A Methodology for Architectural-Level Reliability Risk Analysis

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Risk assessment is an essential process of every software risk management plan. Several risk assessment techniques are based on the subjective judgement of domain experts. Subjective risk assessment techniques are human intensive and error-prone. Risk assessment should be based on product attributes that we can quantitatively measure using product metrics.

This paper presents a methodology for reliability risk assessment at the early stages of the development lifecycle, namely the architecture level. We describe a heuristic risk assessment methodology that is based on dynamic metrics. The methodology uses dynamic complexity and dynamic coupling metrics to define complexity factors for the architecture elements (components and connectors). Severity analysis is performed using Failure Mode and Effect Analysis (FMEA) as applied to architecture models. We combine severity and complexity factors to develop heuristic risk factors for the architecture components and connectors. Based on analysis scenarios, we develop a risk assessment model that represents components, connectors, component risk factors, connector risk factors, and probabilities of component interactions. We also develop a risk analysis algorithm that aggregates risk factors of components and connectors to the architectural level. Using the risk aggregation and the risk analysis model, we show how to analyze the overall risk factor of the architecture as the function of the risk factors of its constituting components and connectors. A case study of a pacemaker architecture is used to illustrate the application of the methodology. The methodology is used to identify critical components and connectors and to investigate the sensitivity of the architecture risk factor to changes in the heuristic risk factors of the architecture elements.

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1 Introduction

The process of risk assessment is useful in identifying complex modules that require detailed inspection, estimating potentially troublesome modules, and estimating testing effort. According to NASA-STD-8719.13A [20] risk is a function of: the possible frequency of occurrence of an undesired event, the potential severity of resulting consequences, and the uncertainties associated with the frequency and severity. The STD-8719.13A standard [20] defines several types of risks, for example, availability risk, acceptance risk, performance risk, cost risk, schedule risk, etc. In this study, we are concerned with *reliability-based risk*, which depends on the probability that the software product will fail in the operational environment and the adversity of that failure.

For the purpose of this work, we adopt the definition in [23], which defines risk as a combination of two factors: probability of malfunctioning (failure) and the consequence of malfunctioning (severity). The probability of failure depends on the probability of existence of a fault combined with the possibility of exercising that fault. Whereas a *fault* is a feature of a system that precludes it from operating according to its specification, a *failure* occurs if the actual output of the system for some input differs from the expected output [36]. It is difficult to find exact estimates for the probability of failure of individual components in the system. Therefore, in this study we use *quantitative* factors that have been proven to be correlated with the probability of faults in the development of software components, such as complexity factors [18]. Moreover, to account for the probability of a fault manifesting itself into a failure, we use dynamic metrics. Dynamic metrics are used to measure the dynamic behavior of a system based on the premise that active components are sources of failures [34]. A fault may not manifest itself into a failure if never executed. Therefore, it is reasonable to use measurements obtained from executing the system models to perform risk assessment and analysis[1]. To study the second factor in the risk definition, the consequence of a failure (severity), we apply the MIL_STD 1629A Failure Mode and Effect Analysis [7].

Risk assessment can be performed at various development phases. Architecture models abstract design and implementation details and describe the system using compositions of components and connectors. A component can be as simple as an object, a class, or a procedure, and as elaborate as a package of classes or procedures. Connectors can be as simple as procedure calls or as elaborate as client-server protocols, links between distributed databases, or middlewares. We envisage that risk assessment at the architecture level is more beneficial than assessment at later development phases. An early detection and correction of problems is much less costly than detection at the code level. The architecture of a software is critical to all development phases. If the architecture is very complex, then design and coding are likely to take more time and produce more errors.

To conduct risk assessment at the architecture level, we use architecture models that we can simulate. Using simulation models gives our risk assessment methodology two advantages:

- First, we are able to obtain measurement of the dynamic behavior of components and connectors using dynamic metrics. These measures are used as dynamic complexity factors in developing risk indices for individual components and connectors.
- Second, we are able to study the consequences of a failure and its effect (severity) by simulating the architecture. Severity is the second factor used in developing risk indices for components and connectors.

The additional effort of developing these simulation models should be minimized. Therefore, the same architecture models developed by the system analyst during the system analysis phase should be used by the risk assessment and analysis methodology.

1.1 Motivations

We are concerned with risk assessment and analysis for software architectures. This work is motivated by the need to:

- Classify the system architecture elements according to their relative importance in terms of such factors as severity and complexity and identify components with high risk factor, which could require more development resources.
- Assess the system (subsystem) risk as an aggregate of individual component and connector risk factors. In large hierarchical systems, a system is composed of several subsystems, which in turn are composed of components and connectors. To classify subsystems according to risks, we need to develop algorithms that aggregate risk factors of the subsystem constituents to the subsystem level and hence we obtain and compare risk factors for subsystems.
- Develop automatable means to assess software product risks early in the development process. Risk assessment techniques should be based on quantitative metrics that can be evaluated systematically with little involvement of subjective measures from domain experts. Several tools enable us to obtain these metrics early at the specification levels [21,24]. Metrics for risk assessment should provide

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[1] We note that it is not sufficient to draw *general* correlation between the measured complexity of execution structure (using dynamics metrics) and the probability of failure from one case study. Several empirical studies are required to support the correlation.

measurement quantities that integrate risk assessment models, risk management plans, and mitigation strategies.

- Study the sensitivity of the application risk to variations in the risk factors of architecture components and connectors. This could guide the process of identifying critical architecture elements and analyze the effect of replacing components with new ones with improved quality, i.e. lower risk estimates.

1.2 Contributions

In this paper, we

- develop a new methodology to perform reliability risk assessment and reliability risk analysis at the architecture level.
- describe a heuristic risk assessment technique that is based on dynamic metrics. Our methodology uses dynamic complexity and dynamic coupling metrics, which we can obtain from simulating the software architecture specifications. Severity analysis is performed using Failure Mode and Effect Analysis (FMEA) with the aid of simulation runs to study the effect of a failure. We combine severity and complexity factors to develop heuristic risk factors for the architecture components and connectors.
- develop a new risk analysis model and a risk analysis algorithm that aggregates risk factors of components and connectors to the architecture level. We enhance Component Dependency Graphs (CDGs) [33,35] for the purpose of risk assessment and develop a risk aggregation algorithm that traverses the new graphs. Using the algorithm and the model, we show how to analyze the overall risk factor of the architecture as the function of the risk factors of its components and connectors.
- apply the proposed risk assessment methodology to a case study of a pacemaker to identify critical components and connectors.

This paper is organized as follows. Section 2 gives a short background on dynamic metrics and component dependency graphs on which our methodology is based. Section 3 discusses the methodology and its steps. Section 4 is an application of the methodology to the pacemaker case study. Section 5 summarizes the related work. Finally we conclude the paper and discuss future extensions.

2 Background

The work in this study is based on our earlier work on dynamic metrics and reliability modeling and analysis of software architectures. We use dynamic metrics [34] in our risk assessment methodology to develop complexity factors for architecture elements. We also enhance Component Dependency Graphs (CDGs) [33,35] for the purpose of risk assessment and develop a risk aggregation algorithm that traverses the new graphs. The following subsections give a quick overview on dynamic metrics and CDGs. For further detailed the reader is referred to [33, 34, 35].

2.1 Dynamic Metrics

The complex dynamic behavior of many real-time applications motivates a shift in interest from traditional static metrics to dynamic metrics. As components are invoked (executed), they become active for specific duration of time performing the requested functionalities. The most active set of components are sources of errors because they execute more frequently and experience numerous state changes. Therefore there is a higher probability that if a fault exists in an active component, it will easily manifest itself into a failure. For risk analysis at the architecture level, we are interested in the risks of a failure. Hence, we are motivated to assess the complexity of components and connectors as expected at run-time using dynamic metrics.

We perceive that, given advances in architecture modeling and simulation tools [21,24], we are able to evaluate dynamic coupling and dynamic complexity from executable architectures. In [34], we define a set of dynamic metrics for coupling and complexity, and we discuss the impact of these metrics on software quality attributes such as maintainability, reusability, and error-proneness. We also show how to use executable architecture models to obtain measurement for dynamic coupling and dynamic complexity. The dynamic coupling metric measures how active a link between two components (the connector) is during the execution of a particular scenario. This measure can then be prorated with the scenario profile to obtain a measure for connector complexity. The dynamic complexity metric measures the complexity of the dynamic behavior of a particular component in a given scenario. This measure can then be prorated with the scenario profile to obtain a measure for component complexity.

In this study, we use the dynamic metrics defined in [34] to obtain complexity factors for each architecture element. A complexity factor for each component is obtained using the dynamic complexity metric for the behavioral specification of that component. A complexity factor for each connector is obtained using the dynamic coupling metric for the messaging protocol of that connector. Both dynamic coupling and dynamic complexity metrics are discussed as part of the complexity analysis step of the proposed methodology (section 3.2).

2.2 Component Dependency Graphs

Component Dependency Graphs (CDGs) are introduced in [33] as probabilistic models for the purpose of reliability analysis at the architecture level. These graphs are further extended to analyze the reliability of distributed component-based systems [35]. A CDG is a reliability analysis model for component-based systems that extends control flow graphs. It models a system as a composition of subsystems, components, and connectors between components. CDGs are directed graphs that represent components, component reliabilities, connectors, connector (links and interface) reliabilities, and transition probabilities. CDGs are developed from scenarios. A scenario is a set of component interactions triggered by specific input stimulus [31]. One way to model scenarios is using the Unified Modeling Language (UML) [29] *sequence diagrams*. By using sequence diagrams, we are able to collect statistics required for building CDGs, such as the average execution time of a component in a scenario, the average execution time of a scenario, and possible interactions among components[2]. Scenarios are also related to the concept of operations and run-types used for operational profiles [19] as discussed in [33]. Figure 1 illustrates a simple CDG example consisting of four components, C_1, C_2, C_3, and C_4.

A CDG is defined as follows:

$CDG = <N,E,s,t>$; where N is set of nodes, E is set of edges, and s and t are the start and termination nodes, i.e. $N = \{n\}$, $E = \{e\}$,

$n = < C_i, RC_i, EC_i >$; where C_i is the name of the i[th] component, RC_i is component reliability, and EC_i is average execution time of a component C_i. EC_i is given by equation 1:

$$EC_i = \sum_{k=1}^{|S|} PS_k * Time(C_i)_{C_i \text{ in } S_k} \qquad \textit{Eq 1}$$

where:

PS_k : is the probability of execution of scenario S_k,

$|S|$: is the total number of scenarios,

$Time(C_i)$ is the execution time of C_i . $Time(C_i)$ can be estimated as the sum of its active time along its lifeline in a sequence diagram (for example, see the vertical rectangles attached to the lifeline of components in the sequence diagrams in Appendix B),

C_i is said to be in S_k if it participates in the execution of scenario S_k.

$e = <T_{ij}, RT_{ij}, PT_{ij}>$, where T_{ij} is transition from node n_i to n_j in the graph, RT_{ij} is transition reliability, PT_{ij} is transition probability. PT_{ij} is given by equation 2:

$$PT_{ij} = \sum_{k=1}^{|S|} PS_k * \left(\frac{|Interact(C_i, C_j)|}{|Interact(C_i, C_l)|_{l=1,..,N}} \right)_{C_i, C_j, C_l \text{ in } S_k \text{ and } l<>i} \qquad \textit{Eq 2}$$

where:

[2] For details about how to collect these parameters, we refer the reader to [33]

$|S|$: is the number of scenarios,

PS_k : is the probability of execution of scenario S_k,

N : is the number of components in the application, and

$|Interact(C_i,C_j)|$: is the number of times C_i interacts with C_j in a given scenario S_k.

Our risk assessment methodology does not use RC_i and RC_{ij}, instead risk factors for components and connectors are used as explained later in section 3.4.

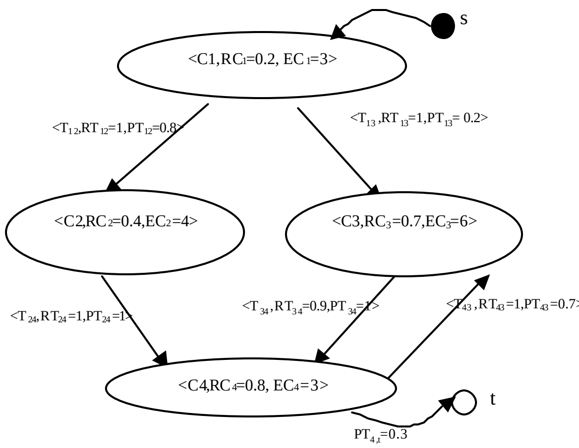


Figure 1 A sample CDG

Based on CDGs, an algorithm has been developed in [33] to analyze the reliability of the application and study the sensitivity of the application reliability to variations in the reliabilities of components and interfaces. In this study, we extend CDGs for the purpose of risk analysis. We use risk factors instead of reliability estimates and we show how to calculate the CDG parameters from simulating the architecture description of a system. We elaborate on CDGs in section 3.5 as part of the proposed risk assessment methodology.

3 The Risk Assessment Methodology

The proposed methodology is defined by the following steps:

1. Modeling the system architecture using an ADL (section 3.1),
2. Performing complexity analysis using simulation (section 3.2),
3. Performing severity analysis using FMEA and simulation runs (section 3.3),
4. Developing heuristic risk factors for components and connectors (section 3.4),
5. Developing CDGs for risk assessment purposes (section 3.5),
6. Performing risk assessment and analysis using a graph traversal algorithm (section 3.6).

3.1 Architecture Modeling

Software development based on architectures shifts the focus towards architecture elements such as components and connectors where connectors are treated as top-level constructs [28, 3]. Architecture Description Languages (ADLs) [1,30] enable the formalization of the description of a software architecture and hence enable the execution of some preliminary analysis to discover early stage problems before the detailed design phase. The literature is plentiful of ADLs that we can use to specify the architecture of a software system [17].

The dynamic behavior specifications of a software system describe how the system is expected to behave at run time. Risks associated with system failures at run time can be studied by analyzing the dynamic behavior of the system and of its individual components. Therefore, our risk analysis methodology is mostly concerned with the dynamic specifications of the software system architecture, which can be captured in terms of the interactions between components as well as behavior of individual components. In our methodology, we require that the ADL provides support for modeling:

- The interactions between components.
- The behavior of individual components.

The former can be specified using sequence diagrams, which define the sequence of interaction between components in a timely ordered manner. The latter can be specified using statecharts that define the component's states and how it responds to external stimuli according to its state. The Unified Modeling Language (UML) [29] is becoming the de facto standard for modeling software systems. UML defines modeling specifications that can be used to specify the dynamic aspects of an architecture. We use UML statecharts diagrams to specify the individual component behavior and UML sequence diagrams to specify interactions between components. However, UML does not specify how to simulate the architecture models. To simulate UML specifications, the Real-Time Object-Oriented Modeling (ROOM)

[27] can be used. ROOM is an ADL that can be used to simulate statechart specifications of individual components and sequence diagram specifications of component interactions.

Several tools are available to simulate ROOM and UML architecture descriptions [24, 21]. In this study, we use the ObjecTime tool [21] to simulate the architecture, obtain dynamic measurements, and study effect analysis. In the ROOM ADL, the architecture is specified using the component (actor) diagrams. Each component is specified using a ROOMchart (the ROOM equivalence of Harel statechart [8]). Each connector is specified as a protocol of message exchange between two components with ports indicating which messages are input and which are output from the port. For details about the ROOM modeling language we refer to [27]. The same study can be conducted using Rose Real-Time simulation environment [24], which integrates a ROOM simulation capability into UML modeling environment.

3.2 Complexity Analysis

Traditionally we measure system reliability in terms of time between failures or number of faults found during a specific period of time. Some empirical studies found a correlation between the number of faults found in a software and the complexity of the system [18]. The more complex the system is, the higher the probability that it will have faults. To improve software quality and develop risk mitigation strategies, we should be able to predict early on in the development lifecycle those components that are likely to have higher fault rates. Hence complexity metrics are used in our risk assessment technique. To incorporate the fact that risk assessment should take in consideration the probability of exercising the fault, we use dynamic metrics. In our study, we use dynamic complexity of statecharts and dynamic coupling between components as dynamic metrics of architecture elements [34]. These metrics are obtained at the specification level - statechart specification of components and scenarios of component interactions- which are different from traditional code level metrics.

3.2.1 Component Complexity

Software complexity metrics have been used by scientists and engineers for a long time. In 1976, McCabe introduced cyclomatic complexity measurement as an indicator for system quality in terms of testability and maintainability. Cyclomatic complexity is based on program graphs and is defined in equation 3.

$$VG=e-n+2 \qquad \textit{Eq. 3}$$

where: e=number of edges, n=number of nodes

In our study, we develop complexity factor for each component using the cyclomatic complexity of the statechart specification [8] of a component. For each execution scenario, say S_k, a subset of the statechart specification of the component is executed in terms of state entries, state exits, and fired transitions. This subset of the statechart model contains segments of specification code required to fire transitions, send messages to other components, check condition and triggers, etc. Hence, we are able to aggregate the cyclomatic complexity of the executed path for each component C_i for a scenario S_k. This measure is called operational complexity [34] and is denoted as $cpx_k(C_i)$

Sometimes, the large number of states in a statechart of a complex component can be reduced by breaking these states into separate sub-machines and packaging them within composite states. A composite state is composed of lower level states. In statecharts, transitions between composite states are cut into transition segments. A transition segment is part of the transition that belongs to a composite state. Transition points provide a basis for correlating different segments of the same transition. To estimate the cyclomatic complexity of the transition between composite states we sum the cyclomatic complexity of all transition segments, the exit code segment of the source node, and entry code segment of the destination node. For example in Figure 2, *VG* for the transition from state *s11* to *s22* is $VG_x(s11) + VG_a(t11) + VG_x(s1) + VG_a(t12) + VG_e(s1) + VG_a(t13) + VG_e(s22)$, where VG_x is the complexity of the *exit* code segment, VG_a is the complexity of the *action* code segment, and VG_e is the complexity of the *entry* code segment.

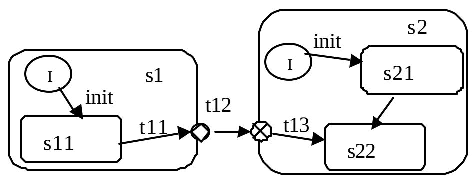


Figure 2 An example of a transition between composite states

To obtain the dynamic complexity metric from ROOM simulation models, we attribute the model with a complexity variable for each component. For each execution scenario, these variables are updated with the complexity measure of the thread of execution that is triggered for that particular scenario. At the end of the simulation, the simulation tool reports the dynamic complexity value for each component. Using the probabilities of scenarios (PS_k), we calculate the average operational complexity measure for each component as shown in equation 4.

$$cpx(C_i) = \sum_{k=1}^{|S|} PS_k \times cpx_k(C_i) \qquad \textit{Eq. 4}$$

where $|S|$ is the number of scenarios.

We then obtain a normalized complexity measure for each component by dividing the complexity measure of each component by the highest complexity value of all components in the architecture.

3.2.2 Connector Complexity

To assign complexity factors to architecture connectors we use dynamic coupling metrics. Dynamic coupling metrics are defined in [34] as export dynamic coupling and import dynamic coupling. The distinction between export and import coupling is mainly in the direction of data and control flow from/to a component in the software architecture. Export coupling measures coupling as a component sends (export) messages or data to other components. Import coupling measures coupling as a component receives (imports) messages or data from other components in the architecture.

For this case study, we use export dynamic coupling. Export coupling is used as opposed to import coupling because the structure of the CDG model (section 3.5) as well as the risk analysis algorithm (section 3.6) are mainly based of sequence of component interactions, i.e. one component invoking the next. Export coupling accounts for the fact that an error in a currently executing component could be exported to the called component (next in the execution list).

$EC_k(C_i,C_j)$, the export coupling for component C_i with respect to component C_j, is the percentage of the number of messages sent from C_i to C_j with respect to the total number of messages exchanged during the execution of the scenario S_k. Equation 5 shows the mathematical definition of $EC_k(C_i,C_j)$.

$$EC_k(C_i,C_j) = \frac{|\{M_k(C_i,C_j) \mid C_i,C_j \in A \wedge C_i \neq C_j\}|}{MT_k} \times 100 \qquad \textit{Eq. 5}$$

where, $M_k(C_i,C_j)$ is set of messages sent from component C_i to component C_j during the execution of scenario S_k, MT_k is the total number of messages exchanged between all components during the execution of scenario S_k, and A is the architecture.

The $EC_k(C_i,C_j)$ metric is defined for a specific execution scenario S_k. We can extend the scope of the metric to incorporate the probabilities of execution scenarios (or usage profile). We apply the metric to components for a given scenario, then average the measurements weighted by the probability of executing the scenario PS_k. Thus, the metric definition becomes:

$$EC(C_i,C_j) = \sum_{k=1}^{|S|} PS_k \times EC_k(C_i,C_j) \qquad \textit{Eq. 6}$$

where, $|S|$ is the total number of scenarios and PS_k is the probability of scenario S_k.

To calculate the connector complexity from ROOM simulation models, we attribute the model with variables that count the number of messages sent from one component to another for each execution scenario. Using the probabilities of scenarios, we calculate the average dynamic coupling metric for each connector.

3.3 Severity Analysis

The complexity of a component is not a sufficient measure for assessing the risk associated with its failure. We must take into consideration those components in the system which require special development resources due to the severity and/or criticality of their failures. Some components could have low complexity measure but they have a major safety role that could cause catastrophic failures.

Therefore the methodology takes into consideration the severity associated with each component based on how its failures affect the system operation.

Severity analysis is a procedure by which each potential failure mode is ranked according to the consequences of that failure mode. According to MIL_STD_1629A, severity considers the worst case consequence of a failure, determined by the degree of injury, property damage, system damage, and mission loss that could ultimately occur. The Failure Mode and Effect Analysis (FMEA) technique is a systematic approach that details all possible failure modes and identifies their resulting effect on the system [7]. FMEA is suitable for severity analysis at the architectural level. When analyzing failure modes, the analyst focuses on those modes for each individual architecture element (a component or a connector). First, the analyst identifies failure modes of architecture elements, studies the effect of these failures, ranks the severity of each failure, and identifies the worst-case effect on the system. Guidelines for conducting FMEA are given in [7]. The ability to simulate the architecture models helps the analyst in conducting the FMEA procedures, specially, in identifying the effect and severity of faults as described in the following subsections.

3.3.1 Identifying Failure Modes

In defining the possible failure modes of each architecture element, we can consider functional fault analysis, interface fault analysis, and piece part fault analysis [4]. Several fault injection and mutation testing techniques that have been developed at the code level can be ported for application at the specification level. However, for simplicity, we consider the following limited set of fault analysis techniques:

- *Failure modes of individual components*. In the architecture simulation models that we use, each component is specified by a statechart, which is state-based description of the component behavior. In identifying failure modes of individual components, we consider functional fault analysis and state-based fault analysis.
- *Failure modes of individual connectors*. In the architecture simulation models that we use, connectors are specified by the message protocol between ports of individual components. In identifying failure modes of individual connectors, we consider interface fault analysis where possible mismatches between messages and message parameters are considered. We can also consider protocol mismatch errors where possible mismatches between message sequencing are considered. For simplicity, we only considered interface faults in this study.

Sequence diagrams capture interactions between components. In identifying failure modes for component and connectors, we derive failure modes for each execution scenario. This facilitates the identification process since we focus on the role of a component or a connector in one particular scenario at a time.

3.3.2 Conducting Effect Analysis

The architecture simulation models can be used to facilitate the effect analysis process. By injecting a fault in the model the domain analyst can precisely study the failure propagation throughout the system. By simulating the faulty model, monitoring the simulation outputs, and comparing with expected outputs the analyst can identify and rank the effect of a component or a connector failure on the system.

3.3.3 Ranking Severity

The domain expert plays a major role in ranking the severity of a particular failure. The domain expert estimates the severity of the outcome of the simulation of a faulty module based on his experience with other systems in the same field. Our methodology helps the domain expert by providing him with the possible outcome of a simulation. Domain experts can rank severity in more than one way and for more than one purpose [15]. In this study, we use severity classifications that are recommended by MIL_STD_1629A [7] which are:

- Catastrophic: A failure may cause death or total system loss.
- Critical: A failure may cause severe injury, major property damage, major system damage, or major loss of production.
- Marginal: A failure may cause minor injury, minor property damage, minor system damage, or delay or minor loss of production.
- Minor: A failure is not serious enough to cause injury, property damage, or system damage, but will result in unscheduled maintenance or repair.

Through dynamic simulation and based on the effects observed after injecting faults to mimic the failure of components, we assign severity indices ($svrty_i$) of 0.25, 0.50, 0.75, and 0.95 to minor, marginal, critical, and catastrophic severity classes respectively. The domain expert determines a severity for the faulty component/connector for each simulation scenario by comparing the result of the simulation with the expected (normal) operation. The final severity value assigned to a particular component/connector is the worst-case severity (the highest value) as determined by the domain expert for each simulation run. The selection of values for the severity indices equally partitions the severity range and is based on the study conducted by Ammar *et.al.* [37].

3.4 Develop Reliability Risk Factors for Architecture Elements

In this step, we calculate a heuristic risk factor for each component and connector in the architecture based on the complexity and severity factors.

The heuristic risk factor for a *component* in the architecture is given by equation 7:

$$hrf_i = cpx_i \times svrty_i \qquad \textit{Eq. 7}$$

where:

$0 <= cpx_i <= 1$, is the dynamic complexity for the i[th] component normalized to the complexity value of the most complex component in the architecture.

$0 <= svrty_i < 1$ is the severity level for the i[th] component.

The heuristic risk factor for a *connector* in the architecture is given by equation 8:

$$hrf_{ij} = cpx_{ij} \times svrty_{ij} \qquad \textit{Eq. 8}$$

where:

$0 <= cpx_{ij} <= 1$, is the dynamic coupling for the connector between the i[th] and the j[th] components, which is given by $EC(C_i,C_j)$ (equation 6) normalized to the dynamic coupling value of the most complex connector in the architecture.

$0 <= svrty_{ij} < 1$ is the severity level for the connector between the i[th] and the j[th] components.

3.5 Develop Component Dependency Graphs

So far we have developed risk factors for architecture components and connectors. To assess a risk value for the system or for individual subsystems, in case of hierarchical system, that are composed of components and connectors, we need to define a risk aggregation algorithm. Our methodology utilizes the CDGs models developed in [33] and a risk aggregation algorithm to perform system level risk assessment. In this section, we discuss the CDG models that we adapt for risk analysis and in section 3.6 we discuss the risk aggregation algorithm.

To construct the CDGs, we follow the following guidelines:

- Estimate the probability of execution of each scenario by estimating the frequency of execution of each scenario relative to all other scenarios.
- For each scenario, estimate the execution time of each component using time stamps that are recorded in the simulation report. We then calculate the average execution time of each component using its execution time in each scenario and the probability of a scenario.
- Calculate the *transition probability* (section 2.2) from one component to another for all scenarios using the probability of a scenario and the transition probabilities in each scenario. The transition probability from one component to another in a given scenario is estimated from the percentage of the number of messages that the source component sends to the target component to the total number of messages that the source component send to all other components in the architecture.

- Using simulation, estimate the complexity factor for each component (as discussed in section 3.2.1) and assign severity index (as discussed in section 3.3). Obtain a risk factor for each component by combining the complexity factor and the severity index (as discussed in section 3.4).
- Using simulation, estimate the complexity factor for each connector (as discussed in section 3.2.2) and assign severity index (as discussed in section 3.3). Obtain a risk factor for each connector by combining the complexity factor and the severity index (as discussed in section 3.4).

We note the improvements that we made to estimate the parameters of the CDGs as compared to the technique developed in [33]:

- Instead of estimating the link transition probability from sequence diagrams we use simulation results to estimate the number of messages exchanged between components in a specific scenario together with the probability of each scenario. For example if component C_1 sends 4 messages to component C_2 and 6 messages for component C_3 then the probability of transition from C_1 to C_2 is 0.4 and from C_1 to C_3 is 0.6. Now consider two scenarios. In the first scenario, the messages sent from C_1 to C_2 and C_3 are as above. In the second scenario, component C_1 sends 5 messages to component C_2 and 5 messages to component C_3 then the probability of transition from C_1 to C_2 is 0.5 and from C_1 to C_3 is 0.5. Assuming equal probable scenarios, then the probability of transition from C_1 to C_2 in the CDG is 0.45 and from C_1 to C_3 is 0.55.
- In estimating the average execution times of each component we use simulation reports that capture the active periods of components. In the original CDGs, these were estimated from the sequence diagrams.

We attribute the CDG with the following parameters, which are used for risk assessment:

- We use heuristic component risk factors (hrf_i) for each node in the graph instead of its reliability estimates (RC_i). The risk factor for each component is based on dynamic complexity of the statechart of the component and the severity index calculated from conducting FMEA.
- We use heuristic connector risk factors (hrf_{ij}) for each link between nodes (n_i and n_j) instead of reliability estimates (RT_{ij}). Risk factors for each connector is calculated from dynamic coupling between components and the severity index calculated from conducting FMEA.

3.6 A Reliability Risk Analysis Algorithm

The architecture risk factor is obtained from aggregating the risk factors of individual components and connectors. For example, assuming a sequence of component execution of length "L" (i.e. L components are executed one after the other), then the risk factor for that sequence of execution is given by:

$$HRF = 1 - \prod_{i=1}^{L}(1 - hrf_i) \qquad \textit{Eq. 9}$$

After constructing the CDG model, we can analyze the risk of the application as the function of risk factors of components and connectors using the following risk assessment algorithm.

```
Algorithm
Procedure AssessRisk
Parameters
        consumes CDG, AE_appl //** average execution time for the application **//
        produces Risk_appl
Initialization:
        R_appl = R_temp = 1 //** temporary variables for (1-RiskFactor) **//
        Time = 0
Algorithm
push tuple <C_1, hrf_1, EC_1 >, Time, R_temp
while Stack not EMPTY do
        pop < C_i, hrf_i , EC_i >, Time, R_temp
        if Time > AE_appl  or C_i = t;      //** terminating node **//
                R_appl += R_temp ;          //** an OR path **//
        else
        ∀ < C_j ,hrf_j , EC_j > ∈ children(C_i)
                push (<C_j, hrf_j ,EC_j>, Time += EC_i , R_temp = R_temp*(1-hrf_i)*(1-hrf_ij )*PT_ij )  //**AND path**//
        end
end while
        Risk_appl = 1- R_appl
end Procedure AssessRisk
```

Figure 3 The Risk Aggregation Algorithm

The algorithm expands all branches of the CDG starting from the start node. The breadth expansions of the tree represent logical "OR" paths and are hence translated as the summation of aggregated risk factors weighted by the transition probability along each path. The depth of each path represents the sequential execution of components, the logical "AND", and is hence translated to multiplication of risk factors (in the form of $(1\text{-}hrf_i)$). The "AND" paths take into consideration the connector risk factors (hrf_{ij}). The depth expansion of a path terminates when the summation of execution time of that thread sums to the average execution time of a scenario or when the next node is a terminating node. Due to the probabilistic nature of the dependency graph, several loops might exist in traversing the graph. However, these loops don't lead to a deadlock by virtue of using the average execution time of a scenario to terminate the depth traversal of the graph. Therefore, deadlocks are not possible in executing the algorithm and a termination of the algorithm execution is evident.

The complexity of the algorithm is highly dependent on the number of times nodes in the graph are visited. The number of visits to a node is a function of several factors including: the average execution time of a scenario, the scenarios' profile, the average execution time of a component, patterns of component interactions as modeled in the scenarios, and the number of nodes in the graph. These factors are highly dependent on the architecture considered and hence on the structure of the graph, which is not uniform. Studying the effect of these factors on the complexity of the algorithm is outside the scope of this paper.

4 Case Study

We have selected a case study of a pacemaker device [6] to discuss the applicability of the proposed methodology. The pacemaker is a critical real-time application. An error in the software operation of the device can cause loss of the patient's life. Therefore, it is necessary to model its architecture in an executable form to validate the timing and deadline constraints. These executable architecture are also used, based on the proposed methodology, to conduct risk analysis. We use the ObjecTime simulation environment [21] to model and obtain simulation statistics.

4.1 System Description and Architecture Modeling

A cardiac pacemaker is an implanted device that assists cardiac functions when the underlying pathologies make the intrinsic heartbeats low. The pacemaker runs in either a programming mode or in one of operational modes. During programming, the programmer specifies the type of the operation mode in which the device will work. The operation mode depends on whether the Atrium (A), Ventricle (V), or both are being monitored or paced. The programmer also specifies whether the pacing is inhibit (I), triggered (T), or dual (D). For example, in the AVI operation mode, the Atrial portion (A) of the heart is paced (shocked), the Ventricular portion (V) of the heart is sensed (monitored), and the Atrial is only paced when a Ventricular sense does not occur (inhibited mode).

Figure 4 shows the pacemaker architecture model based on the specification in [6]. The pacemaker consists of the following components:

Reed_Switch (RS): A magnetically activated switch that must be closed before programming the device. The switch is used to avoid accidental programming by electric noise.

Coil_Driver (CD): Receives/sends pulses from/to the device programmer. These pulses are counted and then interpreted as a bit of value zero or one. These bits are then grouped into bytes and sent to the communication gnome. Positive and negative acknowledgments as well as programming bits are sent back to the programmer to confirm whether the device has been correctly programmed and the commands are validated.

Communication_Gnome (CG): Receives bytes from the coil driver, verifies these bytes as commands, and sends the commands to the Ventricular and Atrial models. It sends the positive and negative acknowledgments to the coil driver to verify command processing.

Ventricular_Model (VT) and *Atrial_Model (AR)*: These two components are similar in operation. They both could pace the heart and/or sense heartbeats. Once the pacemaker is programmed the magnet is removed from the Reed_Switch. The Atrial_Model and Ventricular_Model communicate together without further intervention. Only battery decay or some medical maintenance reasons force reprogramming.

Figure 4 shows the components in shaded boxes and the links between components as solid lines. The figure also shows the input/output port to the *Heart* as an external component as well as the two input ports to the *ReedSwitch* and the *Coil_Driver* components.

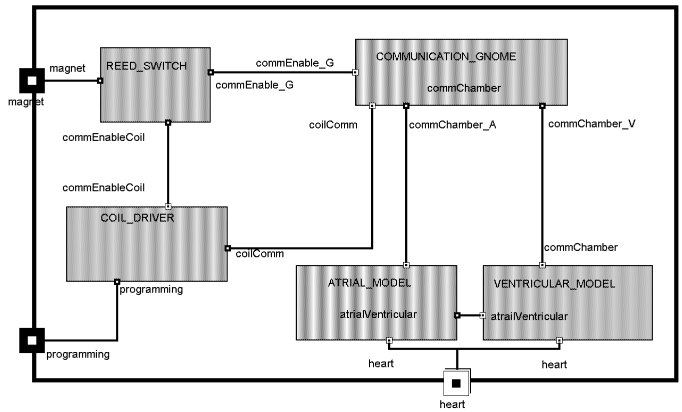


Figure 4 The architecture of the pacemaker example

The behavior of each of the components is modeled by a statechart [8]. A sample of the statechart specification for the CG component is shown in appendix A. As mentioned earlier, a pacemaker can be programmed to operate in one of several modes depending on which part of the heart is to be sensed and which part is to be paced. We use six scenarios. The first is *Programming* scenario in which the programmer sets the operation mode of the device. The programmer applies a magnet to enable communication with the device, then he sends pulses to the device which in turn interprets these pulses into programming bits. The device then sends back the data to acknowledge valid/invalid program. The second scenario is the *AVI* scenario. In this scenario, the VT component monitors the heart. When a heart beat is not sensed, the AR component paces the heart and a refractory period is then in effect. The third (fourth) scenario is the *VVI* (*AAI*) scenario in which the VT component (AR component) paces the heart when it does not sense any heart pulse. The fifth (sixth) scenario is the *VVT* (*AAT*) in which the VT component (AR component) continuously paces the heart.

The sequence diagrams for two scenarios (*Programming* and *AVI*) are shown in appendix B. The programming scenario is executed less frequently than any operation scenario because the device is only programmed during maintenance periods, which could be several months apart.

4.2 Complexity Analysis

4.2.1 Component Complexity Factors

For each scenario, we simulate the model to obtain the dynamic complexity measure (defined in section 3.2.1). Figure 5 illustrates the complexity measures for each component in each scenario as percentages of the overall complexity measure for that particular scenario. Domain experts determine scenario probabilities. This is similar to the problem of defining the operational profile of a system in which analysts study how the system will be used and determine the relative execution times of usage scenarios. There has been a lot of research on techniques to identify the operational profile of a system, such research has found great deal of interest in the field of software reliability [19]. For the pacemaker example, according to [6] we realize that inhibit modes are more frequent usages of the pacemaker than the triggered mode. We also observe that the execution of programming mode is much less frequent than the regular usage of the pacemaker in any of it operational modes. Hence, we assume the following scenarios profile: *Programming* = 0.01, *AVI* = 0.29, *AAI* =0.20, *VVI* = 0.20, *AAT* = 0.15, *VVT* = 0.15. Using the probability of each scenario, we develop the last row, the dynamic complexity measures for each component normalized to the highest complexity value (found to be the complexity of the AR component).

	RS	**CD**	**CG**	**AR**	**VT**
Programming (0.01)	8.3	67.4	24.3		
AVI (0.29)				53.2	46.8
AAT (0.15)				100	
AAI (0.20)				100	
VVI (0.15)					100
VVT (0.20)					100
% of architecture complexity	.083	0.674	0.243	50.428	48.572
Normalized to max. complexity	**0.002**	**0.013**	**0.005**	**1**	**0.963**

Figure 5 Complexity values for the pacemaker components

4.2.2 Connector Complexity Factor

For each scenario (*Programming*, *AVI*, *VVI*, *VVT*, *AAI*, *AAT*), we simulate the model to determine the dynamic coupling measure for each connector. We use the matrix representation for coupling, developed in [32] where rows and columns are indexed by components and the matrix cell represents coupling between the two components of the corresponding row and column. Components in the row index describe which component is sending (exporting) messages to components in the column index. For example, the cell (row=RS, column=CD) is the export coupling value from RS to CD while the cell (row=CD, column=RS) is the export coupling value from CD to RS (i.e. import from CD into RS). We then use the probability of each scenario to develop the final coupling matrix shown in Figure 6. The coupling values used in the matrix are normalized to the highest coupling value (found to be coupling value between AR and Heart).

	RS	*CD*	*CG*	*AR*	*VT*	*Programmer*	*Heart*
RS		0.0014	0.0014				
CD			0.003			0.011	
CG		0.002		0.0014	0.0014		
AR					0.25		1
VT				0.27			0.873
Programmer	0.0014	0.006					
Heart				0.123	0.307		

Figure 6 The coupling matrix for the pacemaker

4.3 Severity Analysis

To develop risk factors for each architecture element, we need to analyze the severity associated with components and connectors in the architecture. Basic failure modes of each architecture element and their effects on the overall system operation are studied according to the outlines described in section 3.3. The ROOM simulation model of the pacemaker architecture is used to study the effects of failures on a component-by-component and a connector-by-connector basis. Using ROOM models as a tool for FMEA, we inject faults (one at a time) into components and we run the simulator to study effects of a failure. Similarly, we inject faults (one at a time) into connectors and run the simulator and study the effects of a failure. Figure 7 illustrates sample results from assessing the severity of components and Figure 8 illustrates sample results from assessing the severity of connectors.

Component Name	Failure Mode	Cause of Failure	Effect of Failure	Criticality of effects
RS	Failed to enable communication	Error in translating magnet command	Unable to program the pacemaker, schedule maintenance task.	Minor
CD	Failed to generate good command	Fault in developing the command	Unable to program the pacemaker, schedule maintenance task.	Minor
CG	Failed to validate command	Fault in the validation procedure	Cannot program the pacemaker, schedule maintenance task.	Minor
	Mis-interpreting a VVT command for VVI	Fault in processing command routine	Heart is continuously triggered but device is still monitored by physician, need immediate fix or disable.	Marginal
VT	No heart pluses are sensed though heart is working fine.	Heart sensor is malfunctioning.	Heart is incorrectly paced, patient could be harmed by continuous pulses.	Critical
	Refract timer does not generate a timeout in an AVI mode	Timer not set correctly.	AR and VT are in refractoring state, no pace is generated for the heart, patient could die.	Catastrophic
AR	Wait timer does not generate a timeout in AAI mode	Timer not set correctly.	AR stuck at the wait state, no pacing is done to the heart	Catastrophic

Figure 7 FMEA table for the pacemaker components[3]

The worst case severity found for the RS, CD, CG, VT, and AR are Minor(0.25), Minor(0.25), Marginal(0.50), Catastrophic(0.95), and Catastrophic (0.95) respectively.

[3] The two components *Programmer* and *Heart* are not included in the complexity analysis since they are external components. They are included in figure 6 because in coupling analysis, we should consider coupling to external components as well.

Connector Name	Failure Mode	Cause of Failure	Effect of Failure	Criticality of effects
RS-CG	Failure to enable communication of the CG	Magnet malfunctioning. RS failed to generate message.	Pacemaker is not programmed, schedule maintenance task	Minor
RS-CD	Unable to disable communication of the CD with the programmer	Magnet malfunctioning. RS failed to generate correct disable message.	Pacemaker receives bits accidentally from communication hazards but device is never programmed because CG is disabled, schedule maintenance task.	Minor
CD-Programmer	Failed to acknowledge programming	Fault in coding the sending message	Pacemaker is not programmed, schedule maintenance task.	Minor
CD-CG	Failed to send bytes of program data to CG	Inappropriate count of number of bits in a byte.	Pacemaker is not programmed, schedule maintenance task.	Minor
CG-AR	Send incorrect command (ex ToOff instead of ToIdle)	Incorrect interpretation of program bytes	Incorrect operation mode and incorrect rate of pacing the heart. Device is still monitored by the physician, immediate maintenance or disable is required.	Marginal
CG-VT	Send incorrect command (ex ToOff instead of ToIdle	Incorrect interpretation of program bytes	Incorrect operation mode and incorrect rate of pacing the heart. Device is still monitored by the physician, immediate maintenance or disable is required.	Marginal
AR-Heart	Failed to sense heart in AAI mode	Sensor error.	Heart is always paced while patient condition requires only pacing the heart when no pulse is detected	Critical
	Failed to pace the heart in AVI mode	Pacing hardware device malfunctioning	Heart operation is irregular because it receives no pacing.	Catastrophic
VT-AR	VT failed to inform AR of finishing refractoring in AVI mode	Timing mismatches between AR and VT operation.	Failure to pace the heart.	Catastrophic

Figure 8 FMEA table for the pacemaker connectors

4.4 Developing Risk Factors

To obtain the component heuristic risk factors, we use equation 7 (section 3.4), the component complexity factors (section 4.2.1), and severity indices (section 4.3). Figure 9 shows the heuristic risk factors for the pacemaker components.

	RS	CD	CG	AR	VT
Dynamic Complexity	0.002	0.013	0.005	1	0.963
Severity	0.25	0.25	0.5	0.95	0.95
Risk Factors	***0.0005***	***0.00325***	***0.0025***	***0.95***	***0.91485***

Figure 9 Risk factors for components of the pacemaker example using dynamic complexity

The results from Figure 9 shows that the VT and AR components are the highest risk components in the architecture. To compare the risk factors based on dynamic metrics and those based on static metrics, consider the two static metrics the *Coupling Between Object* classes (CBO) [5] and *Number of Associations* (NAS) [9]. Figure 10 shows risk factors calculated based on CBO and NAS.

	RS	CD	CG	AR	VT
CBO	0.47	0.8	1	0.6	0.6
NAS	0.75	0.75	1	0.75	0.75
Severity	0.25	0.25	0.5	0.95	0.95
Risk factors based on CBO	***0.119***	***0.2***	***0.5***	***0.57***	***0.57***
Risk factors based on NAS	***0.1875***	***0.1875***	***0.5***	***0.71***	***0.71***

Figure 10 Risk factors for components of the pacemaker example using static complexity

Figure 11 compares the risk factors based on static and dynamic metrics. It is obvious from the figure that using dynamic metrics distinguishes the AR and VT components as high-risk components as compared to RS, CD, and CG components. Using static metrics does not significantly distinguish the AR and VT as high-risk components from the rest of the components, in fact, CG is considered at the same risk level as the AR and VT if risk factors are based on static metrics. In the pacemaker architecture, AR and VT components control the operation of the heart and hence they are the highest risk components. CG controls the programming, which is monitored by the physician before the device is put into operation. Though these results strengthen the rationale for using dynamic metrics as opposed to static metrics, they are insufficient, as results from a single case study, to draw a general meaningful conclusion that dynamic metrics are correlated to probability of failures. Application of the methodology to multiple case studies would provide more evidence to support/weaken the decision of using dynamic metrics, this is the subject of future empirical validation studies.

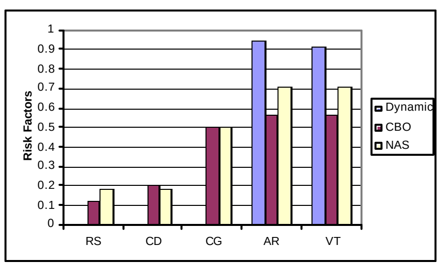


Figure 11 Comparison between risk factors using dynamic and static metrics

To obtain the connector heuristic risk factors, we use equation 7 (section 3.4), the connector complexity factors (section 4.2.2), and severity indices (section 4.3). Figure 12 illustrates the heuristic risk factors for the pacemaker connectors.

Connector Risk Factors	RS	CD	CG	AR	VT	Programmer	Heart
RS		0.00035	0.00035				
CD			0.00075			0.00275	
CG		0.0005		0.0007	0.0007		
AR					**0.2375**		**0.95**
VT				**0.2565**			**0.82935**
Programmer	0.00035	.0015					
Heart				0.11685	**0.29165**		

Figure 12 Risk factors for connectors in the pacemaker example

From Figure 12, we can identify connectors of highest risks that deserve more development resources and testing. High risk connectors indicate that the interfaces and the communication protocol of messages exchanged over that connector should be carefully implemented. Figure 12 illustrates that the connectors between VT, AR, and the Heart are those of the highest risk in the architecture.

4.5 Constructing the pacemaker's CDG

Using the guidelines of section 3.5 and in [33], we develop the CDG for the pacemaker using the six scenarios (*Programming*, *AVI*, *VVI*, *VVT*, *AAI*, and *AAT*). Figure 13 illustrates the CDG for the pacemaker. We use the pacemaker's CDG to conduct risk analysis as described in the following section.

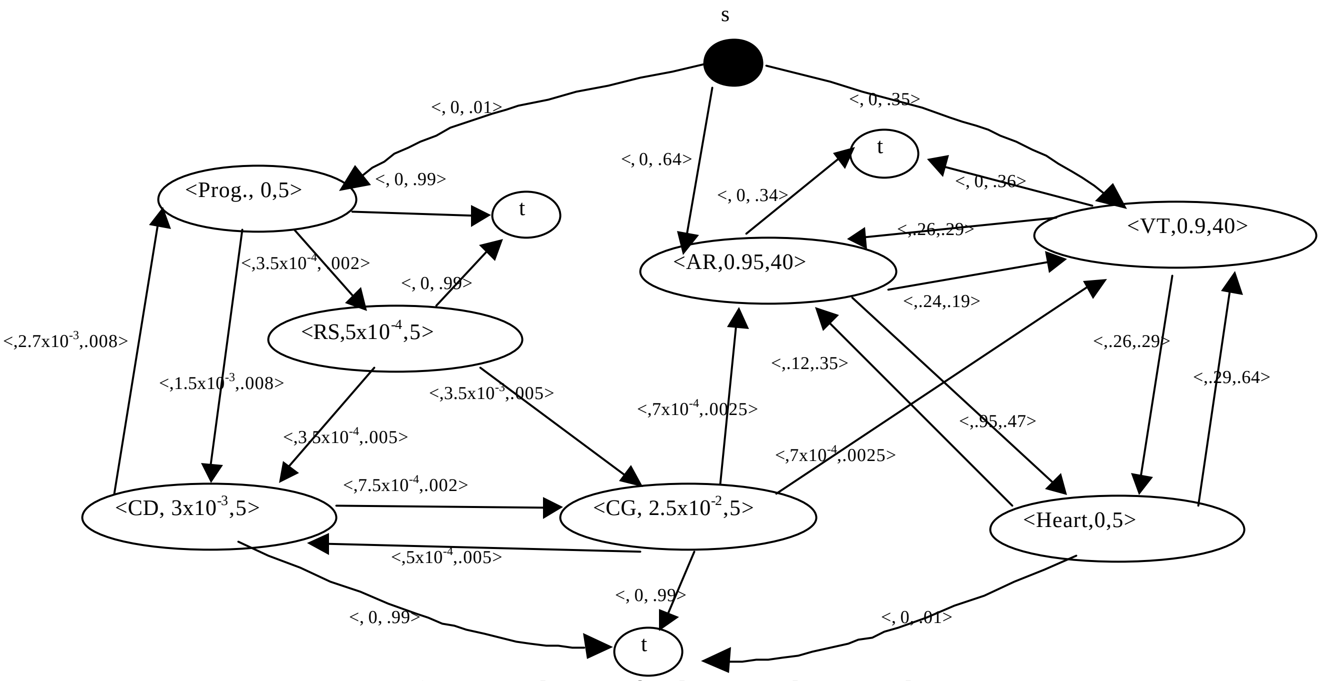


Figure 13 The CDG for the pacemaker example

4.6 Performing Risk Analysis

We implemented the algorithm defined in section 3.6, and applied it to the CDG of the pacemaker shown in Figure 13. In this section, we discuss two types of analysis: *risk assessment* and *sensitivity analysis*. These analysis methods make use of the algorithm and the pacemaker CDG described earlier.

4.6.1 Risk Assessment

We can use the algorithm as applied to the CDG graph to assess the overall risk of the pacemaker as an aggregation of the risk factors of components and connectors in the architecture. This gives an overall estimate of the risk of the pacemaker that is found to be ~ 0.9. This indicates that the pacemaker architecture is very critical and failures are most likely to be catastrophic.

Using the algorithm and the graph to aggregate risk factors is useful for analyzing the risks in complex hierarchical systems. Such systems are usually decomposed into subsystems where each subsystem is composed of a number of components. We can apply the proposed methodology to various individual subsystems (which have their own CDGs). We obtain a risk factor for a subsystem using risk factors of its individual components. Then we use the results to compare subsystems risk factors; i.e. relative ranking of subsystem risk factors as opposed to calculating one factor for the system risk. The application of this approach to large hierarchical system is the subject of future work.

4.6.2 Sensitivity Analysis

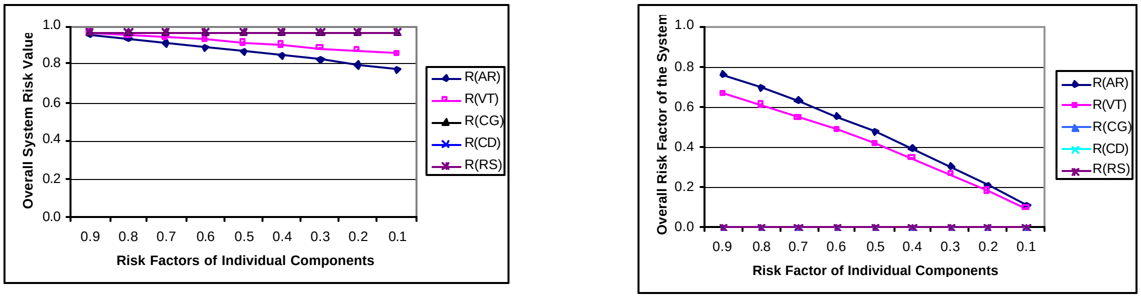
Given that we already have the individual component risk factors (in the first three steps) and the overall system or subsystems risk factors (in the first five steps), we can conduct another type of analysis that reveals the effect of uncertainties in any of the risk factors (that we calculated so far) on the overall risk value of the system. This is useful in many applications because with the involvement of domain experts in the evaluation of the severity as well as the operation complexity, a human error may occur which can be accounted for as uncertainty in a specific risk value. This type of analysis is useful when the analyst is uncertain about some of the parameters that he/she uses in developing the CDG risk model. If we have a range of values for the parameter that we are uncertain about, the analyst could look this range up in a sensitivity graph and determines the corresponding uncertainty in the system/subsystem risk value. This is particularly useful in applications where it is difficult for domain experts to provide usage data or severity assessments.

In this type of analysis, we analyze the sensitivity of the estimated system risk as a function of variations in the component and connector risk factors. For instance, we can study uncertainties in severity level of components or uncertainties in severity level of connectors. This type of analysis is also useful to study the effect of replacing one component with another of improved quality, i.e. lower risk factor.

As an example of sensitivity analysis, consider the following cases:

a) Sensitivity to Uncertainties in Component Risk Factors

Figure 14 illustrates the variations in the overall risk value of the pacemaker as a function of changes in the risk factors of individual components one at a time. Figure 14-a illustrates the uncertainty in the system risk value obtained in section 4.6.1 using the risk factors of components and connectors obtained in section 4.4 and varying the risk factor of one component at a time. Figure 14-b illustrates the uncertainty in the system risk value by varying the risk factor of one component at a time and assuming zero-risk for the rest of the components. These results indicate that uncertainties in the risk factors of the AR and VT components are more likely to affect the overall system risk.

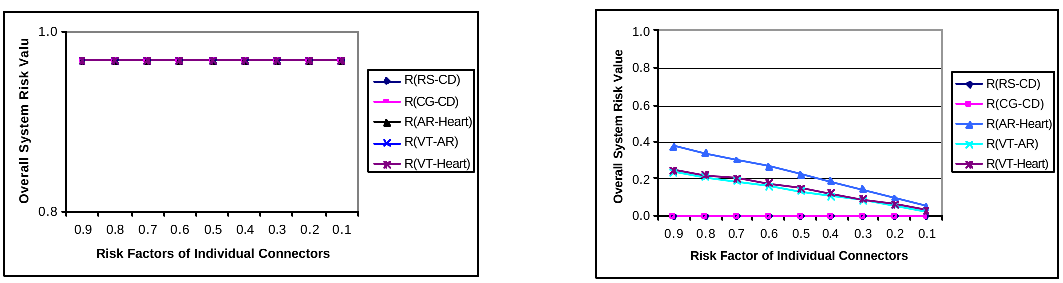


(a) (b)

Figure 14 Application risk factor as function of *component* risk factors (one at a time) using, a) risk factors obtained in section 4.4 for the rest of the components, b) zero risk factors for the rest of the components

b) Sensitivity to Uncertainties in Connector Risk Factors

Figure 15 illustrates the variations in the overall risk value of the pacemaker as a function of changes in the risk factors of individual connectors one at a time. Figure 15-a illustrates the uncertainty in the system risk value obtained in section 4.6.1 using the risk factors of components and connectors obtained in section 4.4 and varying the risk factor of one connector at a time. Figure 15-b illustrates the uncertainty in the system risk estimate by varying the risk factor of one connector at a time and assuming zero-risk for the rest of the connectors.



(a) (b)

Figure 15 Application risk factor as function of *connector* risk factors (one at a time) using, a) risk factors obtained in section 4.4 for the rest of the connectors, b) zero risk factors for the rest of the connectors

Note: In figure 14 and 15, some of the lines overlap, which means they have similar behavior (effect).

4.7 Results

Using results obtained from applying our methodology, the analyst can:

- Decide which components in the architecture require more development resources (e.g. testing, quality control, etc.). From Figure 9, we identify the VT and the AR components are the highest risk components. This result is intuitively correct since these two components are the most active and the most critical components that directly control the operation of the heart.
- Decide which connectors in the architecture are of highest risk. A high risk connector indicates that the interfaces between the corresponding components and the messaging protocol should be carefully

designed. From Figure 12, we identify that the connection between the VT, AR, and Heart components are the highest risk connectors. This result is intuitively correct in the context of the pacemaker example since these connectors deliver critical messages controlling the heart operation such as sensing and pacing.

- Study how uncertainties in component risk factors affect the overall risk value of the system. From Figure 14, we identify that the increase in the risk factors VT and the AR components highly affect the risk factor of the system as compared to any increase in the risk factors of the CD, CG, or RS components which have almost negligible effect.
- Study how uncertainties in connector risk factors affect the overall risk value of the system. From Figure 15-a, we identify that uncertainties in the connectors risk factors do not have a significant impact on the estimated risk factor of the system. However, if we consider zero-risk for the rest of the component and connectors, we find that the increase in the risk factor of connection between AR and Heart components highly affect the risk factor of the system as compared to any increase in the risk factors of the connection between CG and CD. This could be interpreted for the pacemaker example as follows: in the context where risk factors of components are considered, the system risk becomes more dependent on the component risk factors rather than the connector risk factors.

5 Related Work

In this paper, we present a methodology for risk assessment that uses dynamic complexity metrics and severity ranking. In the sequel we summarize research work related to this work.

Complexity metrics provide substantial information for distinguishing differences between software systems whose reliability is being modeled. There are some predictive models that incorporate a functional relationship between program errors measures and software complexity metrics [14]. Software complexity measures are also used for developing and executing test suites [10]. Therefore, static complexity is used to assess the quality of a software. The level of exposure of a module is a function of its execution environment. Hence, dynamic complexity [13] evolved as a measure of complexity of the subset of code that is actually executed. Dynamic complexity was discussed by Munson *et.al.* [18] for reliability assessment purposes. The authors emphasize that it is essential to not only consider complex modules but how frequently they are executed. They define execution profiles for modules that reflect what percentage of time a module is executing, and hence derived functional complexity and operational complexity as dynamic complexity metrics. Ammar *et.al.* [2] extend dynamic complexity definitions to incorporate concurrency complexity. They further use Coloured Petri Nets models to measure dynamic complexity of software systems using simulation reports. Yacoub *et. al.* [34] define dynamic metrics that include dynamic complexity and dynamic coupling metrics to measure the quality of architectures. Their approach is based on dynamic execution of UML statechart specification of a component and the complexity metrics proposed is based on simulation reports. In this paper, we use dynamic metrics as measures of the components and connectors complexities.

The work by Kazman *et.al.* [39] addresses the problem of measuring architecture complexity. The approach involves determining the proportion of the architecture covered by particular patterns (architecture regularity), and the number of different types of patterns composing the architecture. A pattern recognition system is used to analyze the regularity of the architecture and to explore some properties such as fan-in and fan-out of elements (i.e., the number of elements that control, or are controlled by, an element, respectively), and particular design problems (e.g., layer bridging). The *Architecture Trade-Offs Analysis Method* (ATAM) [40] is concerned with the development of techniques and models to assess and evaluate software architectures with respect to analytical attributes such as performance and availability and other qualitative attributes based on formal inspections such as modifiability, safety, and security. The methodology is heavily scenario-based, it uses attribute-specific questions to ensure proper coverage of an attribute by a specific scenario. Each component is then assigned a quality measure that is a combination of the quality attributes gathered from answers to the attribute-specific questions. The ATAM method helps in discovering risks at early development stages, and in defining sensitivity and trade-off points (points where change could affect multiple attribute) in a candidate architecture. Although the technique formalizes the steps of evaluating an architecture, it is still mostly qualitative (a question-answer approach).

Criticality analysis has gained the interest of many researches and has been integrated in FMEA procedures, i.e. Failure Mode Criticality and Effect Analysis (FMECA). In FEMCA, severity of the effect of failures is considered. The most commonly used methods for assessing criticality in FEMCA are : Risk Priority Number (RPN) [25], the MIL_STD 1629A Criticality Number ranking [7], and the multi-criteria Pareto ranking [26]. In RPN, the risk number is function of occurrence ranking, severity ranking, and detection ranking. In the MIL_STD 1629A FMECA, criticality number is function of failure mode ratio, failure effect probability, failure rate of the component, and time period of interest. Pareto ranking is an enhancement to the MIL_STD 1629A FMECA criteria in which severity is measured on a ratio scale instead of ordinal scale. These methods are mostly developed for hardware design and manufacturing. The main drawback of these method is that they use failure rate values or probability of failure which are difficult to estimate. In our study, we use factors that affect the probability of finding fault and executing that fault, i.e., dynamic metrics.

There are several ongoing fault-risk assessment approaches and tools that mainly uses static product metrics or process metrics. For example, the Nortel's Enhanced Measurement for Early Risk Assessment of Latent Defects system, EMERALD, is an example of an analysis system in production use for assessing the risk of faults [11]. Bellcore's Analyzer for Reducing Module Operational Risk, ARMOR, is a prototype software-risk analysis tool [16]. Bellcore's Software Architecture Based Analysis, SABA, technology has been integrated into Lucent Technologies' software update risk assessment process [22].

The CDGs used in our methodology resembles the task and function graphs developed by Smith *et. al.* [38] for performance engineering, where function times are estimated and then the overall time of the application is estimated from the graphs. The proposed risk analysis methodology and the performance engineering methodology both use estimates for component (module) execution times. However, the proposed methodology is concerned with reliability risk analysis while Smith's methodology is more concerned with performances analysis of architectures.

6 Conclusion and Future Work

This paper presents a methodology for risk analysis of software architectures. The proposed methodology is based on the statechart specification of individual components and on the scenarios of component interactions. The execution profiles of these scenarios are assumed to be available. We develop a risk analysis model and a risk aggregation algorithm that we use to perform risk assessment and risk analysis. A simple case study is used to illustrate the applicability of the approach.

The proposed methodology has the following benefits:

- The methodology is applicable early at the *architectural level* and hence it is possible to identify critical components and connectors early in the lifecycle. Those components would require further development resources in terms of design, implementation, testing, etc.
- The methodology is based on *dynamic metrics*. We use dynamic metrics to account for the fact that a fault in a frequently executed component will frequently manifest itself into a failure. Results from the pacemaker example (shown in Figure 11) illustrate the benefits of using dynamic metrics.
- The methodology is based on *simulation* of architecture models. Simulation helps in:
  1. Performing FMEA procedures because it minimizes the effort required to analyze the effect of failures. The analyst can inject faults and study their effect by simply running the simulator and observing simulation outputs and reports.
  2. Calculating the CDG parameters such as probability of transitions that is based on number of messages transmitted from one component to another.
- The methodology is automatable. We have implemented the algorithm and used it in our case study. Also, we obtain measurement values for dynamic metrics using simulation reports.

We identified the following issues that could be addressed as future work:

- We use an ordinal scale for measuring severity and assign severity indices to each category. To develop risk factors we combine complexity factor (ratio scale) with severity factor (ordinal scale). This problem is common to many risk assessment methods [25, 7]. The Pareto ranking [26] uses ratio scale with severity, but it is confronted with the problem of defining boundaries between various severity categories. Perhaps one solution is to apply the same methodology discussed above to each risk category separately. In this case, severity ratios can be developed under each of the severity categories, catastrophic, critical, marginal, and minor, such that components and connectors are compared within one category and not across categories (i.e. a ratio scale under each ordinal category).
- We developed the CDGs for the pacemaker example manually from simulation reports and scenarios. Automating the development of CDGs would promote the application of our methodology. Towards the automation of the methodology, we developed a utility that processes simulation logs and automatically produces measurement values for the dynamic metrics for components and connectors. We also developed a utility that allows the domain expert to feed in data such as the operational profile for system usage and severity indices and automatically get parameters for the CDG such as risk factors for components and connectors. In the future, we plan to automate the construction of the graph nodes and links and provide a GUI that presents to the analyst the CDGs for the system and its subsystems and the associated graphical representations of the risk analysis results.
- Another area that is worth investigation is studying the effect of uncertainties in some parameters such as the scenario probabilities and the estimated average execution times. Future work would investigate the effect of these parameters on the system risk estimate.
- We applied the methodology to the pacemaker case study. Future research could experiment with applying the methodology to larger case studies with multiple subsystem to compare the aggregated risk factors of individual subsystem.

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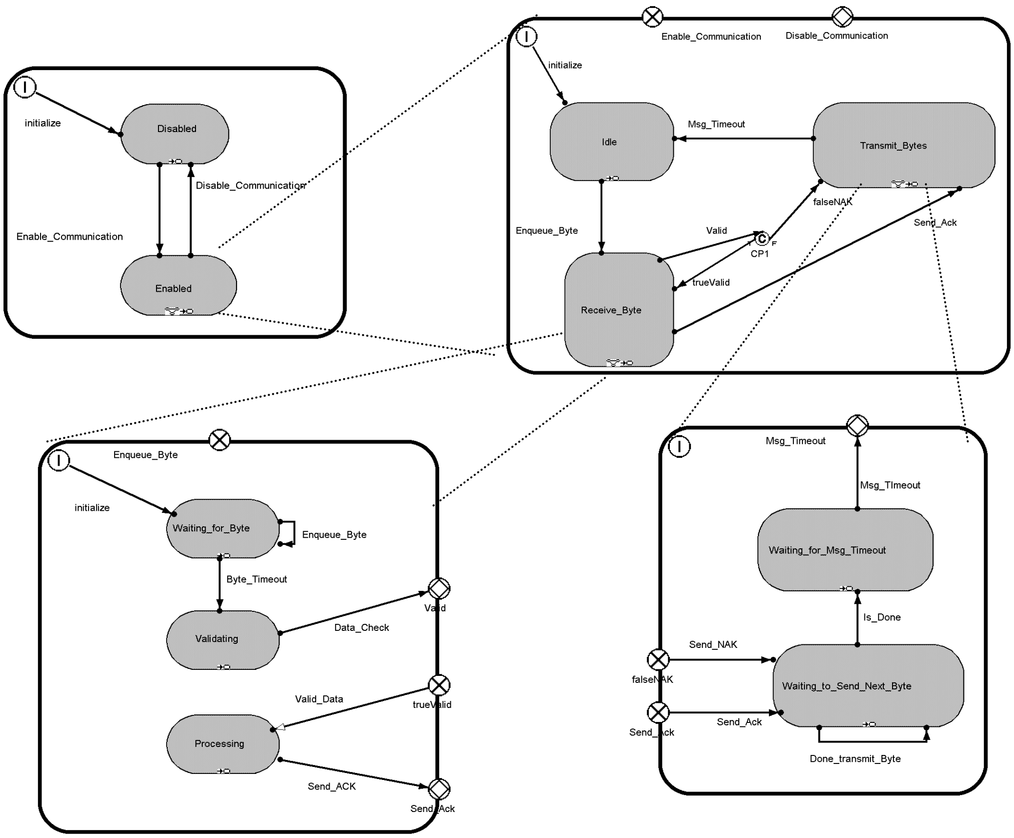
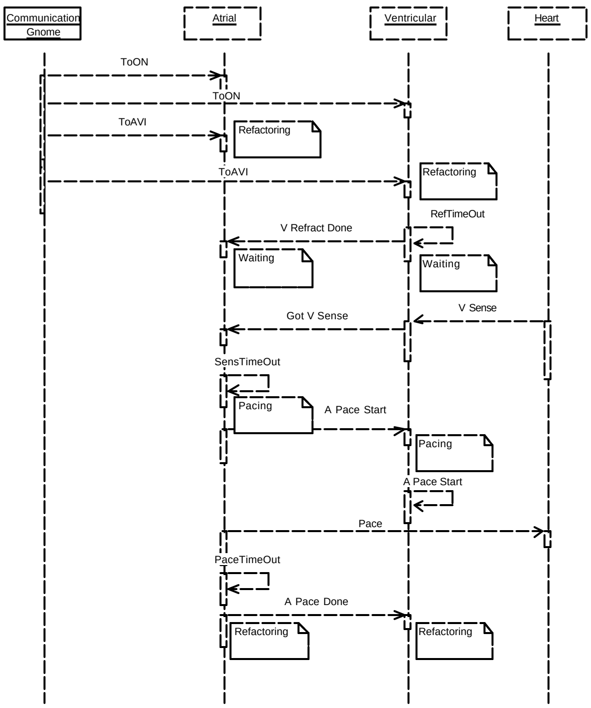
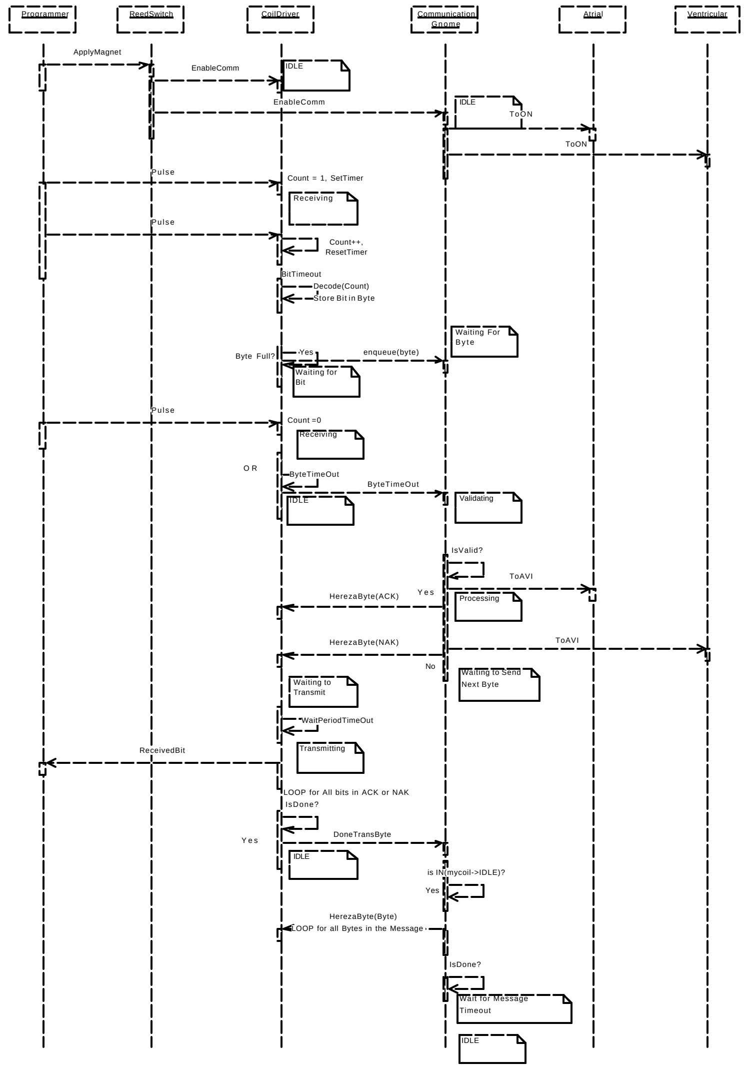
Appendix A : A UML Statechart specification for the Communication Gnome



Appendix B : UML sequence diagrams for two scenarios of the pacemaker example



Sequence Diagram for Programming Scenario



Sequence Diagram for AVI_Operation Scenario

Appendix C : Acronyms and Notation

Acronyms

ADL	Architecture Description Language
AR	Atrial_Model, a component in the pacemaker architecture
CBO	Coupling Between Object classes, an OO design metric
CD	Coil_Driver, a component in the pacemaker architecture
CDG	Component Dependency Graph
CG	Communication_Gnome, a component in the pacemaker architecture
FEMA	Failure Mode and Effect Analysis
FMECA	Failure Mode Criticality and Effect Analysis
MSC	Message Sequence Charts
NAS	Number of Associations, an OO design metric
ROOM	Real-time Object Oriented Modeling
RPN	Risk Priority Number
RS	Reed_Switch, a component in the pacemaker architecture
UML	Unified Modeling Language
VT	Ventricular_Model, a component in the pacemaker architecture

Notations

S	A set of scenarios
S_k	Scenario number k
$\|S\|$	Total number of scenarios
PS_k	Probability of scenario number k
AE_{appl}	Average execution time of a scenario
s	A start node in a CDG
t	A termination node in a CDG
N	A set of nodes in a CDG, $N=\{n\}$
n	A node in a CDG.
E	A set of edges in a CDG, $E=\{e\}$.
RC_I	A parameter in the CDG, the reliability estimate of component C_i
EC_i	A parameter in the CDG, the average execution time of the component C_i
T_{ij}	A parameter in the CDG, the name of the transition from node n_i to n_j,
RT_{ij}	A parameter in the CDG, the reliability estimate of a transition from node n_i to node n_j.
PT_{ij}	A parameter in the CDG, the probability of a transition from node n_i to node n_j.
Ci	Component number i
$svrty_I$	Severity factor for component C_i
hrf_I	Heuristic risk factor for component C_i
hrf_{ij}	Heuristic risk factor for the connector between the components C_i and C_j.
$cpx_k(C_i)$	Complexity of component C_i in scenario S_k.
$cpx(C_i)$	Complexity of component C_i
$EC_k(C_i,C_j)$	Export coupling for component C_i with respect to component C_j in scenario S_k
$EC(C_i,C_j)$	Export coupling for component C_i with respect to component C_j
$M_k(C_i,C_j)$	The set of messages sent from component C_i to component C_j during the execution of scenario S_k
MT_k	The total number of messages exchanged between all components during the execution of scenario S_k
VG	Cyclomatic complexity of a graph.

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