Stepwise Construction and Refinement of Dependability Models

Claudia Betous-Almeida, Karama Kanoun

Stepwise Construction and Refinement of Dependability Models

Cláudia Betous-Almeida and Karama Kanoun

LAAS-CNRS
7, Avenue du Colonel Roche
31077 Toulouse Cedex 4 - France
E-mail: {almeida,kanoun}@laas.fr

Abstract

This paper presents a stepwise approach for dependability modeling, based on Generalized Stochastic Petri Nets *(GSPNs). The first-step model called functional-level model, can be built as early as system functional specifications and then completed by the structural model as soon as the system architecture is known, even at a very high level. The latter can be refined according to three different aspects: Component decomposition, state and event fine-tuning and distribution adjustment to take into account increasing event rates. We define specific rules to make the successive transformations as easy and systematic as possible. This approach allows the various dependencies to be taken into account at the right level of abstraction: Functional dependency, structural dependency and those induced by non-exponential distributions. A part of the approach is applied to an instrumentation and control system (I&C) in power plants.*

1. Introduction

Dependability evaluation plays an important role in critical systems' definition, design and development. Modeling can start as early as system functional specifications, from which a high-level model can be derived to help in analyzing dependencies between the various functions. However the information that can be obtained from dependability modeling and evaluation becomes more accurate as more knowledge about the system's implementation is incorporated into the models.

The starting point of our work was to help (based on dependability evaluation) a stakeholder of an I&C system in selecting and refining systems proposed by various contractors in response to a *Call for Tenders*. To this end, we have defined a stepwise modeling approach that can be easily used to select an appropriate system and to model it thoroughly. This modeling approach is general and can be applied to any system, to model its dependability in a progressive way. Thus, it can be used by any system's developer.

The process of defining and implementing an I&C system can be viewed as a multi-phase process starting from the issue of a call for tenders by the stakeholder. The call for tenders gives the functional and non-functional (e.g., dependability) requirements of the system and asks candidate contractors to make offers for possible systems/architectures satisfying the specified requirements. A preliminary analysis of the numerous responses by the stakeholder, according to specific criteria, allows the pre-selection of two or three candidate systems. At this stage, the candidate systems are defined at a high level and the application software is not entirely written. The comparative analysis of the pre-selected candidate systems, in a second step, allows the selection of the most appropriate one. Finally, the retained system is refined and thoroughly analyzed to go through the qualification process. This process is illustrated in Figure 1. Even though this process is specific to a given company, the various phases are similar to those of a large category of critical systems.

Dependability modeling and evaluation constitute an efficient support for the selection and refinement processes, thorough analysis and preparation for the system's qualification. Our modeling approach follows the same steps as the development process. It is performed in three steps as described in Figures 1 and 2:

Step 1. Construction of a functional-level model based on the system's specifications;

Step 2. Transformation of the functional-level model into a high-level dependability model, based on the knowledge of the system's structure. A model is generated for each pre-selected candidate system;

Step 3. For the retained system, refinement of the high-level model into a detailed dependability model.

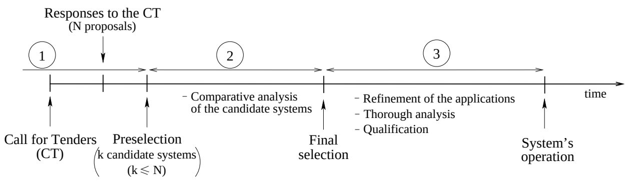


Figure 1. Various steps of I&C definition process

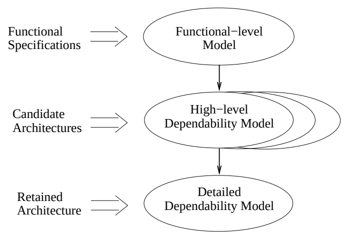


Figure 2. Main steps of our modeling approach

Modeling is based on *Generalized Stochastic Petri Nets* (GSPN) [2] due to their ability to cope with modularity and model refinement. The GSPN model is processed to obtain the associated dependability measures (i.e., availability, reliability, safety, ...) using an evaluation tool such as SURF-2 [4].

The relevance of our approach lies in supplying a set of coherent techniques, allowing to master step by step dependability model construction, based on GSPNs. It allows the progressive incorporation of the newly available information into the existing model, changing its initial organization according to a well identified set of rules. Model refinement can be achieved to take into account: component decomposition, event fine-tuning and distribution adjustment. In particular, the same set of rules is used for generating the high-level model from the functional-level model and for component refinement. We have adapted the method of stages (used for simulating increasing failure rates) to take into account dependencies between interacting components without changing their initial models.

This modeling approach has been applied to three different I&C systems, to help select the most appropriate one. In this paper we illustrate our approach on a small part of one of them. This paper is an elaboration of our previous work [3] that was devoted only to the functional-level model construction and did not address at all the structural model refinement.

The remainder of the paper is organized as follows. Section 2 describes the functional-level model. The high-level dependability model is presented in Section 3. Section 4 deals with the structural model's refinement and Section 5 presents a small example of application of the proposed approach to an I&C system. Finally, Section 6 concludes the paper.

2. Functional-level model

The derivation of the system's functional-level model is the first step of our method. This model is independent of the underlying system's structure. Hence, it can be built even before the call for tenders, by the stakeholder. It is formed by places representing possible states of functions. For each function, the minimal number of places is two (Fig. 3): One represents the function's nominal state (F) and the other its failure state ($\overline{\mathrm{F}}$).

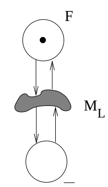


Figure 3. Functional-level model related to a single function

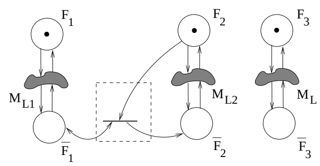
In the following, we assume only one failure mode, but it is applicable in the same manner when there are several failure modes per function. Between states F and $\overline{\mathrm{F}}$, there are events that manage changes from F to $\overline{\mathrm{F}}$ and vice-versa. These events are inherent to the system's structure that is not specified at this step, as it is not known yet. The model containing these events and the corresponding places, is called the *link model* (M_L). Note that the set $\{F, M_L, \overline{F}\}$, that constitutes the system's GSPN model, will be completed once the system's structure is known.

However, systems generally perform more than one function. In this case we have to look for dependencies between these functions due to the communication between them. We distinguish two degrees of dependency: Total dependency and partial dependency. Figure 4 illustrates examples of the two degrees of functional dependency between two functions F_1 and F_2. F_3 is independent from both F_1 and F_2.

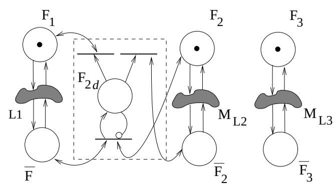
Case (a) *Total dependency* – F_2 depends totally on F_1 (noted $F_2 \hookleftarrow F_1$): If F_1 fails, F_2 also fails;

Case (b) *Partial dependency* – F_2 depends partially on F_1 (noted $F_2 \leftarrow F_1$): F_1's failure does not induce

F_2's failure. In fact, F_1's failure puts F_2 in a degraded state that is represented by place F_{2d} that is marked whenever F_1 is in its failure state and F_2 in its nominal one. In Figure 4(b), the token is removed from F_{2d} as soon as F_1 returns to its nominal state, however other scenarios might be considered.



(a) $F_2 \hookleftarrow F_1$ (total)



(b) $F_2 \hookleftarrow F_1$ (partial)

Figure 4. Functional dependencies

3. High level dependability model

The high level dependability model is formed by the function's states and the link model that gathers the set of states and events related to the system's structural behavior. This behavior is modeled by the so-called *structural model* and then it is connected to F and $\overline{F}$ places through an *interface model*. The link model is thus made up of the structural model and of the interface model.

The *structural model* represents the behavior of the hardware and software components taking into account fault-tolerance mechanisms, maintenance policies as well as dependencies due to the interactions between different components.

The *interface model* connects the structural model with its functional state places by a set of immediate transitions.

In this section we concentrate mainly on the interface model. In particular, we assume that the structural model can be built by applying one of the many existing modular modeling approaches (see e.g., [5, 9, 10, 11]), and we focus on its refinement in section 4. Note that the structural models presented in this section are not complete. We present simple examples to help understand the notion of interface model before presenting the general interfacing rules.

3.1 Examples of interface models

For sake of simplicity, we first consider the case of a single function then the case of multiple functions.

Single Function: Several situations may be taken into account. Since the two most important cases are the *series* and the combination *series-parallel* components, we limit the illustrations to these two basic cases which allow modeling of any system. More details are given in [3].

Series case: Suppose function F carried out by a software component S and a hardware component H. Then, F and $\overline{F}$ places' markings depend upon the markings of the hardware and software components models (Fig. 5).

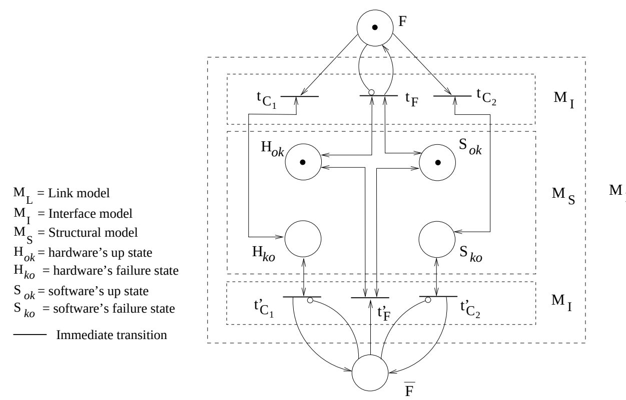


Figure 5. Two series components

The behavior of H and S is modeled by the structural model and then it is connected to places F and $\overline{F}$ through an interface model. Note that there is only one interface model. We split it into two parts, an upstream part and a downstream part, so that it is constructed in a systematic way. This allows our approach to be re-usable, facilitating the construction of several models related to various architectures. Also, the case of simultaneous failures is not treated at this level.

Series-parallel case: Consider function F implemented by two *redundant* software components S_1 and S_2, running on the same hardware component H. F's up state is the combined result of H's up state and S_1 or S_2's up states and F's failure state is the result of H's failure or S_1 and S_2's failure, as indicated in Fig. 6.

Multiple Functions: Consider two functions (the generalization is straightforward) and let $\{C_{1i}\}$ (resp. $\{C_{2j}\}$) be the set of components associated to F_1 (resp. F_2). We distinguish the case where functions do not share resources (such as components or repairmen), from the case where they share some. Examples of these two cases are presented hereafter.

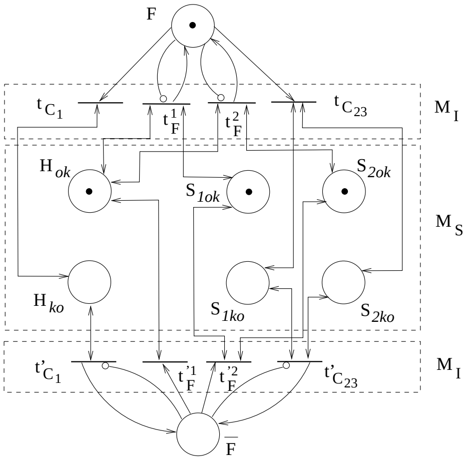


Figure 6. Two redundant software components on a hardware component

F_1 and F_2 have no common components: $\{C_{1i}\} \cap \{C_{2j}\} = \emptyset$. The interface models related to F_1 and F_2 are built separately in the same way as explained for a single function. There are no structural dependencies, only functional ones.

F_1 and F_2 have some common components: $\{C_{1i}\} \cap \{C_{2j}\} \neq \emptyset$. This corresponds to the existence of structural dependencies, in addition to functional dependencies. This case is illustrated on a simple example:

- F_1 done by three components: A hardware component H and two redundant software components S_{11} and S_{12}. F_1's model corresponds to Fig. 6.
- F_2 done by two components: The same hardware component H as for F_1 and a software component S_{21}. F_2's model corresponds to Fig. 5.

The global model of F_1 and F_2 is given in Fig. 7. It can be seen that i) both interface models (M_{I1} and M_{I2}) are built separately, and ii) in the global model, the common hardware component H is represented only once by a common component model. Sharing of H thus creates a structural dependency. The functional dependencies are not represented in this figure.

3.2. Interfacing rules

The interface model M_I connects the system's components with their functions by a set of transitions. This model is a key element in our approach. Particular examples of interface models have been given in Figures 5 to 7. In this section the general organization of the interface model is

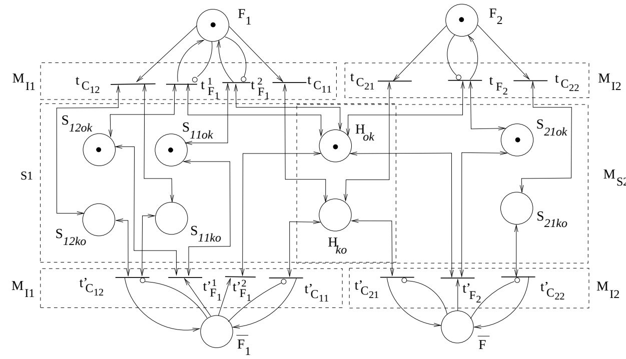


Figure 7. Two functions with a structural dependency

presented. Interfacing rules have been defined in formal terms. However, the main rules are stated here in an informal manner.

Upstream and downstream M_I have the same number of immediate transitions and the arcs that are connected to these transitions are built in a systematic way:

- **Upstream M_I:** It contains one function transition t_F for each series (set of) component(s), to mark the function's up state place, and one component transition t_{Cx} for each series, distinct component that has a direct impact on the functional model, to unmark the function's up state place.

  - Each t_F is linked by an inhibitor arc to the function's up state place, by an arc to the function's up state place and by one bidirectional arc to each initial (ok) component's place;
  - Each t_{Cx} is linked by an arc to the function's up state place and by one bidirectional arc to each failure component's place.

- **Downstream M_I:** It contains one function transition t'_F for each series (set of) component(s), to unmark the function's failure state place, and one component transition t'_{Cx} for each series, distinct component that has a direct impact on the functional model, to mark the function's failure state place.

  - Each t'_F is linked by an arc to the function's failure state place and by one bidirectional arc to each initial (ok) component's place;
  - Each t'_{Cx} is linked by an inhibitor arc to the function's failure state place, by an arc from the function's failure state place and by one bidirectional arc to each component's failure place.

4. Refinement of the structural model

We assume that the structural model is organized in a modular manner, i.e., it is composed of sub-models representing the behavior of the system's components and their interactions. For several reasons, the first model that is built, starting from the functional-level model, may be not very detailed. One of these reasons could be the lack of information in the early system's selection and development phases. Another reason could be the complexity of the system to be modeled. To master this complexity a high level model is built and then refined progressively.

As soon as more detailed information is available concerning the system's composition and events governing component evolution, the structural model can be refined.

Another refinement may be done regarding event distributions. Indeed, an assumption is made that all events governing the system's behavior are exponentially distributed, which, in some cases, is not a good assumption. In particular, failure rates of some components may increase over time.

Model refinement allows detailed behavior to be taken into account and leads to more detailed results compared to those obtained from a high level model. In turn, these detailed results may help in selecting alternative solutions for a given structure. For our purpose, we consider three types of refinement: Component, state/event and distribution. Given the fact that the system's model is modular, refinement of a component's behavior is undertaken within the component sub-model and special attention should be paid to its interactions with the other sub-models. However, in this paper due to the lack of space, we will mainly address the new dependencies created by the refinement, without discussing those already existing.

Component refinement consists in replacing a component by two or more components. From a modeling point of view, such a refinement leads to the transformation of the component's sub-model into another sub-model. Our approach is to use the same transformation rules as those used for the interface model presented in section 3.

State/event fine-tuning consists in replacing, by a subnet, the place/transition corresponding to this state/event. We define basic refinement cases, whose combination covers most usual possibilities of state/event refinement.

For distribution adjustment, we use the method of stages. Consider an event whose distribution is to be transformed into a non-exponential one. This method consists in replacing the transition associated with this event, by a subnet. We have adapted already published work to take into account dependencies between the component under consideration and components with which it interacts. This is done without changing the sub-models of the latters.

A section is devoted to each refinement type.

4.1. Component decomposition

Consider a single function achieved by a single software component on a single hardware component. Suppose that the software is itself composed of N components. Three basic possibilities are taken into account (combinations of these three cases model any kind of system):

- The N components are redundant, which means that they are structurally in parallel;
- The N components are in series;
- There are Q components in parallel and R+1 components in series (with Q+R=N).

Our goal is to use refinement rules identical, as far as possible, to the ones used in Section 3.

In the following we explain how a single component is replaced by its N components. These decompositions are respectively called *parallel*, *series* and *mixed*.

4.1.1. Parallel decomposition. Consider software S's decomposition into two redundant components S1 and S2. Thus, S's up state is the result of S1 or S2's up states, and S's failure state is the combined result of S1 and S2's failure states.

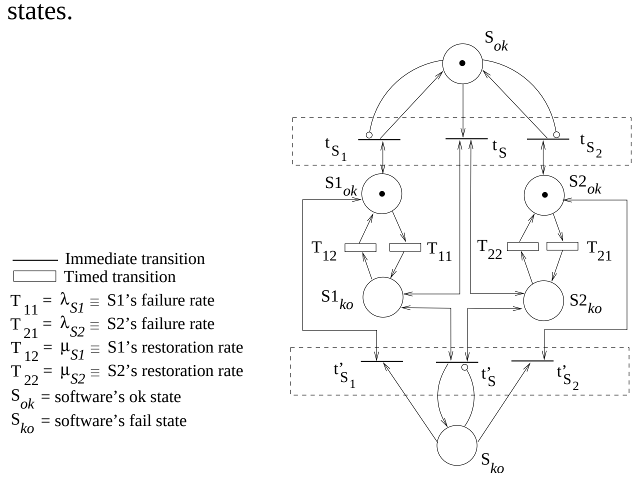


Figure 8. Parallel decomposition

Figure 8 gives a GSPN model of this case. The generalization to N components is straightforward. It is worth mentioning that the interface model between the system and its components is built exactly in the same manner as the interface model between a function and its associated components.

4.1.2. Series decomposition. Consider the decomposition of software S into two series components S1 and S2. Hence, this case is identical to the one presented in Fig. 5 when replacing F by S, H by S1 and S by S2.

4.1.3. Mixed decomposition. Suppose S is composed of three components: S1, S2 and S3, where S3 is in series with S1 and S2, that are redundant. This case is identical to the example presented in Fig. 6 when replacing F by S and H by S3.

4.1.4. Conclusion. In all the cases illustrated above, we have considered only one token in each initial place. K identical components can be modeled by a simple model with K tokens in each initial place. When refining the behavior of such components, a dissymmetry in their behavior may appear. Indeed, this is due to the fact that some components that have the same behavior at a given abstraction level, may exhibit a slightly different behavior when more details are taken into account. If this is the case, one has to modify the model of the current abstraction level before refinement. This may lead to changing the interface model either between the functional-level and the structural model, or between two successive structural models. This is the only case where refinement leads to changing the model at the higher level.

4.2. State/Event fine-tuning

In GSPNs, places correspond to system's states and timed transitions to events that guide state changes. The fine-tuning of places/transitions allows more detailed behavior to be modeled. Refinement has been studied in Petri nets ([13, 12]) and more recently in Time Petri Nets [8].

Our goal is to detail the system's behavior by refining the underlying GSPN. Our sole constraint is to ensure that the net's dynamic properties (aliveness, boundness and safeness), at each refinement step, are preserved. The main motivation for model refinement is to have more detailed results about system behavior, that better reflect reality.

We define three basic refinement cases. Combinations of these three cases cover most usual situations for dependability models' refinement. They are given in Table 1.

TR1 allows the replacement of one event by two competing events. It allows the event's separation into two other events with different rates. TR2 allows a sequential refinement of events, while TR3 allows the refinement of a state into two or more states. These transformations are illustrated on the following simple example.

Consider the hardware model given in Fig. 9(a). Several successive refinement steps are depicted in Figures 9(b), (c) and (d).

After a fault activation (T_1) two types of faults are distinguished: Temporary and permanent, with probability a and $1 - a$ respectively. Using TR3, we obtain the model depicted in Fig. 9(b).

To take into account error detection latency ($1/\delta$) for hardware components, we apply TR2 to transition T_{21} of

Table 1. State/Event refinement

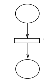
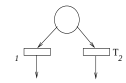
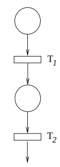
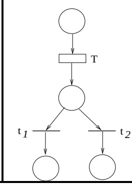
Initial model		
TR1: Separation into two events		Two competing events
TR2: Sequence of events		Refinement of the action represented by transition T
TR3: State refinement		$t_1 = p_1 \equiv$ prob. of firing t_1, $t_2 = p_2 \equiv$ prob. of firing t_2 and $p_1 + p_2 = 1$

Fig. 9(b). The resulting model is presented in Fig. 9(c).

Finally, we model the error detection efficiency by applying TR3. Detected errors allow immediate system's repair. We then add a perception latency (transition T_{2122}), Fig. 9(d). This latency is important to be modeled because, as long as the non-detected error is not perceived, the system is in a non-safe state. Repair can be performed only after perception of the effects of such errors.

This is a small example of a state/event refinement application. Other details can be added to the model using the cases presented in this section.

4.3. Distribution adjustment

It is well known that the exponential distribution assumption is not appropriate for all event rates. For example, due to error conditions accumulating with time and use, the failure rate of a software component might increase.

The possibility of including timed transitions with non-exponential firing time is provided by the method of stages [7]. This method transforms a non Markovian process into a Markovian one, by decomposing a state (with a non exponential firing time distribution) into a series of k successive states. Each of these k states will then have a negative exponential firing time distribution, to simulate an increasing rate. In GSPNs, a transition, referred to as extended transition, is replaced by a subnet to model the k stages.

The transformation of an exponential distribution into a non-exponential one might create new timing dependencies. Indeed, the occurrence of some events in other components might affect the extended transition. For example, the restart of a software component might lead to the restart of

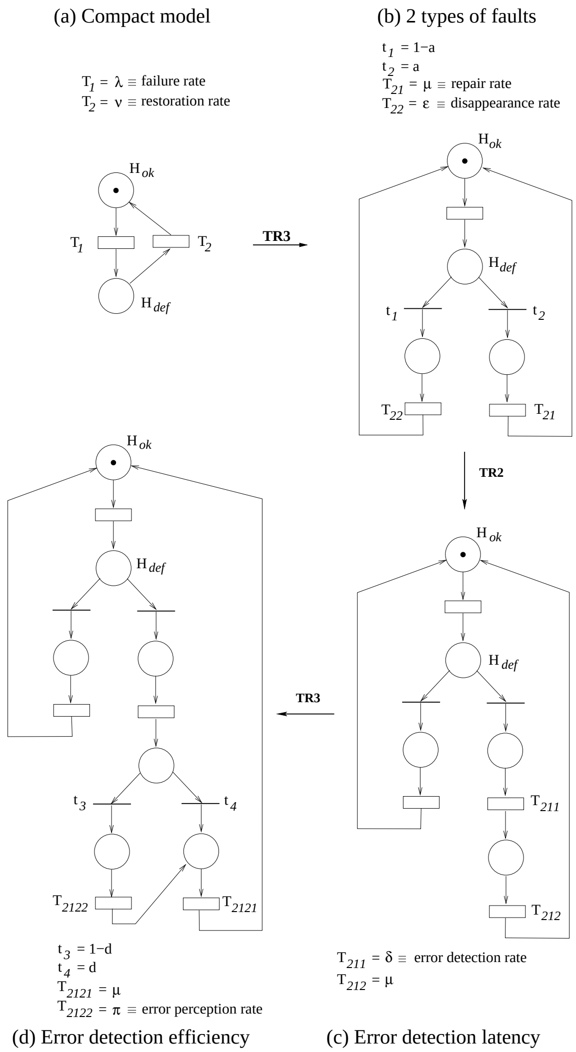


Figure 9. State/Event refinement

the component under consideration (that has an increasing failure rate) and thus stop the accumulation of error conditions, bringing back the software under consideration to its initial state.

In previously published work [1, 2], the dependency between events is modeled only by concurrent transitions enabled by the same place. This is not very convenient when several components interact with the component under consideration, as it could lead to changing their models. We have adapted this extension method to allow more flexibility and take into account this type of dependency.

The salient idea behind our approach is to refine the event's distribution without changing the sub-models of the components, whose behavior may affect the component under consideration (when assuming a non-exponential distribution).

In the rest of this section, we first present the extension method presented in [2] and then present our adapted extension method.

4.3.1. Previous work. Concerning the transitions' timers, three memory policies have been identified and studied in the literature, namely, resampling, age memory and enabling memory. The latter is well adapted to model the kind of dependency that is created when modeling system's dependability as mentioned above. It is defined as follows: At each transition firing, the timers of all the timed transitions that are disabled by this transition are restarted, whereas the timers of all the timed transitions that are not disabled hold their present values.

In [1] and [2] an application of the enabling memory policy in structural conflict situations has been given. It concerns the initial model of Fig. 10, in which transition T_1 to be extended is in structural conflict with transition T_{res}.

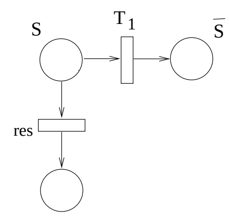


Figure 10. Initial model

When applying the enabling memory policy as given in [2] to transition T_1 of Fig. 10, the resulting model is presented in Fig. 11. In this figure, the k series stages are modeled by transitions t_{c1}, t_{c2}, T_1^1 and T_1^2 and places P_1, P_2 and P_3. Token moving in these places is controlled by the control places P_{c1}, P_{c2} and P_4.

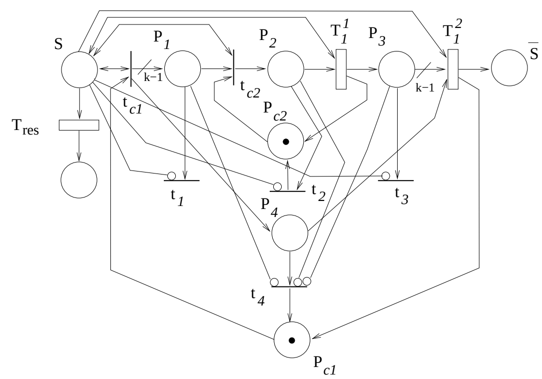


Figure 11. Enabling memory with structural conflict

After removal of the token from S by firing of transition T_{res}, the clearing of places P_1, P_2 and P_3 is accomplished in two steps. As soon as S becomes empty, immediate transitions t_1, t_2 and t_3 are fired as many times as needed to remove all tokens from these three places. At the end of this step, places P_{c2} and P_4 are marked with one token each. The return to the initial state is then performed by immediate transition t_4 that puts one token in place P_{c1}, after places P_1, P_2 and P_3 are empty.

4.3.2. Enabling memory with external dependencies. Our approach replaces the transition to be extended by two subnets: One internal to the component, to model its internal evolution, and a dependency subnet, that models its interaction with other components. The initial model is given in Figure 12(a). In this model we assume that T_1, T_{dis1} and T_{dis2} are exponentially distributed. Suppose that in refining T_1's distribution, its timer becomes dependent on on T_{dis1} and T_{dis2}. The transformed model is given in Fig. 12(b). A token is put in P_{dep} each time the timer of transition T_1 has to be restarted, due to the occurrence of an event that disables the event modeled by T_1 (firing of T_{dis1} or T_{dis2} in other components models). Like in the previous case, this is done in two steps. As soon as place P_{dep} is marked, t'_1, t'_2 and t'_3 are fired as many times as needed to remove all tokens from these three places. The return to the initial state is performed by transition t_4 that removes a token from place P_{dep} and puts one token in place P_{c1}, after places P_1, P_2 and P_3 are empty.

Note that transitions t'_1, t'_2 and t'_3 replace respectively t_1, t_2 and t_3. Also, we simplified Fig. 12(b), by replacing place P_4 by an inhibitor arc between t'_4 and P_{c1}. Thus, the two major differences between Figures 11 and 12(b) are: 1) Place P_1 of Fig. 12(b) is replaced by an inhibitor arc going from place P_{c1} to immediate transition t; 2) Place P_{dep}, that manages dependencies between this net and the rest of the model, is added.

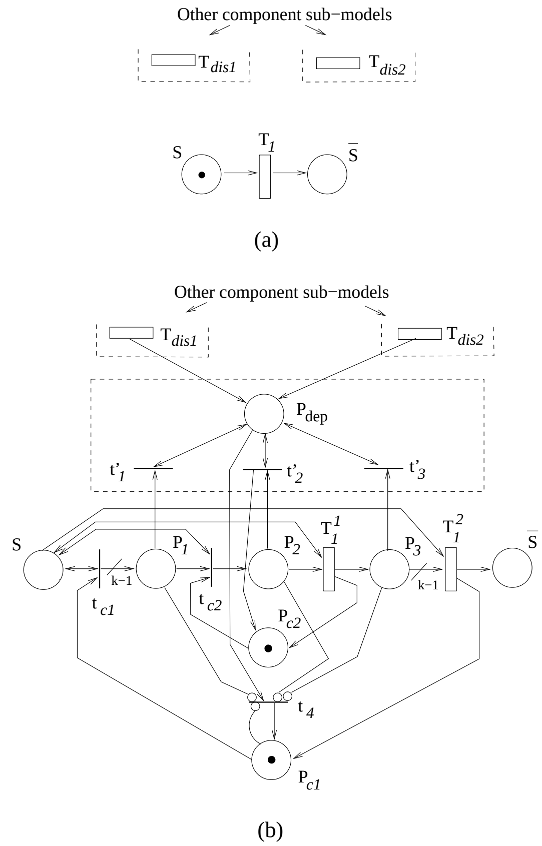


Figure 12. Enabling memory with external dependencies

5. Application to I&C systems

In this section we illustrate our modeling approach. Due to space limitations we only present a small part of it.

We start by presenting the functional-level model for a general I&C system. Then we describe how the high-level dependability model is built for one of the I&C systems. Finally we show some results concerning a small part of a detailed dependability model.

An I&C system performs five main functions: *Human-machine interface* (HMI), *processing* (PR), *archiving* (AR), *management of configuration data* (MD), and *interface with other parts of the I&C system* (IP). The functions are linked by the partial dependencies : HMI $\hookleftarrow$ $\{$AR, MD$\}$, PR $\hookleftarrow$ MD, AR $\hookleftarrow$ MD and IP $\hookleftarrow$ MD. These relations are modeled by the functional-level model depicted in Fig. 13.

To illustrate the second step of our modeling approach, we consider the example of an I&C system composed of five nodes connected by a *Local Area Network* (LAN). The mapping between the various nodes and their functions is given in Fig. 14. Note that while HMI is executed on four nodes, Node 5 runs three functions. Nodes 1 to 4 are composed of one computer each. Node 5 is fault-tolerant: It is composed of two redundant computers. The initial structural model of this I&C is built as follows:

- Node 1 to Node 3 – in each node, a single function is achieved by one software component on a hardware component. Its model is similar to the one presented in Figures 5 and 15 (that will be explained later);
- Node 4 – has two functions that are partially dependent. Its functional-level model will be similar to F_1 and F_2's functional-level model given in Fig. 4(b). Its structural model will be similar to the one depicted in Fig. 7, followed by a model slightly more complex than the one of Figure 15;
- Node 5 – is composed of two hardware components with three independent functions each. Its structural model is more complex than the one given in Figure 15 due to the redundancy.

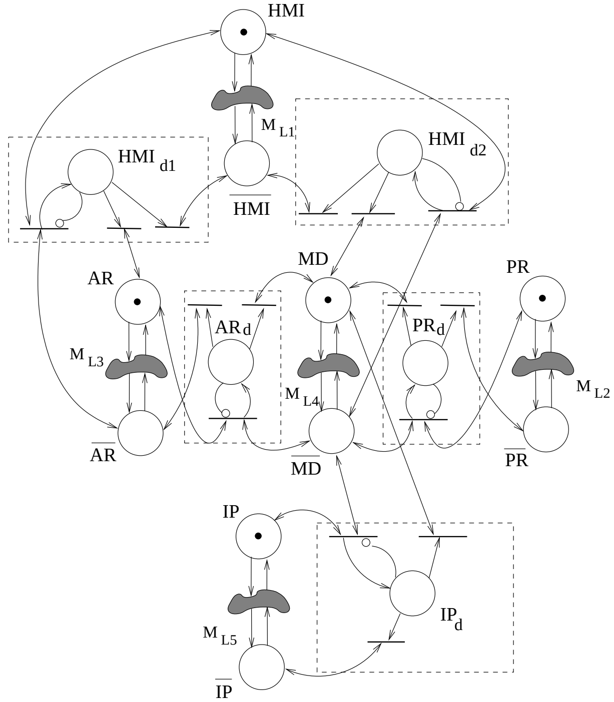


Figure 13. Functional-level model for I&C systems

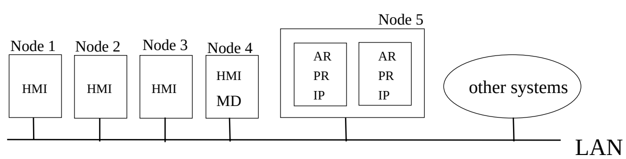


Figure 14. I&C structure

- LAN – the LAN is modeled at the structural level by the structural dependencies that it creates.

The complete high level dependability model for this system is composed of 41 places and 19 tokens. The other two I&C systems of our case study are composed of 76 places and 38 tokens and of 27 places and 13 tokens. It is worth mentionning that these model sizes correspond to the high-level models. After refinement, the models are much larger, as it is illustrated on the following example.

Let us consider the simple case of Fig. 5. The associated detailed structural model is given in Fig. 15 in which the S_{ko} place of Fig. 5, corresponds to either place S_{ed} or S_{ri}. The detailed GSPNs presented are obtained using the rules described in section 4.2. The following assumptions and notations are used:

- The activation rate of a hardware fault is λ_h (Tr_1), and of a software fault is λ_s (Tr_6);
- The probability that a hardware fault is temporary is t (tr_1). Such faults will disappear with rate ε (Tr_2);
- A permanent hardware fault (resp. software) is detected by the *fault-tolerance mechanisms* with probability d_h (resp. d_s for software faults). The detection rate is δ_h (Tr_3) for the hardware, and δ_s (Tr_7) for the software;
- The effects of a non detected error are perceived with rate π_h (Tr_4) for the hardware, and rate π_s (Tr_8) for the software;
- Errors detected in the hardware component require its repair: repair rate is μ (Tr_5);
- Permanent errors in the software may necessitate only a reset. The reset rate is ρ (Tr_9) and the probability that an error induced by the activation of a permanent software fault disappears with a reset is r (tr_7);
- If the error does not disappear with the software reset, a re-installation of the software is done. The software's re-installation rate is σ (Tr_{10}).

Note that a temporary fault in the hardware may propagate to the software (tr_{11}) with probability p. We stress that when the software component is in place S_{ed} or S_{ri}, it is in fact not available, i.e., in a failure state.

Also, when the hardware is in the repair state, the software is on hold. The software will be reset or re-installed as soon as the hardware repair is finished. Due to the size of the subsequent model, this case is not represented here.

Thus, from the original 4 places model, we have a 15 places model after refinement.

6. Conclusions

Our modeling approach follows in the footsteps of most of the existing work on dependability modeling. Where this approach is unique is in the inclusion of the system's functional specifications into the dependability model, by means of a functional-level model. Also, it allows modeling of one system from its functional specification up to its implementation. The existing refinement techniques are conceived in order to preserve the result values. On the contrary, ours provides more accurate models and associated results.

Thus, the modeling approach presented in this papers gives a generally-applicable process for system's analysis, based on generalized stochastic Petri nets. This process involves a stepwise refinement in which dependencies are introduced at the appropriate level of refinement. A careful and precise definition of the constructs and of the refinement process is given. Indeed, we have shown how starting from functional specifications, a functional-level model can be

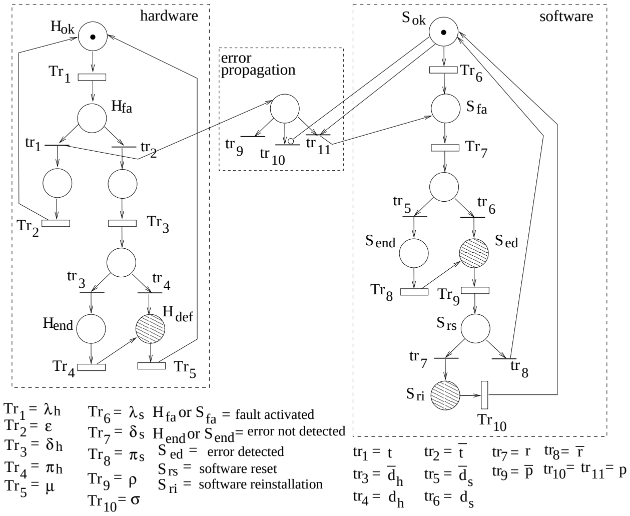


Figure 15. Structural model of a software and a hardware components

transformed progressively into a dependability model taking into account the system's structure. We have also shown how the structural model can be refined to incorporate more detailed information of the system's behavior. Refinement is a very powerful tool for mastering progressively model construction. It will allow experimented, but not necessarily specially-trained, modelers to analyze the dependability of one or several systems and compare their dependability at the same level of modeling abstraction, if required.

The approach was illustrated here on simple examples related to a specific structure of an instrumentation and control system in power plants. However, we have applied this approach to three different I&C systems to identify their strong and weak points, in order to select the most appropriate one.

Acknowledgements

The authors wish to thank Mohamed Kâaniche for his helpful comments on an earlier version of this paper. We also wish to thank the anonymous reviewers for their useful suggestions for improvement.

References

[1] M.A. Ajmone Marsan and G. Chiola. On Petri Nets with Deterministic and Exponentially Distributed Firing Time. LNCS 266:132–145, 1987.

[2] M.A. Ajmone Marsan, G. Balbo, G. Conte, S. Donatelli and G. Franchescinis. *Modelling with Generalized Stochastic Petri Nets*. Series in Parallel Computing, Wiley, 1995.

[3] C. Betous-Almeida and K. Kanoun. Dependability Evaluation: From Functional to Structural Modelling. *Proc. 20th Int. Conf. on Computer Safety, Reliability and Security (SAFECOMP 2001)*, LNCS 2187:227–237, 2001.

[4] C. Béounes and *al.* SURF-2: A Program for Dependability Evaluation of Complex Hardware and Software Systems. *Proc. 23rd. Int. Symp. on Fault-Tolerant Computing (FTCS-23)*, 668–673, 1993.

[5] A. Bondavalli, I. Mura and K.S. Trivedi. Dependability Modelling and Sensitivity Analysis of Scheduled Maintenance Systems. *Proc. 3rd European Dependable Computing Conf. (EDCC-3)*, LNCS 1667:7–23, 1999.

[6] P. Chen, S.C. Bruell and G. Balbo. Alternative Methods for Incorporating Non-Exponential Distributions into Stochastic Timed Petri Net. *Proc. of the 3rd Int. Workshop on Petri Nets and Performance Models (PNPM'89)*, IEEE Computer Society Press:187–197, Decembre 1989.

[7] D.R. Cox and H.D. Miller. *The Theory of Stochastic Processes*. Chapman and Hall Ltd, 1965.

[8] M. Felder, A. Gargantini and A. Morzenti. A Theory of Implementation and Refinement in Timed Petri Net. *Theoretical Computer Science*, 202(1–2):127–161, 1998.

[9] N. Fota, M. Kâaniche and K. Kanoun. Incremental Approach for Building Stochastic Petri Nets for Dependability Modeling. Statistical and Probabilistic Models in Reliability (D. C. Ionescuand N. Limnios, Eds.):321–335, Birkhäuser, 1999.

[10] K. Kanoun, M. Borrel, T. Morteveille and A. Peytavin. Availability of CAUTRA, a Subset of the French Air Traffic Control System. *IEEE Trans. on Computers*, 48(5):528–535, May 1999.

[11] M. Rabah, and K. Kanoun. Dependability Evaluation of a Distributed Shared Memory Multiprocessor System. *Proc. 3rd European Dependable Computing Conf. (EDCC-3)*, LNCS 1667:42–59, 1999.

[12] I. Suzuki and T. Murata. A Method for Stepwise Refinement and Abstraction of Petri Net. *Journal of Computer and System Sciences*, 27:51–76, 1983.

[13] R. Valette. Analysis of Petri Nets by Stepwise Refinement. *Journal of Computer and System Sciences*, 18(1):35–46, February 1979.