $\vee$ $\neg$ Transmitted(ad,ALARM,DB) $\vee$ $\neg$ Concerns(ad,fi,ai) $\Big)$

PerformedBy COMMUNICATION

- *UpdateAlarmData*

Def Update Alarm data in the DataBase

Input ai: AlarmInformation, ad: AlarmDiagnosis

Output /

DomPre $\neg$ Stored(ai) $\vee$ $\neg$ Stored(ad)

DomPost Store(ai) $\wedge$ Stored(ad)

ReqTrig For AlarmDataCorrectlyUpdated
$\neg$ Stored(ai) $\vee$ $\neg$ Stored(ad) $\mathbf{S}_{=1s}$ Transmitted(ai,ALARM,DB) $\wedge$
Transmitted(ad,ALARM,DB) $\wedge$ $\big($ $\neg$ Stored(ai) $\vee$ $\neg$ Stored(ad) $\big)$

PerformedBy

- *SwitchAlarmStatusOn*

  Def switch the Alarm Status on

  Input a: Alarm, fi: FaultInformation, PowerPlant

  Output PowerPlant/AlarmStatus

  DomPre PowerPlant.AlarmStatus = off

  DomPost PowerPlant.AlarmStatus = on

  ReqTrig For AlarmStatusUpdated
  Raise(fi,a)

  Operationalizes AlarmStatusUpdated

  PerformedBy ALARM

- *SwitchAlarmStatusOff*

  Def switch the Alarm Status off

  Input a: Alarm, fi: FaultInformation, PowerPlant

  Output PowerPlant/AlarmStatus

  DomPre PowerPlant.AlarmStatus = on

  DomPost PowerPlant.AlarmStatus = off

  ReqPre For AlarmStatusUpdated
  $\neg$ Raise(fi,a)

  Operationalizes AlarmStatusUpdated

  PerformedBy ALARM

- *TransmitAlarmQuery*

  Def transmit a alarm query to the DataBase

  Input a: Alarm

  Output /

  DomPre $\neg$ Transmitted(a,ALARM,DB)

  DomPost Transmitted(a,ALARM,DB)

  ReqTrig For AlarmQuerryTransmitted
  $\neg$ Transmitted(a,ALARM,DB) $\mathbf{S}_{=1s}$ Query(a) $\wedge$ $\neg$ Transmitted(a,ALARM,DB)

  PerformedBy COMMUNICATION

- *AnswerAlarmQuery*

Def Answer to a alarm query

Input a: Alarm

Output ai: AlarmInformation

DomPre $\neg$ Transmitted(ai,DB,ALARM)

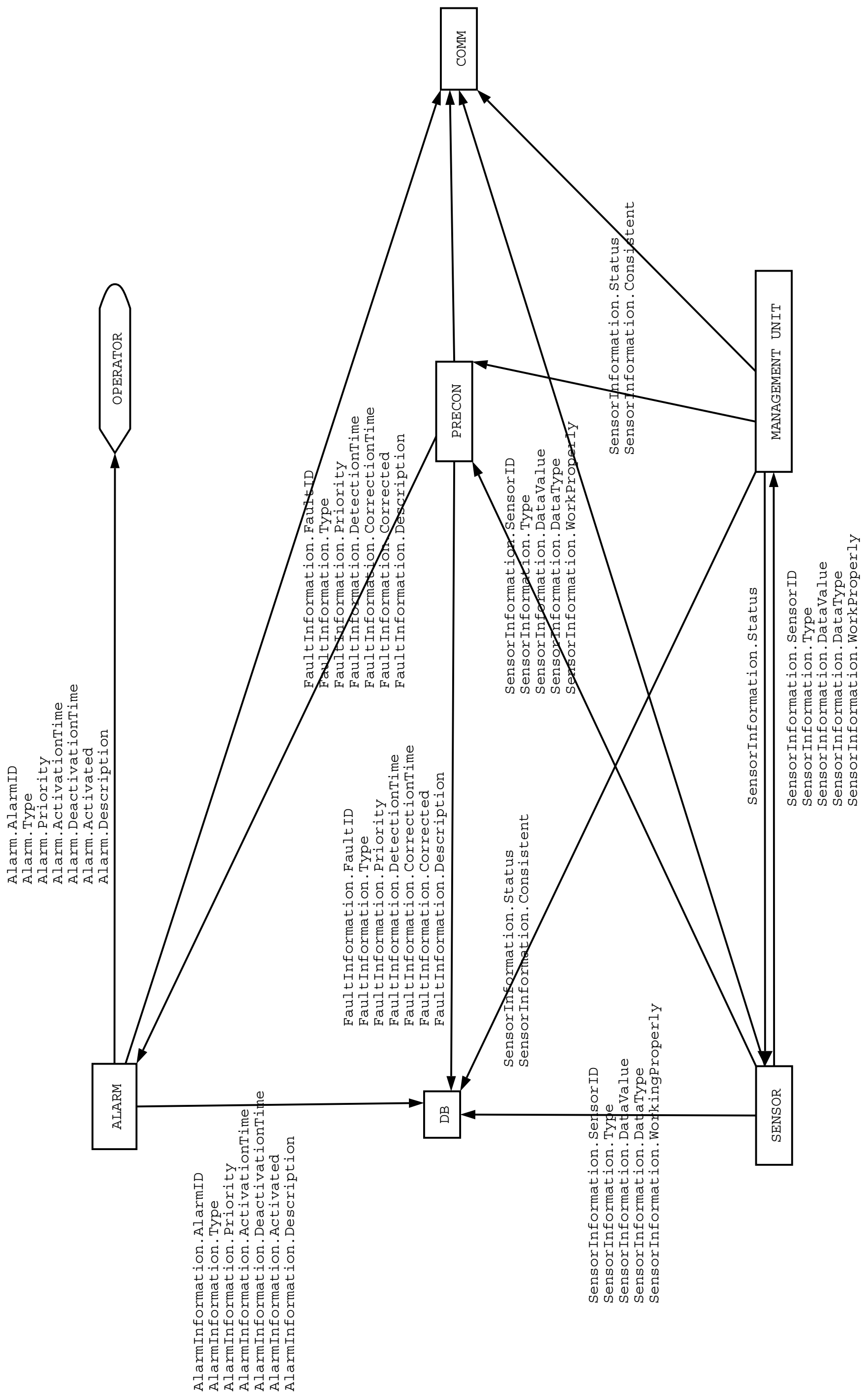
DomPost Transmitted(ai,DB,ALARM)

ReqTrig For AlarmQueryAnswered
$\neg$ Transmitted(ai,DB,ALARM) $\mathbf{S}_{=1s}$ Transmitted(a,ALARM,DB)$\wedge$
Query(a)$\wedge$ Stored(ai) $\wedge$ ai.ID = a.ID $\wedge$ $\neg$ Transmitted(ai,DB,ALARM)

PerformedBy DB

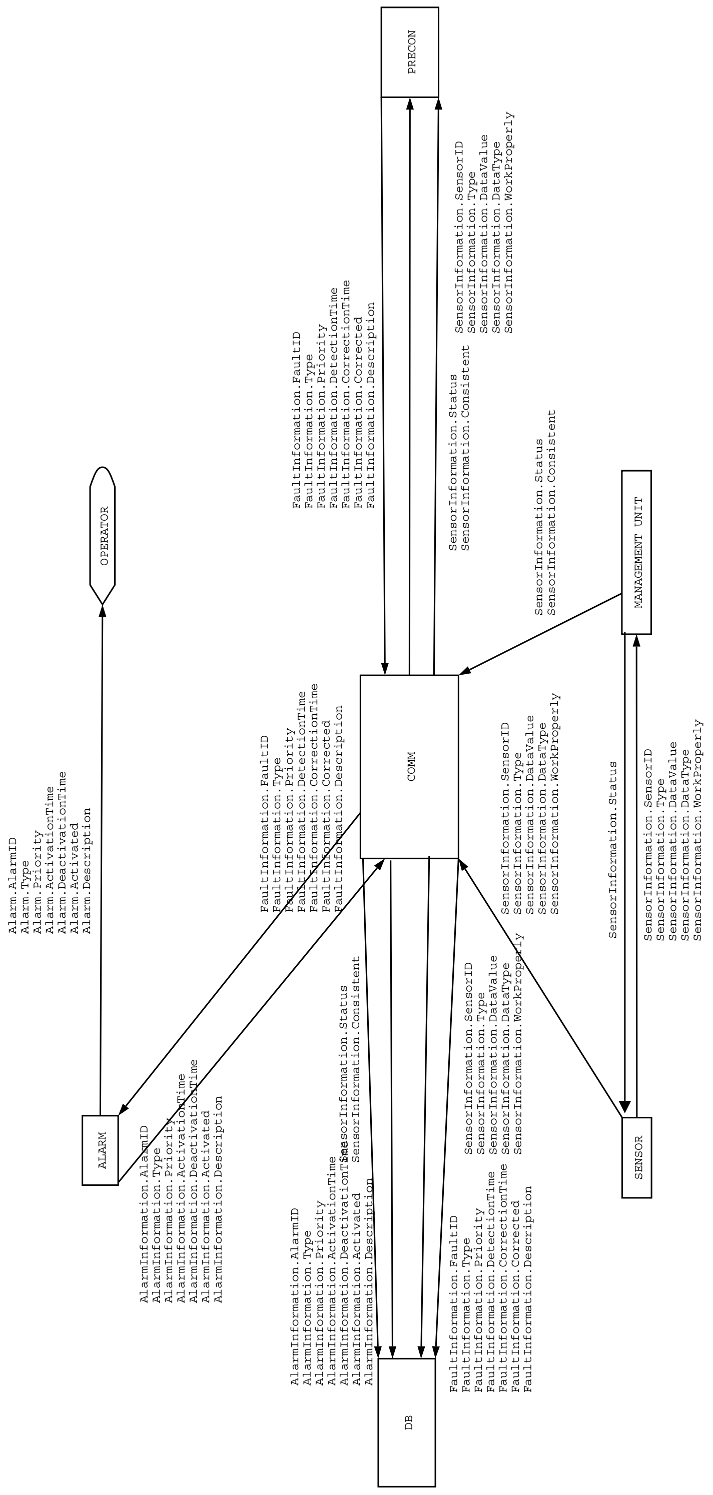
Appendix B

Architecture description: method 1



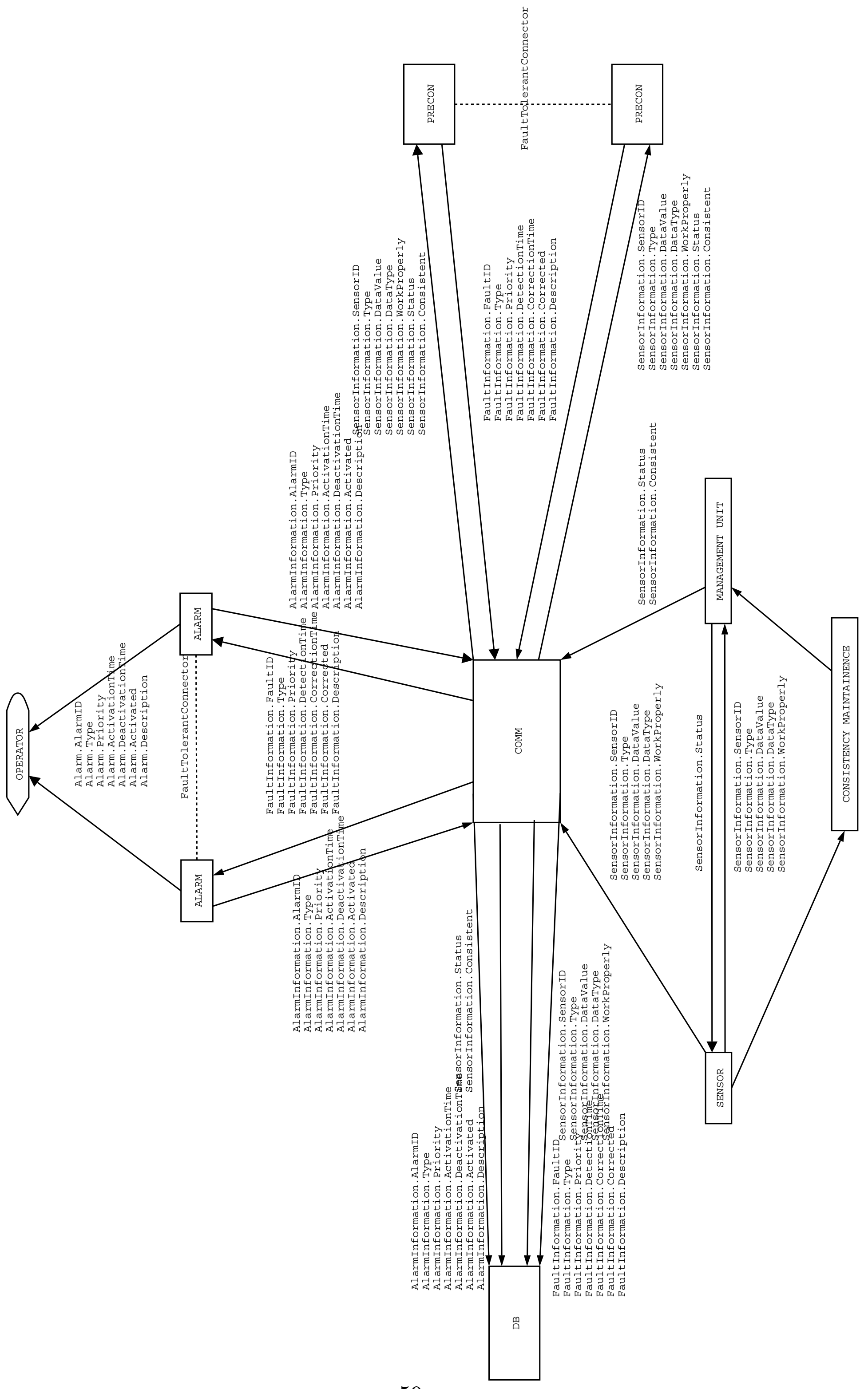
COMM
OPERATOR
PRECON
MANAGEMENT UNIT
ALARM
DB
SENSOR
Alarm.AlarmID
Alarm.Type
Alarm.Priority
Alarm.ActivationTime
Alarm.DeactivationTime
Alarm.Activated
Alarm.Description
FaultInformation.FaultID
FaultInformation.Type
FaultInformation.Priority
FaultInformation.DetectionTime
FaultInformation.CorrectionTime
FaultInformation.Corrected
FaultInformation.Description
FaultInformation.FaultID
FaultInformation.Type
FaultInformation.Priority
FaultInformation.DetectionTime
FaultInformation.CorrectionTime
FaultInformation.Corrected
FaultInformation.Description
SensorInformation.SensorID
SensorInformation.Type
SensorInformation.DataValue
SensorInformation.DataType
SensorInformation.WorkProperly
SensorInformation.Status
SensorInformation.Consistent
SensorInformation.Status
SensorInformation.Consistent
SensorInformation.Status
SensorInformation.SensorID
SensorInformation.Type
SensorInformation.DataValue
SensorInformation.DataType
SensorInformation.WorkProperly
AlarmInformation.AlarmID
AlarmInformation.Type
AlarmInformation.Priority
AlarmInformation.ActivationTime
AlarmInformation.DeactivationTime
AlarmInformation.Activated
AlarmInformation.Description
SensorInformation.SensorID
SensorInformation.Type
SensorInformation.DataValue
SensorInformation.DataType
SensorInformation.WorkingProperly

Figure B.1: Step 1: dataflow architecture



PRECON
FaultInformation.FaultID
FaultInformation.Type
FaultInformation.Priority
FaultInformation.DetectionTime
FaultInformation.CorrectionTime
FaultInformation.Corrected
FaultInformation.Description
SensorInformation.SensorID
SensorInformation.Type
SensorInformation.DataValue
SensorInformation.DataType
SensorInformation.WorkProperly
SensorInformation.Status
SensorInformation.Consistent
OPERATOR
MANAGEMENT UNIT
SensorInformation.Status
SensorInformation.Consistent
COMM
Alarm.AlarmID
Alarm.Type
Alarm.Priority
Alarm.ActivationTime
Alarm.DeactivationTime
Alarm.Activated
Alarm.Description
FaultInformation.FaultID
FaultInformation.Type
FaultInformation.Priority
FaultInformation.DetectionTime
FaultInformation.CorrectionTime
FaultInformation.Corrected
FaultInformation.Description
SensorInformation.SensorID
SensorInformation.Type
SensorInformation.DataValue
SensorInformation.DataType
SensorInformation.WorkProperly
SensorInformation.Status
SensorInformation.SensorID
SensorInformation.Type
SensorInformation.DataValue
SensorInformation.DataType
SensorInformation.WorkProperly
ALARM
AlarmInformation.AlarmID
AlarmInformation.Type
AlarmInformation.Priority
AlarmInformation.ActivationTime
AlarmInformation.DeactivationTime
AlarmInformation.Activated
AlarmInformation.Description
SensorInformation.Status
SensorInformation.Consistent
SensorInformation.SensorID
SensorInformation.Type
SensorInformation.DataValue
SensorInformation.DataType
SensorInformation.WorkProperly
SENSOR
AlarmInformation.AlarmID
AlarmInformation.Type
AlarmInformation.Priority
AlarmInformation.ActivationTime
AlarmInformation.DeactivationTime
AlarmInformation.Activated
AlarmInformation.Description
FaultInformation.FaultID
FaultInformation.Type
FaultInformation.Priority
FaultInformation.DetectionTime
FaultInformation.CorrectionTime
FaultInformation.Corrected
FaultInformation.Description
DB

Figure B.2: Step 2: style-based refined architecture



PRECON
PRECON
FaultTolerantConnector
SensorInformation.SensorID
SensorInformation.Type
SensorInformation.DataValue
SensorInformation.DataType
SensorInformation.WorkProperly
SensorInformation.Status
SensorInformation.Consistent
FaultInformation.FaultID
FaultInformation.Type
FaultInformation.Priority
FaultInformation.DetectionTime
FaultInformation.CorrectionTime
FaultInformation.Corrected
FaultInformation.Description
AlarmInformation.AlarmID
AlarmInformation.Type
AlarmInformation.Priority
AlarmInformation.ActivationTime
AlarmInformation.DeactivationTime
AlarmInformation.Activated
AlarmInformation.Description
MANAGEMENT UNIT
CONSISTENCY MAINTAINENCE
ALARM
ALARM
OPERATOR
Alarm.AlarmID
Alarm.Type
Alarm.Priority
Alarm.ActivationTime
Alarm.DeactivationTime
Alarm.Activated
Alarm.Description
FaultTolerantConnector
COMM
SensorInformation.Status
SensorInformation.Consistent
SENSOR
DB

Figure B.3: Step 3: pattern-based refined architecture

Appendix C

Architecture description: method 2

C.1 Architecture Prescriptions

Preskriptor Specification: PowerPlant Monitoring System

Problem Goals Specifications: PowerPlant Monitoring Process

Components:

- **Component** PowerPlantMonitoringSystem
  Type Processing
  Constraints PerformancOfThePlantMonitored
  Composed of PRECON
  ALARM
  DataBase
  Communication
  Uses /
- **Component** PRECON
  Type Processing
  Constraints FaultDetected
  RemedyActionSuggested
  PeriodicalChecksPerformed&ReportWritten
  Composed of FaultDetectionEngine
  FaultInformation
  FaultDiagnosis
  SensorInformation
  SensorConnect
  Uses /
- **Component** ALARM
  Type Processing

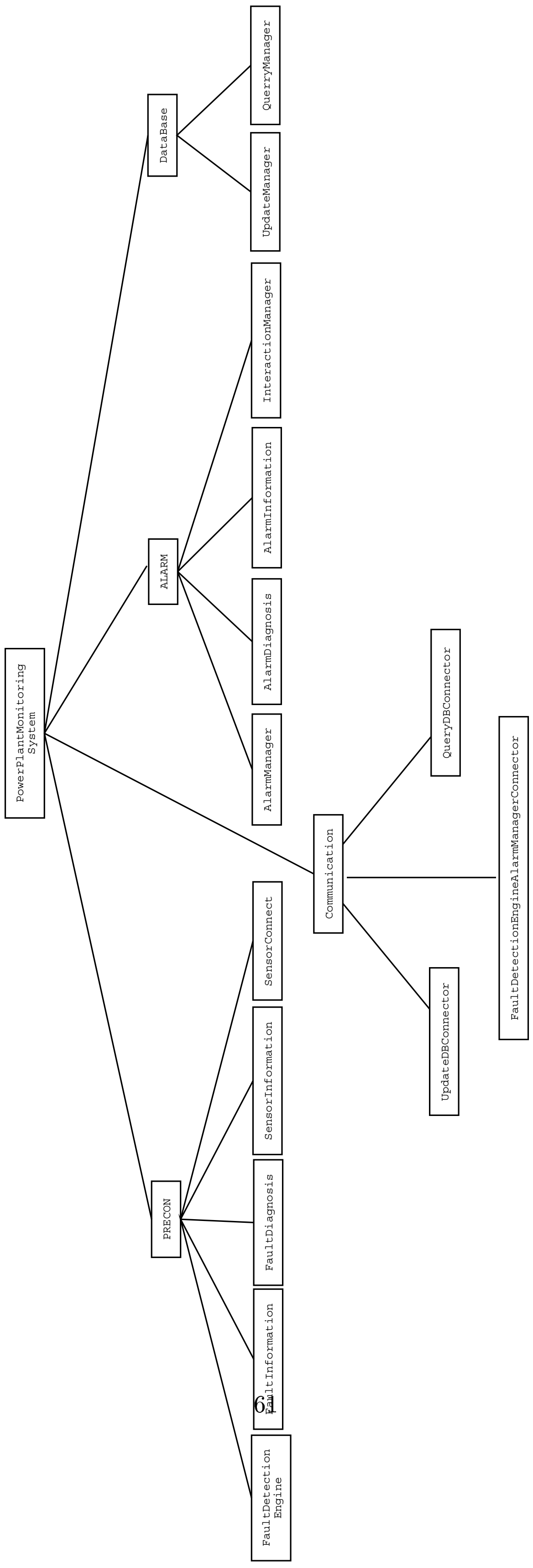


Figure C.1: Component refinment tree

Constraints AlarmCorrectlyManaged
AlarmRaisedIffFaultDetected
AlarmTraced

Composed of AlarmManager
AlarmInformation
AlarmDiagnosis
InteractionManager

Uses /

- **Component** Database

  Type Processing

  Constraints CorrectDataPersistentlyStored

  Composed of QueryManager
  UpdateManager

  Uses /

- **Component** Communication

  Type Connector

  Constraints NoDataIntroduced
  NoDataLost
  SequencePreserved
  DataTransmittedInTime
  DataTransmittedToTheDB
  QueryTransmitted
  FaultInformationTransmittedWhenFaultDetected

  Composed of UpdateDBConnect
  QueryDBConnect
  FaultDetectionEngineAlarmManagerConnect

  Uses /

- **Component** FaultDetectionEngine

  Type Processing

  Constraints CalculationDone
  FaultDetectedWhenCalculationDone
  FaultStatusUpdated
  CheckPerformedWhenDataAcquired
  ReportWrittenWhenCheckPerformed

  Composed of /

  Uses SensorConnect *to interract with* SensorInformation
  FaultDetectionEngineAlarmManagerConnect *to interract with* Alar-mManager
  UpdateDBConnect *to interract with* UpdateManager

- **Component** FaultInformation

  Type Data

  Constraints FaultInformationTransmittedWhenFaultDetected

Composed of /

Uses FaultDetectionEngineAlarmManagerConnect *to interract with* AlarmManager
UpdateDBConnect *to interract with* UpdateManager

- **Component** FaultDiagnosis

  Type Data

  Constraints DiagnosisWritten
  ComputedVariablesStored

  Composed of /

  Uses UpdateDBConnect *to interract with* DBUpdateManager

- **Component** SensorInformation

  Type Data

  Constraints AnalogDataAcquired
  DigitalDataAcquired
  SanityCheckPerformed
  ConsistencyCheck

  Composed of /

  Uses SensorConnect *to interract with* DB
  SensorConnect *to interract with* FaultDetectionEngine

- **Component** SensorConnect

  Type Connector

  Constraints DataAcquiredFromTheField

  Composed of /

  Uses /

- **Component** UpdateDBConnect

  Type Connector

  Constraints Secure
  TimeConstraint = 2s

  Composed of /

  Uses /

- **Component** QueryDBConnect

  Type Connector

  Constraints TimeConstraint = 5s

  Composed of /

  Uses /

- **Component** FaultDetectionEngineAlarmManagerConnect

  Type Connector

  Constraints FaultTolerant
  Secure
  TimeConstraint = 1s

Composed of /
Uses /

- **Component** AlarmManager
  Type Processing
  Constraints AlarmRaisedWhenFaultInformationTransmitted
  FaultInformationTransmitted
  AlarmStatusUpdated
  AlarmNotRaisedIfFaultNotDetected
  Composed of /
  Uses FaultDetectionEngineAlarmManagerConnect *to interract with* FaultDetectionEngine UpdateDBConnect *to interract with* UpdateManager
- **Component** AlarmInformation
  Type Data
  Constraints AlarmInformationStoredWhenAlarmRaised
  Composed of /
  Uses UpdateDBConnect *to interract with* UpdateManager
- **Component** AlarmDiagnosis
  Type Data
  Constraints DiagnosisWritten
  Composed of /
  Uses UpdateDBConnect *to interract with* UpdateManager
- **Component** InteractionManager
  Type Processing
  Constraints OperatorInteractionManaged
  Composed of /
  Uses QueryDBConnect *to interract with* QueryManager
- **Component** QueryManager
  Type Processing
  Constraints QueryAnswered
  DataQueriedUponUserRequest
  AlarmInformationProvidedUponUserRequest
  DataAcquired
  Composed of /
  Uses QueryDBConnect *to interract with* InteractionManager
- **Component** UpdateManager
  Type Processing
  Constraints DataCorrectlyUpdated DataUpdatedIfConsistent
  Composed of /

Uses SensorConnect *to interact with* SensorInformation
UpdateDBConnect *to interact with* FaultDetectionEngine
UpdateDBConnect *to interact with* FaultDiagnosis
UpdateDBConnect *to interact with* AlarmManager
UpdateDBConnect *to interact with* AlarmDiagnosis

C.2 Additional constraints on the system

C.2.1 Constraints on the Database

1. **Informal Def :** Every update on the main database has to be done on the backup database

   Formal Def : $\forall$ x:Data Update(x,mainDB) $\Rightarrow \Diamond$ Update(x,backupDB)

2. **Informal Def :** No additional update should to be made

   Formal Def : Update(x,backupDB) $\wedge$ mainDB.Status = working $\Rightarrow \blacklozenge$ Update(x,mainDB)

3. **Informal Def :** If the main database fails the backup database should take the relay

   Formal Def : mainDB.Status = failure $\wedge$ backupDB.Status=working $\Rightarrow$ $\circ$ $\neg$ mainDB.work $\wedge$ backupDB.work

4. **Informal Def :** If the main database recovers after a failure all the updates made on the backup database have to be done on the main database. The main database has also to reused instead of the backup one.

   Formal Def : $\forall$ x:Data Update(x,backupDB) $\wedge \bullet$ mainDB.Status = failure $\wedge$ mainDB.Status = working $\Rightarrow$ Update(x,mainDB)

5. **Informal Def :** No Query on something that is currently updated can be performed

   Formal Def : $\forall$ x:Data Query(x) $\Rightarrow \big($ $\neg$ Update(x,mainDB) $\wedge$ mainDB.Work $\big) \vee \big($ $\neg$ Update(x,backupDB) $\wedge$ backupDB.Work $\big)$

6. **Informal Def :** Only one database can work at a time

   Formal Def : mainDB.Work $\Rightarrow \neg$ backupDB.Work $\wedge$ backupDB.Work $\Rightarrow \neg$ mainDB.Work

C.2.2 Constraints on the connector between ALARM & PRECON (i.e., FaultDetectionEngineAlarmManagerConnect)

1. **Informal Def :** There has to be two copies of PRECON and ALARM

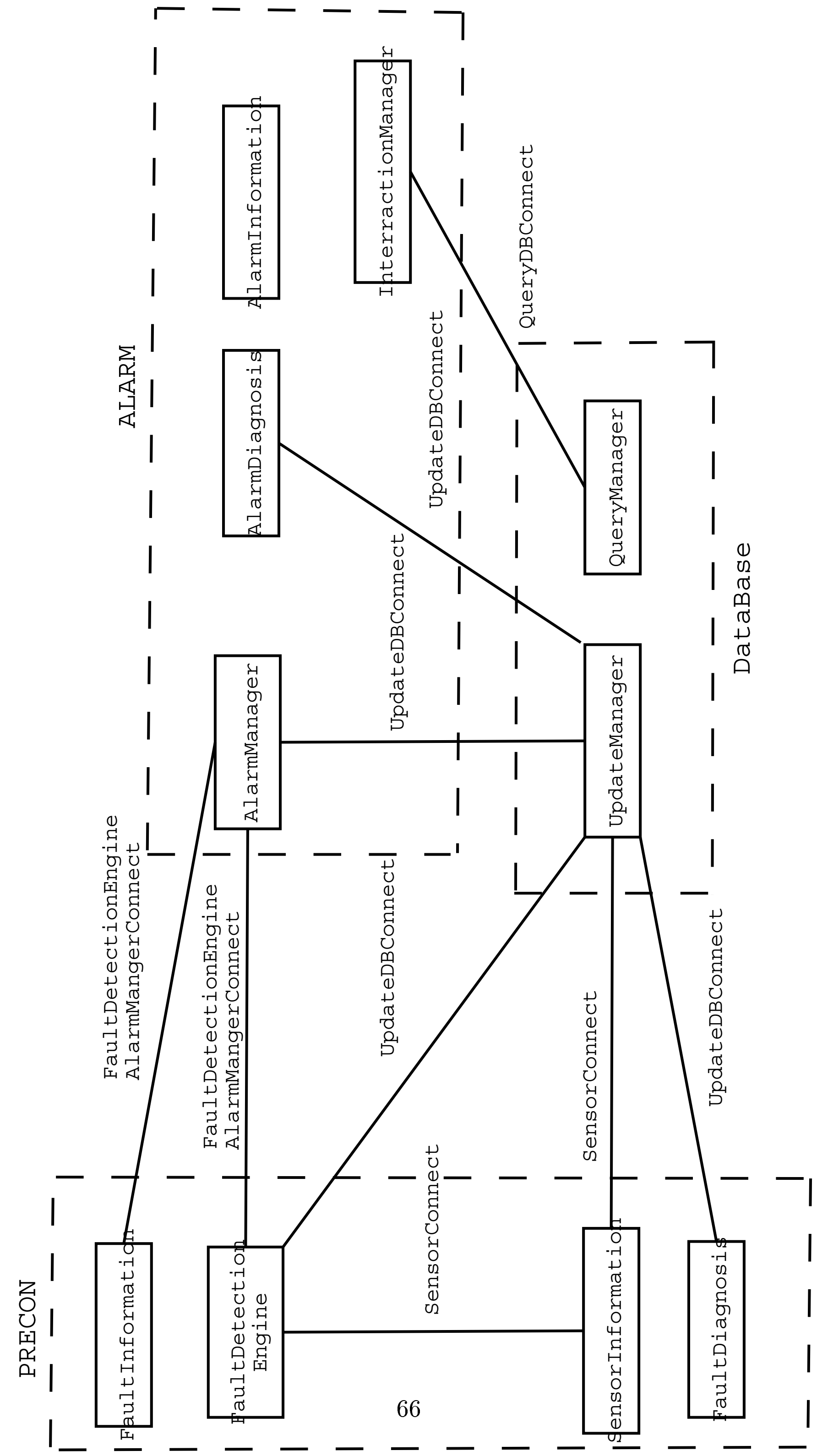


Figure C.2: Box diagram of the architecture

Formal Def : $\forall$ x: Component x.type = PRECON $\vee$ x.type = ALARM $\Rightarrow \exists$ y:Component x.type = y.type $\wedge \neg$ x = y $\wedge$ x $\equiv$ y

2. **Informal Def :** Every time a component fails (PRECON or ALARM), the copy should take te relay

   Formal Def : $\forall$ x:Component $\big($x.type = PRECON $\vee$ x.type = ALARM $\big) \wedge$ x.Status = failure $\Rightarrow \exists$ y:Component x.type = y.type $\wedge$ y.Status = working $\wedge \circ \big($ y.Work $\wedge \neg$ x.Work $\big)$

3. **Informal Def :** Only one component (PRECON or ALARM) should be working at a time

   Formal Def : $\forall$ x:Component $\big($ x.type = PRECON $\vee$ x.type = ALARM $\big) \wedge$ x.Work $\Rightarrow \neg \exists$ y:Component x.type=y.type $\wedge \neg$ x = y $\wedge$ y.Work

4. **Informal Def :** There is no difference in importance between the copies. So the switch should only occur in case of a failure

   Formal Def : $\bullet \neg$ x.Work $\wedge$ x.Work $\Rightarrow \exists$ y $\bullet$ y.status=working $\wedge$ y.status=failure $\wedge$ x.type=y.type $\wedge \neg$ x = y $\wedge$ x $\equiv$ y

5. **Informal Def :** A failure of PRECON or ALARM should not affect the other. The other should continue to work fine

   Formal Def : $\exists$ x:Component $\bullet$ x.Status = working $\wedge$ x.Status=failure $\Rightarrow \big(\forall$ y:Component x.type $\neq$ y.type $\wedge \bullet$ y.Satus=working $\Rightarrow$ y.Status =woking $\big)$