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Modeling Framework based on SysML and AltaRica Data Flow languages for developing models to support complex maintenance program quantification

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Abstract: With the financial crisis attacking every industry and the new sustainability requirements such as the extension of a system operation time subject to ageing life (i.e., nuclear power plant), the importance of maintenance being effective and efficient is one of the top priorities for any industrial company. This challenge cannot be achieved only through conventional maintenance optimization models focusing mainly on few components but through maintenance programs based on “system thinking” considerations. In that way, managers need to have at their disposal new decision-making tools well adapted to support these considerations and allowing comparing off-line the impact of maintenance programs on complex system performances like costs and availability (Complex Maintenance Program Quantification – CMPQ). Thus, this paper proposes a model driven framework based both on the use of SysML to model a system-of-interest subject to ageing and maintenance and on the use of formal language AltaRica Data Flow to support model simulation.

Keywords: Maintenance engineering, Discrete-Event simulation, SysML, AltaRica Data Flow

1. INTRODUCTION

Production systems (or system-of-interest; SoI) are planned and controlled with the objective to supply products with the expected performances. In that way, the system features and capabilities are designed a priori knowing that initially, the production system performs as designed. As time passes, the components age and unplanned failures occur, causing the system performance to drift away from its initial state (Wiendahl and al., 2007). Thus maintenance is needed to restore or maintain the system in operational conditions. It means, for keeping performance optimality, to offer maintenance managers models allowing to take decisions about the maintenance strategies and programs (selecting new ones; re-designing existing ones) to be implemented (Takata and al., 2005). So, the importance of maintenance being effective and efficient is one of the top priorities for any industrial company. In that way, models used to support optimal maintenance strategies generally cover four main aspects (Dekker, 1996):

- a description of the SoI being maintained;
- knowledge on the SoI deteriorates and deterioration consequences;
- a description of the available information on the SoI and the available response options
- an objective function according to which the optimal maintenance strategy has to be derived.

Therefore there is a proliferation of “optimal maintenance models” (Wang and Pham, 2006) not well adapted to the industrial reality, in terms of mastering the SoI complexity, the interactions between the SoI and its enabling systems such as the support (maintenance and resources) one, the new sustainability considerations, the reuse of model based on COTS (Components Off The Shelf) principle (INCOSE, 2010).

For example, the extension of SoI operation time subject to ageing life (i.e., in the case of French nuclear power plants) implies to model new constraints. Indeed at their initial planned End-Of-Life, these systems must continue to operate during an additional period rather than to be dismantled or destroyed (i.e., economical reasons). These new constraints are the management of the additional inspections, the ignorance of some degradation processes (e.g. emergence of new degradation laws) related to duration extension and its evolving under fluctuating environmental and operational conditions. To face most of the lacks on current optimization models previously mentioned, the contribution developed in this paper consists in proposing a generic modeling framework for Complex Maintenance Program Quantification (CMPQ) built in two parts:

- A “static and interactional” part based on SysML semi formal language to model all the knowledge related to the SoI, its missions, the support system (i.e. maintenance strategies and resources) and their common interactions. This set of knowledge is structured with generic concepts (i.e. components, functions, maintenance etc.) in consistence with standards such as MIMOSA (www.mimosa.org) and (EN13306, 2001) in order to obtain a reference (ideal) model for CMPQ. Reference means “able to address all the CMPQ considerations whatever SoI application domains are”.

- A “concept behaviour” part resulting from the transformation of the previous concepts formalized with SysML into dynamic behaviour based on AltaRica Data Flow (ADF) formal language.

The main result of the generic framework is a library of generic “concept behaviour” modeled with ADF. Then this library can be used, for a specific SoI, to develop the specific executable model needed to support, by simulation, the
The translation of these steps for CMPQ context imp lies:

- Model building
- Model execution

Costs related to maintenance.

Monnin and al. (2011) focused on support system aspects in order to assess contributions related to maintenance optimization and more to the applications domains of the SoI. Nevertheless, only few techniques can be used as shown in Table 1 mainly in relation to applying to a wide number of components. In comparison, in that way, CMPQ can be considered as a dependability study with a wider modeling scope because it has to take into account not only the maintenance strategies but also the whole support system. It leads that CMPQ relies on the framework proposed by the System Engineering (INCOSE, 2010) to assess Key Performance Indicators (KPI) (Crespo-Marquez, 2008), and described by the following steps:

- Choice of the indicators to be assessed (KPIs),
- Model building according to expected KPIs,
- Model execution to assess KPIs.

The translation of these steps for CMPQ context implies:

- To define required KPIs both related at least to maintenance costs and dependability,
- To create reference model of the concepts (SoI and Maintenance considerations) in order to reduce the modeling effort for each study,
- To build any SoI according this reference model in order to assess required KPIs.

In relation to CMPQ modeling phase, different modeling techniques can be used as shown in Table 1 mainly in relation to the applications domains of the SoI. Nevertheless, only few of them (Medina and al., 2011; Monnin and al., 2011) focused on support system aspects in order to assess costs related to maintenance.

Table 1 puts in evidence two kinds of approaches:

- (a) Approaches driven by the simulation tool (Stochastic Petri Nets, Bayesian Networks). Although these tools present the advantage to support both modeling and simulation aspects (and to allow a gain of time), they cannot model some complex processes and interactions. It induces crucial problems for the model reusability.
- (b) Model-driven approaches where the simulation tool modeling is preceded by a high level (or natural) language modeling step. They present the advantage to model knowledge from a generic informal or semi formal (and so capitalizable) model, but imply a transformation language step between the model building language and the model execution language. Semi formal languages (UML2 (2010), SysML (2008),... ) provide, by means of different views (static, interaction and behavioural), a semantic frame needed to create a static (reference) model but also helping the transformation language step to create simulation model. Thus in relation to CMPQ considerations, the main challenge for such approaches consists in selecting a formal language (supporting model execution) well adapted to represent the “concept behaviour” knowing that the concepts have been previously formalized. Most of the time, a state-transition formal tool/language is chosen and has to perform the following constraints:
  - to be able to model accurately CMPQ related knowledge in formal concepts,
  - to manage SoI complexity (i.e. concepts reusability).

A lot of specific tools exist to be in phase with previous considerations. (Trivedi and al., 1993) studied classical ones (Petri Nets, Markov Chains...) and highlighted lacks notably in model reusability. New high level formal languages for FIGARO (Bouissou and al., 2002), SDM (Ramesh and al. 2000), AltiRicaDF (Rauzy, 1999)...) appeared some years ago. They own interesting genericity abilities and allow representing easily a complex system according to COTS libraries and remain able to model complex interactions and phenomenon (Boiteau and al., 2006).

On the basis of the semi-formal and formal languages previously identified for approaches (b), it is necessary now to select the more suitable ones in relation to CMPQ framework for supporting both the “static-interactional” part and the “concept behaviour” one.

3. LANGUAGES PROPOSED FOR THE FRAMEWORK

3.1 The use of a SysML-based framework for « static and interactional » modeling.

Although some works deals with the transformation from UML language to simulation tools (SAN (Monnin and al., 2011), Stochastic Petri Nets (Bernardi and al., 2008)), this language remains more suitable for information system modeling. SysML language, which is an extension of UML, appears more adapted not only for industrial system modeling but also for the model reusability during the design phase. Indeed, Hoffman (2008) proposes the use of different SysML.
diagrams (providing static, interactional and behavioural
views) during the whole life cycle of a system. However,
some lacks remain for the quantification of the support
system impact on the SoI leading to mistakes in design. The
use of SysML for CMPQ allows to fulfill this lack, and to
allow quantifying the Support System organization on the SoI
design. However, although blocks, sequences, and parametric
diagrams are particularly suitable to model interactions
between different concepts needed for CMPQ, the SysML
“concept behavior” view (State Machine diagrams) does not
provide a well defined semantic frame (Borger and al., 2000)
inducing difficulties for simulation. It leads to keep the
principle of selecting another language to support simulation
(with a step of language transformation): ADF language.

3.2. The use of AltaRicaDF language for « concept
behaviour » modeling.

Among formal languages identified previously in section 2,
ADF presents a system engineering construction philosophy,
in order to be compatible with other languages like Lustre or
Modelica dedicated to other modeling views. The ADF
language presents a well defined semantics relying on the
mode automaton formalism. A mode automaton, formally
defined in Rauzy (2002), is an input/output automaton. It has
a finite number of states that are called modes. At each
instant, it is in one (and only one) mode. It may change of
mode when an event occurs. In each mode, a transfer
function determines the values of output flows from the
values of input flows. In addition, this formalism allows both
to model and store reusable objects as libraries elements and
to minimize the SoI modeling effort. Some simulation
environments (Safety Designer (www.3ds.com),
SIMFIA(www.apsys.eads.net)) allowing to manage these
libraries without generate complementary ADF code.
(David and al., 2010) already deal with the creation of a ADF
code from a SysML model. Moreover, this language is more
and more used in industry and some dependability dedicated
software tools are able to execute it. They allow both to store
the “concept behaviour” models within libraries and to
perform stochastic simulation by assembling and instantiation of
the suitable “concept behaviour”. Although this language
is used in the proposed framework, it can be noted that it
presents some restrictions like the impossibility to model
looped systems (i.e. the state of a node is function of the state
of another and vice versa). However, recent works on ADF
new versions tend to address this issue (Rauzy, 2008).

In summary, Fig. 1 illustrates the proposed framework,
through its different steps: from the initial SysML based
reference model until ADF-based simulation. From now on,
SysML related items (extracted from SysML (2008)), will be
marked in italic characters and ADF elements in thick ones.

4. “STATIC AND INTERACTIONAL” MODELING

This part modeled with SysML diagrams has been supported
by Rational Rhapsody tool (www.ibm.com).

4.1 The static model: the use of SysML block diagrams

On the static model, a first scientific investigation has been
published in (Ruin and al., 2012). This model is constructed
in terms of block diagrams formalizing in concepts the
CMPQ related knowledge. Thus the blocks attributes are
extracted from maintenance related standards and works with
regards to the required KPIs. Diagrams are structured with
three main items:
- the SoI composed of its components/asset including
  related concepts (e.g. failure modes, degradation
  mechanisms, symptoms…) and their links (e.g. parallel),
- the SoI missions (e.g. environmental and operational
  conditions…),
- the support system composed with the maintenance
  system (e.g. maintenance strategies…) and the resources
  (operators, spare parts…).

These block diagrams do not contain whole CMPQ
information. Indeed, interactions between objects are just
specified by relations between blocks. Thus static additional
knowledge regarding relations between attributes (modeled
by means of SysML internal block diagrams) is required.
Moreover, knowledge on dynamic aspects (modeled by
means of SysML sequence diagrams) is needed to go towards
the simulation.

4.2 The interaction model: the use of SysML-additional
diagrams

Sequence diagrams allow to model CMPQ system scenarios.
For example, making part in CMPQ, interactions between
different lifelines equivalent to different blocks defined
previously are modeled. In that way, the model shown in
Fig.2, formalizes the interactions between concepts
describing corrective strategy. This kind of strategy is divided
in three states modeled by condition marks (plan: modeling
the strategy waiting state; “in_prep”: modeling the strategy
requested state; “in_progress”: modeling the maintenance
action application). Each condition mark occurrence is
preceded by looped back messages modeling the corrective
maintenance internal event. These messages can be (a)
temporized (e.g. the message ”end_mc” is related to
maintenance duration parameters), or (b) immediate and
triggered by the occurrence of a receipted message (e.g. the
message ”prep_mc” is triggered by the message “fail”).
In summary, these two additional diagrams provide a global view of a set of blocks in interactions. At this step, SysML state machine diagrams can be generated according previous sequence diagrams in order to perform model checking on the model. However, this paper focus on stochastic simulation, and next session addresses the creation of a “concept behaviour” library by transforming the concepts into ADF formalism.

5. “CONCEPT BEHAVIOUR” MODELING

Now as the previous diagrams, it is necessary to translate previously built SysML diagrams into the ADF language, more suitable for execution and simulation requirements. ADF is based on the mode automaton formalism are not suitable

5.1 The ADF language

An ADF code is structured in 7 main items: The part node where the object is defined; the part state where the set reachable in a node is defined; the part flow where the different flows able to transit in a node, their direction and their type (real, bool…) are defined; the part event, where the different events related to a node are defined; the part trans where the impact of different events on states of a node are modeled; the part assert where the transfer function of a node is model, according to the node states, flows, and transition; and finally the part init where initial state is given.

As it is a high level language, node automaton allows the systems description like hierarchies of reusable components to master system complexity. It is done by means of three operations: the parallel compositions, the connections and the synchronizations.

5.2 From SysML language to ADF language

SysML diagrams were constructed with a semantic frame making the transformation language step to ADF easier. ADF “concept behaviour” can be created exhaustively by means of algorithms from both parametric diagrams and sequence diagrams elements, to ADF parts (7 items).

For example, Fig. 4 describes the algorithm allowing the part creation of every ADF (node, state, event, init, and trans, only if messages parameters are not constraintsparameters) code formalizing “concept behaviour” from a sequence diagram according to the following notations presented on table 2

<table>
<thead>
<tr>
<th>$\mathcal{E}=[E]$</th>
<th>Set of lifelines</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>Number of lifelines</td>
</tr>
<tr>
<td>$S^i=[S^i_j]$</td>
<td>Set of condition marks on the $i^{th}$ lifeline</td>
</tr>
<tr>
<td>$p$</td>
<td>Number of condition marks on the $i^{th}$ lifeline</td>
</tr>
<tr>
<td>$T_{j,j+1}^i=[T_{j,j+1}^i]$</td>
<td>Set of looped back messages between condition marks $j$ and $j+1$</td>
</tr>
<tr>
<td>$q$</td>
<td>Number of looped back messages between condition marks $j$ and $j+1$</td>
</tr>
</tbody>
</table>

![Fig 2. Sequence diagram for corrective maintenance scenario](image)

By keeping the same modeling way for all possible scenarios related to each lifeline (corrective maintenance is only one possible scenario), the generic activity diagram related to each lifeline and gathering semantic of all SysML sequence diagrams can be automatically generated. This kind of diagram provides some dynamic information on interactions between blocks identified on the static model suitable for a future transformation into a discrete event formalism.

However, some quantitative modeling is needed to assess KPIs. SysML parametric diagrams are particularly suitable for supporting this issue because their goal is to model the block plus attributes and their relationships. For example, constraintparameters are blocks attributes impacting or impacted by others, as shown in Fig. 3. Their relations are modeled by an equation represented in the constraint. It should be emphasized that, to be suitable with ADF formalism, this step must avoid:
- to model looped systems,
- to express the constraintparameter equations in another form than the logic one.

![Fig 3. Parametric Diagram for a two serial components](image)

The constraint expressed in Fig. 3, models the impact of two serialized components on the system availability (constraintparameter “outflow”). This generic equation will be instanciated according knowledge feedback for any case study. Parametric diagrams can be used also to model the impact of an operator skill on maintenance action efficiency.
Sequence diagrams have been designed by making sure that each looped back message is triggered by a new condition mark, or by a message receiving (from another lifeline). Thus only one or zero received message can occur between two looped back messages, and let’s consider $T_q^i$ the received message before looped back message $q$.

For $i$ from 1 to $n$
Create node $E^i$
Create Init state $S^i$
For $j$ from 2 to $p$
Create state $S^j$
For $k$ from 1 to $j$
Create event $T_k$
Create transition $S_{i-1} \rightarrow T_k \rightarrow S_i$
if $T_k \neq (0)$
Create sync $<T_k, T_i>$
End for
End for
End

Fig. 4. Algorithm to go from SysML sequence diagrams to ADF

Fig. 5a is showing the ADF code obtained by applying these rules to the sequence diagram and its lifeline “CorrectiveStrategy” given Fig. 2. Fig. 5b is illustrating the synchronizations also created. Synchronizations differ for each system. Indeed, synchronization is exhaustive only when all interacting nodes are defined. By proceeding in the same way for parametric diagrams, exhaustive ADF code related to generic “concept behaviour” has been built.

In summary, the results of the entire language transformation step can be materialised by a library of generic “concept behaviour” (COTS) modelled with ADF. These COTS can be then instantiated and assembled (to form an executable model) with regards to a specific application (specific SoI & Support System). The system hierarchy, links between objects, and the completion of synchronizations are defined at this step, according a guideline proposed in future works aiming to help the user of the tool to manage the library of COTS.

6. APPLICATION TO A CASE STUDY: A TWO COMPONENTS SYSTEM SUBJECT TO DIFFERENT MAINTENANCE ORGANIZATIONS

In order to show the interest and feasibility of the proposed framework, instantiation of generic “concept behaviour” is performed with regards to a simple case study in order to develop simulations. Because ADF has been designed to manage system complexity by linking assets functional flows, this case study will focus on a basic system (2 components) considering supply systems objects. Indeed it aims to assess maintenance organization impact on system availability according a set of libraries available. A production system compounded by two serialized identical components is considered. It is modeled according the previous sequence diagram with a component malfunctioning characterized by two two-level degradation mechanisms impacting one failure mode. An “As Good As New - AGAN” corrective maintenance action is applied on the failed component.

Let’s consider the three following maintenance organizations:
(A) 2 independent scheduled preventive strategies acting on each component, with one maintenance operator for each component.
(B) Case (A) with only one maintenance operator for the two components.
(C) Case (A) with opportunistic rules on preventive strategies (e.g. if failure occurs on component 1 then preventive strategy on component 2 is triggered).

Preventive maintenance actions are supposed to be “As good As New”, corrective maintenance duration law and parameters are $exp(0.05)$ while preventive maintenance duration ones are $exp(0.1)$.

Table 3 gives model parameters according to instantiated parametric diagrams and knowledge feedback. For example, the constraint “transferfunction”:

$$f = \text{if } [S1=\text{failed or } S2=\text{failed then failed}]$$

For each organization, an executable model is built from the COTS available in libraries. The library is stored on SIMFIA simulation environment supporting ADF language. Thus for developing the model, COTS are just picked up in a library and linked by the user through the SIMFIA GUI (Fig. 6) according proposed guideline. These links may be done trough flows (e.g. from “asset1” to SerialLink_2Asset”) or through synchronizations (e.g. between operator1, CorrectiveStrategy1 and Asset1). Then, transitions are instantiated according to knowledge feedback and parametric equations.

Table 3. Instantiation parameters for the two two-level degradation mechanisms components

<table>
<thead>
<tr>
<th>Degradation mechanism 1</th>
<th>Degradation mechanism 2</th>
<th>Failure mode impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>level 0</td>
<td>level 0</td>
<td>$\exp(1e-4)$</td>
</tr>
<tr>
<td>level 0</td>
<td>level 1</td>
<td>$\exp(1e-3)$</td>
</tr>
<tr>
<td>level 1</td>
<td>level 0</td>
<td>$\exp(1e-3)$</td>
</tr>
<tr>
<td>level 1</td>
<td>level 1</td>
<td>$\exp(1e-2)$</td>
</tr>
</tbody>
</table>

Simulations have been performed for 1000 stories and 10000 UT. Only few synchronization modifications are needed to go from one model to another (i.e. Model A to Model B) because the reusability is maximal. The simulation results of the three cases are given table 3, for the following KPIs: operator(s) and SoI availability.
Fig. 6. Case A defined on SIMFIA GUI

Table 3. Simulation results for the three cases

<table>
<thead>
<tr>
<th>Preventive maintenance period</th>
<th>Operator(s) availability</th>
<th>SoI availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 100 UT</td>
<td>0.931/0.882</td>
<td>0.882</td>
</tr>
<tr>
<td>B 100 UT</td>
<td>0.553</td>
<td>0.553</td>
</tr>
<tr>
<td>C 100 UT</td>
<td>0.956/0.968</td>
<td>0.956</td>
</tr>
</tbody>
</table>

The results are not industrially significant for such a SoI but they prove that the framework can provide some good indicators to compare different maintenance organizations. These results have been checked analytically under Markovian assumption for the simple case of one component subject to only one degradation mechanism and one failure mode.

7. CONCLUSIONS

This paper proposes a model driven framework based both on the use of SysML semi formal language to model the “static and interaction” part related to CMPQ and on the use of the formal language ADF both to model the “concept behaviour” part and to perform simulation. This high level language, initially made to model a flow propagation through an set of physical components, give satisfying results addressing objects like maintenance strategies or missions. However, some constraints related to simulation algorithm available in SIMFIA (considering only Boolean flow, impossibility to constraint transition parameter) induce to adapt initial model (e.g. impossibility to consider functional degradation…) and to restrict initial assumption (maintenance actions supposed AGAN). In future works, in addition to the implementation of an exhaustive COTS library, developments will be made on these restrictions in order to apply this framework to a wide scale industrial system.

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