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Integrated Model-Based Design and Simulation of Critical Embedded Systems

Bachelor's Thesis.

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“Esperavam nas dos fundos, e saí pela porta da frente.”

Bochincho, Jayme Caetano Braun

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ACRONYMS

2TUP	Two Track Unified Process
A/C	Aircraft
A/C ICD	Aircraft Interface Control Document
ACARE	Advisory Council for Aeronautics Research in Europe
ADIRU	Air Data Inertial Reference Unit
ADF	Automatic Direction Finders
ADR	Air Data Reference
AFDX	Avionics Full Duplex Switched Ethernet
AMISA	Advanced Model-Integrated Specifications for AIRBUS
ARINC	Aeronautical Radio INCorporation
ASPIC	Atelier de Simulation Pour l'Intégration et la Conception
ATA	Air Transport Association
ATL	ATLAS Transformation Language
ATPRO	ATelier de PROduction
ATT-HDG	Autotrim Heading Angle System
BDD	Block Definition Diagram
BNF	Backus-Naur Form
CASE	Computer-Aided Software Engineering
CSV	Comma Separated Values
DAMAS	DAta MAnager for Specifications
DME	Distance Measuring Equipment
DoD-AU	Australian Department of Defence
DoD-US	US Department of Defense
DSL	Domain Specific Language
EADS	European Aeronautic Defense and Space Company
EDYYS	Simulation Department at AIRBUS France
EIS	Entry-Into-Service

EPOPÉE	Etude Prospective d’Organisation d’un Poste d’Equipage Ergonomique
FBW	Fly-By-Wire
GPS	Global Positioning System
IBD	Internal Block Diagram
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
INSIDE	Integrated Simulation Into DEsign
IRS	Inertial Reference System
ISIS	Integrated Standby Instrument System
ISO	International Standardization Office
ISP	Prise de Pression Statique
LR	Left-Recursive Parser
MARTE	Modeling and Analysis of Real-Time Embedded Systems
MBSE	Model-Based Systems Engineering
MDE	Model-Driven Engineering
M&S	Modeling and Simulation
MFP	Multi-Function Probes
MFPR	Model Functional Performance Requirements
MICD	Model Interface Control Document
MMR	Multi Mode Receiver
MOF	Meta Object Facility
MS	Model Specification
OAP	Outside Air Temperature
OCASIME	Outil de Conception Assistée de SImulation Multi-Equipements
OMG	Object Management Group
OOSEM	Object-Oriented Systems Engineering Method
OSMOSE	One Single Methodology supported by the Open Source Environment
PRIM	Primary Flight Control Computer
RA	Radar Altimeter
R&T	Research and Technology
ROI	Return on Investment
RUP	Rational Unified Process
SAS	Société par Actions Simplifiée
SAO	Spécification Assistée par Ordinateur
SEC	Secondary Flight Control Computer

SFPR	UML Profile for Simulation Functional Performance Requirements
SysML	System Engineering Modeling Language
UP2A	UML Profile for AIRBUS AP2633
UML	Unified Modeling Language
V&V	Verification and Validation

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ABSTRACT

Since the introduction of the fly-by-wire system in the Concorde and A320 civil aircraft programs, overall aircraft embedded systems complexity is continuously increasing. Current and forthcoming aircrafts highly depends on embedded avionics to operate. Computer innovation in these embedded avionics enabled us to improve flight safety, and the relation between the aircraft and environment, flying greener, cleaner, quieter, and, furthermore, being economically cheaper and sustainable for airlines. As the complexity grows due to continuous innovation in embedded avionics on aircrafts, Systems Engineering techniques currently employed to devise such systems are becoming insufficient to cope with existing requirements and dynamics in aircraft design, development, and production.

Two activities that suffer the most with the pressure when complexity increases are design and simulation of embedded avionics systems. Design concerns the development of avionics equipments, answering to stakeholders' requirements. Simulation concerns both the validation and refinement of designed equipment, and the development of aircraft simulators for training purposes. Despite the fact that design and simulation are very dependent of each other in order to prospect and to validate embedded avionics, respectively, current state-of-the-practice on Systems Engineering in AIRBUS put them somehow apart; not intentionally, but due to the lack of formalism and standardization when specifying design and simulation requirements, and when realizing them into concrete implementations. The specifications of design and simulation are currently performed in a textual document-centered approach, making very difficult the deployment of techniques to trace how design decisions constrain simulation, and how simulation requirements and results refine design.

To enable sustainable growth in complexity of forthcoming embedded avionics systems, while being economically viable, and continuously add innovation on these systems, this work proposes a Model-Based Systems Engineering approach to integrate design and simulation activities in the aircraft development cycle, adopting UML/SysML as specification language. By adopting a unified specification formalism to design and simulation, we can trace how design elements constrain simulation, and how simulation ones refine design, only by having them connected with UML/SysML language constructs. We have validated the approach with real design artifacts and simulation models from the A380 aircraft, showing a good scaling for complex models.

Keywords: Aircraft, AIRBUS, Code Generation, Eclipse, Metamodel, Model-Driven Engineering, Simulation, System Engineering, SysML, UML.

Projeto e Simulação Integrados Baseados em Modelos para Sistemas Embarcados Críticos

RESUMO

A partir da introdução do sistema de controle *fly-by-wire* nos programas Concorde e A320 de aviação civil, a complexidade dos sistemas aviônicos embarcados aumenta constantemente. A operação dos aviões atuais e futuros é fortemente dependente para seu funcionamento dos seus sistemas aviônicos embarcados. A inovação em termos de computação dessa aviônica embarcada nos permitiu aperfeiçoar a segurança de vôo, bem como a relação entre a aeronave e o ambiente, voando de maneira mais ecologicamente consciente, além de reduzir custos e permitir melhor sustentabilidade para as companhias aéreas. Com o aumento da complexidade devido à constante integração de inovação na aviônica embarcada, as técnicas de Engenharia de Sistemas empregadas atualmente no desenvolvimento desses sistemas estão se tornando insuficientes para gerenciar os requisitos e a dinâmica existentes no projeto, no desenvolvimento e na produção de uma aeronave.

Duas atividades que mais sofrem a pressão com o aumento da complexidade são o projeto e a simulação dos sistemas aviônicos embarcados. Ao projeto compete o desenvolvimento dos equipamentos aviônicos, atendendo aos requisitos dos *stakeholders*. À simulação compete a validação e o refinamento do projeto de um equipamento, bem como o desenvolvimento de simuladores para treinamento de pilotos do avião. Mesmo sendo duas atividades altamente inter-relacionadas, o atual estado da prática na AIRBUS para a Engenharia de Sistemas do projeto e da simulação as distancia; não intencionalmente, mas sim devido à inexistência de formalização e padronização na especificação do projeto e simulação, bem como na implementação das especificações. Atualmente, realizam-se as especificações de projeto e simulação com uma abordagem centrada em documentos textuais, o que acarreta em dificuldade de implantação de técnicas as quais permitam rastrear como as decisões tomadas no projeto restringem a simulação, e como os requisitos de simulação refinam o projeto.

Com o intuito de pavimentar o crescimento sustentável da complexidade dos sistemas aviônicos embarcados nas aeronaves futuras, sendo ainda economicamente viável, além de continuamente agregar inovação nesses sistemas, este trabalho propõe uma abordagem de Engenharia de Sistemas Baseada em Modelos para integrar as atividades de projeto e simulação contidas no ciclo de projeto de uma aeronave, adotando UML/SysML como linguagem de especificação. Ao se adotar um formalismo único para o projeto e para a simulação, faz-se possível rastrearmos como os elementos de projeto restringem a simulação, e como os elementos de simulação refinam os de projeto. Alcança-se rastreabilidade somente através de construções padrão da linguagem UML/SysML. Validamos a nossa proposta com modelos de simulação e artefatos de projeto real do avião A380, demonstrando boa escalabilidade da proposta.

Palavras-Chave: Aeronave, AIRBUS, Geração de Código, Eclipse, Engenharia de Sistemas, Engenharia Dirigida por Modelos, Metamodelo, Simulação, SysML, UML.

Intégration de Conception et de Simulation Basée sur les Modèles pour Systèmes Embarqués Critiques

RÉSUMÉ

Depuis l'introduction du système de commande de vol électrique dans les programmes d'avions civils Concorde et A320, la complexité des systèmes embarqués dans l’avion n’a cessé d'augmenter. Le fonctionnement des avions actuels et à venir est fortement dépendant de l'avionique embarquée. L'innovation dans ces calculateurs nous a permis d'améliorer la sécurité des vols, et a permis des avions plus écologiques et plus silencieux vis-à-vis de l’environnement, tout en réduisant les coûts et en augmentant la viabilité économique pour les compagnies aériennes. Alors que la complexité augmente en raison de l'innovation continue dans l'avionique embarquée, les techniques d’Ingénierie des Systèmes actuellement utilisées pour concevoir ces systèmes deviennent insuffisantes pour faire face aux exigences existantes et à la dynamique nécessaire dans la conception des avions, leur développement et leur production.

Les deux activités qui souffrent le plus de cette augmentation de complexité sont la conception et la simulation de systèmes avioniques embarqués. La conception concerne le développement des équipements avionique, pour répondre aux exigences des parties prenantes. La simulation concerne la validation et le raffinement de la conception des équipements, puis le développement de simulateurs d'avion utilisés pour la formation des pilotes. En dépit du fait que la conception et la simulation sont en principe très dépendants l’un de l’autre pour l’amélioration et validation des systèmes embarqués avionique, les pratiques d’Ingénierie des Systèmes dans AIRBUS les ont séparées, non intentionnellement, mais en raison de l'absence de formalisme et de normalisation d’abord pendant la phase de spécification des exigences de la conception et de la simulation et ensuite lors de leur implémentation concrète en phase de réalisation. Les spécifications de conception et de simulation sont effectuées dans des documents textuels, ce qui rend très difficile le déploiement de techniques permettant d'une part de tracer les décisions de conception qui contraignent la simulation, et d'autre part d'utiliser les résultats de simulation pour affiner la conception.

Afin de permettre une gestion efficace de la complexité des systèmes avioniques embarqués à venir, tout en étant économiquement viables, et d'ajouter de l'innovation sur ces systèmes, ce travail propose une approche Basée sur les Modèles visant à intégrer ensemble les activités de conception et de simulation dans le cycle de développement des avions, en utilisant UML/SysML comme langage de spécification. En adoptant un formalisme unifié pour la spécification des exigences de la conception et de la simulation, nous pouvons tracer comment la conception contraint la simulation, et comment les résultats de simulation permettent d'affiner la conception. Nous avons validé la méthode proposée en utilisant des spécifications réelles de conception et de simulation de l'A380, montrant une bonne mise à l'échelle de la proposition.

Mots-Clés: Avion, AIRBUS, Génération de Code, Eclipse, Ingénierie Basée sur Modèles, Ingénierie de Système, Métamodèle, Simulation, SysML, UML.

1 INTRODUCTION

This chapter presents the main motivation for this work in section 1.1, which explains how AIRBUS can continue to *setting the standards*. Section 1.2 states the problem this work address, based on the motivation we have discussed previously. To improve the comprehension and put this work within a period of technology advances in the Aeronautics domain, section 1.3 briefly introduces the AIRBUS Company history. Finally, section 1.4 presents the subsequent organization of this text.

1.1 Motivation

The aircraft industry is driven by continuous innovation, being this factor decisive for players in this industry. With innovation we can fly cheaper, greener, and with increasingly safety and decreasing costs. Since the milestone introduction of the fly-by-wire in Concorde aircraft, and later in the A320 (Traverse, 2004), embedded computer systems have their place in both civil and military aircraft. Embedded systems have a high pace of adoption in aircrafts, and the days these systems were targeted only to aircraft control is in the past. Currently, the A380 aircraft entertainment systems, devoted to passenger seat music and video players, as well as gaming systems, accounts for around 30% of all wiring in the aircraft. Now modern aircrafts adjusts the interior cabin lightning and pressure to improve passenger conform in flight – everything controlled by embedded computer systems. Therefore, we cannot neglect the increasing complexity we find today in current and we will face in forthcoming aircraft programs, requiring new Systems Engineering techniques to handle this complexity if the aircraft manufacturer wants to stay competitive and innovative.

AIRBUS internal research sees the Model-Based Systems Engineering (MBSE) approach as a promising answer to the increasingly complexity in the forthcoming aircraft designs. There are research projects currently in AIRBUS studying and developing methods for the adoption of UML/SysML as the formalism to specify avionics systems.

The INtegrated Simulation Into DEsign (INSIDE) project is an internal research and technology (R&T) project aiming at foreseeing new systems design techniques and processes for avionics systems (AIRBUS, 2008b). In AIRBUS, the following activities compose system design: formalize specifications; generate the system model – executable specification; test the specification with simulation; analyze results; refine specifications with gathered knowledge from results analyzes. We iteratively perform these activities until results found are acceptable.

Current systems design simulation platform is the OCASIME simulator (we will present it in subsequent chapters), which is integrated with other simulators, enabling model reuse among these simulation platforms. Despite its well-founded simulation platform, OCASIME does not integrate the system validation framework, increasing validation time in the design life cycle. In addition, some models have a long compilation time, incurring in wasted time when these models have errors or are not acceptable. Another problem is that OCASIME test procedures are not reusable by other simulation platforms, increasing test time.

Thus, the main INSIDE goals are, in short-term, to improve the OCASIME simulation platform, and, in long-term, to improve system design and simulation integration. We can accomplish this integration by providing a multi-specification-formalisms platform, enabling to model each system component with the best suitable formalism (not only Simulink and SCADE, as today); enabling real-time interoperability between distinct simulation platforms, reducing turn-around time between simulators; sharing of test scenarios between distinct simulation platforms, what reduces test efforts while improving quality. The current adopted language for specifying simulations is UML/SysML. This work is in the frame of INSIDE.

The Advanced Model-Integrated Specifications for Airbus (AMISA) is also an internal R&T, but differently from INSIDE that is targeted to system simulation, AMISA is targeted to systems design (AIRBUS, 2008c). AMISA will be partially deployed in the A350 aircraft program, but it is intended to be widely deployed in the A30X program (A320 program successor), as well as other model-based approaches. AMISA also adopts UML/SysML as specification language, and Simulink as low-level behavior implementation language. AMISA adopts Telelogics Rhapsody as its CASE tool, integrating automatically with Telelogics DOOR tool for requirements management, and with Simulink through its S-Functions (S-Functions are external behavior to the Simulink environment. Actually, it defines C code function implemented outside Simulink). INSIDE adopts TOPCASED as its CASE tool. As MBSE techniques are yet in research stage, AIRBUS does not have a closed decision in which tools to adopt. The main AMISA goal is to increase system maturity in Entry-Into-Service (EIS) for a new devised aircraft program, correcting some problems to future aircrafts development identified in the A380 program regarding this issue.

1.2 Problem Statement

Concerning the development of design and simulation activities, the pace of innovation poses big challenges to forthcoming projects, and we foresee that current Systems Engineering techniques will not be suitable to handle this new complexity. AIRBUS identified some of these problems based on gathered knowledge from the A380 and previous programs (AIRBUS, 2008c):

- Recurring problems due to misinterpretations of specifications between development teams. The main cause to that is the current way AIRBUS writes specifications, based on text documents and requirements;
- Late identification of errors in the specifications, because currently they are not completely executable. This postpones errors finding when we integrate developed avionics equipments onto simulators;
- Insufficient model exchange with AIRBUS suppliers.

Regarding the problems above, it is desirable to have a well-defined and unambiguously modeling approach for specifying system functions, behaviors, and performance, allowing for early model validation by executing these models, as well as to ensure interoperability between devised models by defining common model interfaces which modeling teams can rely on.

Specific to simulation design, the problems are:

- Currently, the simulation model code generator only accepts Simulink, SCADE, SAO, and C code. If the system is not specified with these formalisms, they cannot be validated with the existing simulation platform;
- Simulation model generation is not fully integrated with its validation, requiring the Simulation Model Designer to use two distinct environments to perform model generation and validation;
- Model generation can be very time-consuming, requiring in some cases a couple of days to generate model code. If we consider an iterative process cycle to correct model errors, these days can become weeks or months until the model reaches stability;
- The simulation platform is not too robust, being quite closed to internal AIRBUS employees, preventing simulation deployment to suppliers;

Another issue is that simulation and design activities are somehow apart in the development process, while ideally they should be very connected. The main problem is that it is quite difficult to trace what design elements a simulation element is simulating. This can incur into redundancies between design and simulation elements.

Simulation in AIRBUS has advanced a lot since its first deployment around twenty years ago. However, clearly, forthcoming requirements and innovation in new aircrafts demand to improve current processes.

1.3 The AIRBUS Company

A consortium of European industries formed the Airbus Company to compete with North American companies such as Boeing. In the mid-60s, tentative negotiations began regarding a European joint venture – some European companies have discussed such a possibility. At the 1965 Paris Air Show, some major European commercial airline companies discussed the requirements for a new passenger aircraft, capable of transporting more than one hundred customers on short to middle distances at a low cost. In 1966, first formed partners were Sud Aviation from France, Deutsch Airbus from Germany, and Hawker Siddeley from the United Kingdom; the three home governments of each company listed above also formed the consortium.

In early 1967, this consortium has launched the A300 brand, and has evolved this aircraft to have 320 passenger seats, being a twin-engine aircraft. In middle July 1967, the three cited governments agreed to start the project. Sud Aviation was in charge of cockpit and flight control systems, as well as fuselage's lower central section. Deutsch Airbus was in charge of forward and read fuselage sections and upper centre section. Fokker from Netherlands was in charge of flaps and spoilers systems; and CASA (not yet a full consortium member) from Spain was in charge of horizontal tail plane. In December 1970, the consortium constituted Airbus Industrie as an Economic Interest Group.

In early 1990, the former AIRBUS CEO wanted to constitute the Company as a conventional one, but due to difficulties in integrating and measuring the economical assets of Airbus at that time, he postponed this initiative until 2000. In 2000, all companies merged, forming the European Aeronautic Defense and Space Company (EADS), enabling the new constitution process.

The consortium constituted Airbus in 1970 and its headquarters are located in Toulouse, France. It has around 57,000 employees in the World, divided in four European sites (France, Germany, Spain and the United Kingdom), as well as in five main subsidiaries (North America, China, India, Japan and Transport International). It has currently 270 clients worldwide and has over 5,400 aircrafts in service.

1.4 Text Organization

This work is organized as follows:

- Chapter 2 introduces the Systems Engineering domain, its concepts, and current approaches for model-based systems engineering. It reviews the basic UML concepts we use throughout this work, and briefly compares model-based versus document-centered approaches for Systems Engineering. It ends with a presentation of the Systems Engineering approach in AIRBUS;
- Chapter 3 introduces the Simulation domain, its concepts, and current standards for simulation of critical hardware and software. It discusses verification and validation of simulation models, and Model Simulation accreditation and certification. It ends with a presentation of System Simulation in AIRBUS;
- Chapter 4 presents our proposed solution to the problems discussed in this chapter, in section 1.2;
- Chapter 5 presents the case studies we have performed to evaluate and validate our proposed approach;
- Chapter 6 draws our technical assessment regarding the proposed approach and the case studies performed, and conclusions concerning the next steps to make our approach better.

2 MODEL-BASED SYSTEMS ENGINEERING

This chapter introduces the main Model-Based Systems Engineering (MBSE) concepts related with this work and how Systems Engineering is at AIRBUS. Section 2.1 introduces what is Systems Engineering and its main concepts and terminology. Section 2.2 introduces the Unified Modeling Language (UML), as well as its main constructs used in this work, while section 2.3 presents the Systems Engineering Modeling Language (SysML), the UML's counterpart targeted to Systems Engineering. Section 2.4 presents some available methodologies supporting the Model-Based Systems Engineering approach. Finally, section 2.5 presents the Systems Engineering approach that both INSIDE project and this work adopt.

2.1 Introduction to Systems Engineering

This section introduces Systems Engineering basic concepts and how they relate to this work. In addition, it presents one of the most used Systems Engineering processes up to now, the IEEE 1220. Section 2.5.2 presented the EIA 632 process, which together with IEEE 1220 are the most well-know Systems Engineering processes in industry.

A *system* is a set of arrangement of related elements [people, products (hardware and software) and processes (facilities, equipment, material, and procedures)], and whose behavior satisfies operational needs and provides for the life cycle sustainability of the products. In addition, it contains the people required to develop, produce, test, distribute, operate, support, or dispose the system (IEEE, 2005). By this definition, the main difference of a system from Systems Engineering to Software Engineering perspective is that a system may compose hardware and software components, being these two different architectures well described in the system's specifications. In Software Engineering, usually the underlying hardware is not a concern, only when we consider Embedded Software (Ferreira, 2009).

A system is a composition of related systems, which together provide some useful service to the environment through its published interfaces, as well as consume services from other systems from this environment. An environment can be either software or hardware systems, or even a human user. The general system hierarchy is: system, product, subsystem, assemblies, components, subcomponents, and parts. Several products can compose a system, and a product can define several subsystems, which are in turn composed of several components (IEEE, 2005).

A *life cycle* is the system or product evolution initiated by perceived stakeholder needs through the disposal of the products (IEEE, 2005). The following functional processes compose the usual Systems Engineering life cycle:

Development, which is the planning and execution of system and subsystem definition tasks required to evolve the system from stakeholder needs to product solutions and their life cycle processes.

Manufacturing, composing tasks, actions, and activities for fabrication and assembly of engineering test models, prototypes, and production of product solutions and their life cycle process products.

Test, composing tasks, actions, and activities for evaluating product solutions and their life cycles processes to measure specification conformance or stakeholder satisfaction.

Distribution, composing the tasks, actions, and activities to initially transport, assemble, install, test, and check out products to effect proper transition to users, operators or consumers.

Operations, tasks, actions, and activities associated with the use of the product or a life cycle process.

Support, involves tasks, actions, and activities providing maintenance, support material and facility management sustaining operations.

Training, measurable tasks, actions, and activities required to achieve and maintain the knowledge, skills, and abilities necessary to perform efficiently and effectively operations, support, and disposal throughout the system life cycle.

Disposal, tasks, actions, and activities to ensure that disposal or recycling of destroyed or irreparable consumer and life cycle processes and by-products comply with applicable environmental regulations and directives.

(IEEE, 2005)

The Systems Engineering process usually composes a set of activities: requirement analysis, requirements validation, functional analysis, functional verification, synthesis, and design verification. These activities are well known in the Software Engineering context, and they are not discussed further here. The main difference between the Systems and Software Engineering is that in the former we consider in addition to software, hardware portions. For details, refer to IEEE (2005).

2.2 Unified Modeling Language

This section discusses the UML metamodel constructs used during through this work. Thus, it assumes that the reader has some user knowledge on the Unified Modeling Language (UML) and its basic diagrams (mainly class, sequence, states, activities, and use cases) and on the class-based Object-Oriented paradigm (the difference between a class and an instance). We refer interested readers aiming at earning good knowledge on UML to Larman (2004) and on Object-Oriented approaches to Craig (2007).

2.2.1 Basic Principles

Currently on its version 2.2, two documents specify the UML language, UML Infrastructure (OMG, 2009a) and UML Superstructure (OMG, 2009b). The *Infrastructure* document specifies the UML core elements, used to specify several

OMG specifications, including UML itself. The *Superstructure* specifies more detailed elements, such as behavior and interactions; usually, it is not reused by other OMG specifications.

UML was devised to meet some requirements (OMG, 2009a): modularity, having strong cohesion and being loosely coupled; layering, to separate UML specification from metamodels and models, as well as to enable different abstraction levels of the same model; partitioning, enabling smooth UML metalanguage extension; extensibility, through the use of *profiles,* having, thus, a built-in support for several application domains; and reuse, enabling new specifications to use the UML concepts coherently.

The UML Infrastructure documents specify the *Core* and *Profiles* package, which contains the PrimitiveTypes, Abstractions, Constructs, and Basic Packages. *PrimitiveTypes* contains the primitive types in UML: Boolean, Integer, String, and UnlimitedNatural. *Abstractions* package contains metaclasses designed to be specialized by other metamodels reusing the UML Infrastructure. *Constructs* define metaclasses related to Object-Oriented modeling, mainly used to implement the UML kernel constructs. *Basic* defines the constructs enabling the UML serialization to XMI. *Profiles* package enables to tailor specific domain model concepts into existing ones in the target metamodel.

The UML language also defines the *four-layer* metamodel hierarchy, used to specify how model levels are interconnected, enabling the concept of *metamodeling*. The four-layers hierarchy is composed by: M3 layer, which corresponds to the *meta-metamodel,* defined by the Meta Object Facility (MOF) (OMG, 2006a) specification; M2 layer, which corresponds to the *metamodel,* defined by the UML language specification; M1 layer, defined by some user application model, expressed by the adopted metamodel language, in this example the UML one; and M0 layer, which is the actual runtime instance of the M1 layer.

When devising the UML metamodel, OMG has adopted some formal techniques, aiming at some goals, to know: *correctness*, by defining well-formed rules and methods to validate a model; *precision*, eliminating syntactic and interpretation ambiguity; *conciseness*, avoiding non-necessary and superfluous constructs; *consistency*, by guaranteeing that metamodel constructs do not create contradictions; and *understandability*, improving the readability and understanding of the specification, preferring to apply a less formal mechanism when it improves readability over the formal one. Due to this last design decision, UML is considered a *semiformal* language. In addition, to some constructs more related with implementation issues, the UML specification can specify this case as a *semantic variation point*, being the correct specification in charge of who implements this construct in the target execution environment.

2.2.2 UML Infrastructure

Two packages compose the UML Infrastructure (OMG, 2009a), *Core* and *Profiles*, decomposed further in more sub packages, as presented above. This section presents the most important UML Infrastructure constructs to this work.

2.2.2.1 Core::Abstractions

The UML metaclasses important to this work are Classifier, Feature, StructuralFeature, BehavioralFeature, Element, InstanceSpecification, and Slot.

- *Classifier* defines a namespace that can contain features; it is some sort of a named container for features. Classifier is an abstract metaclass.
- *Feature* is an abstract metaclass defining a behavioral or structural feature of a Classifier; it is only used to unify methods accessing Features, enabling to handle both structural and behavioral ones.
- *StructuralFeature* is a typed feature of a classifier specifying that this classifier has a structure, which can be instantiated during runtime, being allocated into some slot. StructureFeature is an abstract metaclass.
- *BehavioralFeature* is an abstract metaclass that specifies some behavior attached to the Classifier this BehavioralFeature is contained.
- *Element* is an abstract metaclass with no super class, being the UML metamodel root class.
- *InstanceSpecification* is a concrete metaclass defining some model entity, partially or even completely. This definition is made by assigning values (InstanceValue metaclass) to the entity's slots. InstanceSpecification is used to represent the modeled system during runtime, *e.g.* an InstanceSpecification of the Classifier
- *Class* represents an element of the model domain, and its instance is an object. *Slot* specifies that some StructuralFeature owned by an InstanceSpecification owns a value, *e.g.* the Slot of a Class' *Property* is a value assigned during runtime.

2.2.2.2 Core::Basics

The important metaclasses in this package are: NamedElement, Type, TypedElement, Class, Operation, and Property.

- A *NamedElement* is an *Element* that may have a name.
- *Type* is an abstract metaclass that introduces a typing system, being the type of a TypedElement.
- *TypedElement* is an abstract metaclass extending NamedElement, adding a Type to it.
- *Class* extends Type, enabling itself to have a Type with properties (Class attribute *ownedAttribute[*]*) and operations (Class attribute *ownedOperation[*]*), and to introduce a type hierarchy through the *superClass[*]* attribute – note that multiple inheritance is possible, and how to handle this is a semantic variation point.
- An *Operation* is a kind of container to some behavior, being owned only by instances of Class. An Operation extends both TypedElement and MultiplicityElement, and may have a list of parameters (Operation attribute *ownedParameter[*]*).
- A *Property* is a TypedElement, being an attribute of a Class. The strange is that on the UML Infrastructure is possible for an attribute to exist without a container class, given its *class[0..1]* attribute has the lower bound set to 0

(OMG, 2009a, p.98). The UML Infrastructure document does not specify why this is possible.

2.2.2.3 Core::Constructs

The important metaclasses in this package are DirectedRelationship, and Association.

- *DirectedRelationship* is a Relationship in which it is possible to distinguish between *source* and *target* Elements, through the attributes *source[1..*]::Element* and *target[1..*]::Element*. Note that any kind of metaclass can be a source or target within a DirectedRelationship.
- *Association* defines a set of tuples, whose values refer to typed instances. Association is a Classifier, thus it can be instantiated, and we call its instances *links*. This is sometimes a source of confusion, and it is worthy of a better explanation. Let us have a look in the example in Figure 2.1.

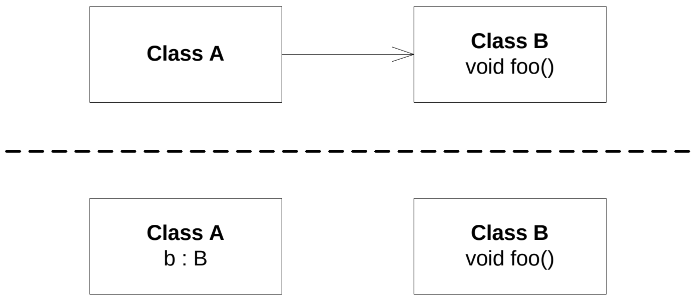


Figure 2.1: Association versus attribute

Are these two UML models equivalents? The answer is yes and no. *Pragmatically*, yes; *semantically*, no. Let us assume that we have an object of type A called *a*. The difference is when we have the call *a.b.foo()*, due to the *context of execution*. In the first case, *b.foo()* execution is going to happen "inside" the link instance created for the association between Class A and Class B, that's why an Association introduces a tuple: in this example, we have <*Class A*, *Class B*> tuple. In the attribute case, *b.foo()* execution is going to be performed "inside" the *a* object. Pragmatically, they are the same, because usually code generators do not create the link object, considering the association target as an attribute of the association source.

2.2.3 UML Superstructure

The UML Superstructure specification (OMG, 2009b) is the actual definition of the UML language, which reuses and extends the majority of the concepts introduced in the UML Infrastructure specification (OMG, 2009a). It divides into two big parts: Structure and Behavior.

From the *Structure* part, the most important metaclasses to this work are: Dependency, from Structure::Classes package; Port, from Structure:: CompositeStructure package; From the *Behavior* part, the most important metaclasses are Behavior, BehavioredClassifier, and BehavioralFeature, from Behavior:: CommonBehavior; and OpaqueAction, from Behavior::Actions.

- *Dependency* specifies that to define a set of *client* NamedElements it requires another set of *suppliers* NamedElements. Thus, the clients' complete definition is only possible with all their suppliers. Dependency has no runtime semantics; it completely defines itself in terms of model elements, not instances. UML enables models to specialize the semantics of Dependency, making it most appropriate for the model's specific domain.

- *BehavioredClassifier* specializes Classifier metaclass enabling a Classifier to own behaviors contained in its namespace. BehavioredClassifier has two main attributes: *ownedBehavior[0..*]*, which is the set of behaviors within the BehavioredClassifier namespace; and *classifierBehavior[0..1]*, which is the behavior of the BehavioredClassifier, being this attribute a subset of *ownedBehavior[0..*]*. The behavior specified in *classifierBehavior* attribute executes just after the BehavioredClassifer instantiation.

- *Behavior* is the specification of how its *context* Classifier changes over time. This behavior specification can be an atomic, emergent, or even an illustration of a subset of real execution. The behavior is said to be *atomic* if it is contained in only one implementation, *e.g.* within an Activity. The behavior is *emergent* if its specification depends on the interaction of more than one BehavioredClassifiers, usually being specified by a CollaborationUse. The illustration is the case when the behavior is specified with a *Sequence Diagram*, which is actually a scenario of execution, not its complete specification. The Behavior has two main attributes: *specification[0..1]::BehavioralFeature*, being the behavior specification itself; and *context[0..1]::BehavioredClassifier*, which defines where this behavior is going to be executed (recall the example from Figure 2.1, *Association versus Attribute*).

- *BehavioralFeature* declares and implements a behavior. The BehavioralFeature specifies, thus, which behavior is executed when the BehavioralFeature is invoked. It has one main attribute, *method[0..*]::Behavior*, which defines the behaviors executed when the BehavioralFeature is invoked. The formal parameter list match against a method is done in the BehavioralFeature context, but how this is done is a semantic variation point, as some languages employ covariance, while others contra-variance.

- *OpaqueAction* is an Action that is used as a placeholder for an implementation. An OpaqueAction enables to implement an Action in a language apart from UML, for example Java or C++, as long as this language source-code has text format.

2.3 Systems Engineering Modeling Language

This section briefly introduces the Systems Engineering Modeling Language (SysML) on a user-centered approach. We are not going to discuss its metamodel, even because metamodel constructs used in this work are fairly the same from UML, which section 2.2 presented. For a gentle introduction to SysML, we refer interested readers to Weilkiens (2008).

Apart from UML which was designed to model software systems, SysML (OMG, 2008b) was designed to smoothly handle systems composed by hardware, information, and so on, not only software-based systems. To do so, it reuses some portions of the

UML 2 language (OMG, 2009a), and extends it to better represent concepts from the systems engineering domain.

The most important changes in SysML from UML are (Weilkiens, 2008):

- Classes are called *Blocks*, and the Class diagram was changed to *Block Definition Diagram* (BDD);
- The Composite diagram was changed to *Internal Block Diagram* (IBD);
- It is possible to specify item flow within an IBD;
- Support for continuous functions through actions and object nodes in Activity diagram;
- Introduction of two new diagrams, *Requirements*, and *Parametric*.

The *Requirement* diagram defines a way to express system requirements in the diagram, and to manage all the requirement life cycle through its defined dependencies: derive requirement (the client was derived from the supplier); satisfy (the set of clients, which are actually model elements, a Block for example, satisfies the supplier requirement); copy (the client requirement is the same as the supplier, but its name and unique identification); verify (the client test case is used to check the supplier consistency); refine (the client is a model refine of the supplier); and trace (a very weak dependency, it is used only to link the supplier requirement with a client model element when the other dependencies presented are not suitable to represent their relationship) (Weilkiens, 2008).

The *Parametric* diagram enables to parameterize the properties of some blocks, creating *parametric functions* with them. A parametric function is a function that is calculated given some parameters, which are properties in the model. For example, y = ax + b is a parametric function. These parameters are specified within *Constraint Blocks*. A Constraint block defines some constraints in its properties, *e.g.* if a Constraint block has an integer property *a*, than a valid constraint would be $a > 6$ (Weilkiens, 2008).

It is important to define model view and viewpoints. A *view* is a representation of the entire system, based on a selected viewpoint. A *viewpoint* specifies the structure of a view based on a set of stakeholders. In other words, a view is an abstraction of the entire subsystem, where the viewpoint defines this abstraction, depending on the stakeholders of interest for a view. In this way, it is possible to create different representations of the same system for different presentation purposes (Weilkiens, 2008).

2.4 Model-Based Systems Engineering

This section presents the basic concepts on Model-Based Systems Engineering (MBSE), as well as some well-know methodologies supporting MBSE. This section is based on a survey from the INCOSE Focus Group on MBSE (Estefan, 2007). Finally, in section 2.4.5 it presents a comparison between the current state-of-the-practice and model-based approaches for Systems Engineering.

2.4.1 Basic Concepts

We find five important concepts in MBSE: process, method, tool, methodology, and environment.

> A *process* is a logical sequence of tasks performed to achieve a particular objective. A process defines *what* is to be done, without specifying *how* each task is performed.
>
> A *method* consists of techniques for performing a task, thus it defines *how* each task is going to be realized.
>
> A *tool* is an instrument that, when applied to a particular method, can enhance the efficiency of the task, provided it is applied properly and by somebody with proper skills and training.
>
> A *methodology* is a collection of related processes, methods, and tools. It is essentially a guide and can be thought of as application of related processes, methods, and tools to a class of problems that all have something in common.
>
> An *environment* consists of surroundings, external objects, conditions, or factors that influence the actions of an object, individual person or group. These conditions can be social, cultural, personal, physical, organizational, or functional. The purpose of a project environment should be to integrate and support the use of tools and methods on that project. Thus, it enables (or disables) the *what* and the *how*.
>
> (Estefan, 2007)

2.4.2 Harmony-SE

I-Logix (now Telelogics) has created the Harmony-SE methodology to support Systems Engineering with SysML. Its improvement is mainly due to its integration with a strong requirement management tool, in this case Telelogic DOORS. It had a good acceptance because the US Department of Defense (DoD) used a tool called Software Architect from Popkin Software Company, which was bought by Telelogic, and integrates with Harmony-SE. Harmony-SE was designed to be vendor-neutral, but it is only supported by Telelogic Rhapsody tool.

The key objectives that Harmony-SE methodology accomplishes are:

- Identify/derive required system functionality;
- Identify associated system states and modes;
- Allocate system functionality/modes to a physical architecture.

As usual on SysML, Harmony-SE is service-oriented, and uses SysML blocks to represent the system structure. The communication between blocks is given with *service requests*, which induces some state (or mode in Harmony-SE terminology) in the requested block. Sequence Diagrams represents the communication between system structures, and the system structure with internal block definition diagrams.

The interesting is that every Harmony-SE element traces and synchronizes with a requirement on the requirements repository using Telelogic DOORS. For a more detailed introduction to Harmony-SE, refer to (Estefan, 2007).

2.4.3 OOSEM

The Object-Oriented Systems Engineering Method (OOSEM) employs a top-down approach for specification, verification, analysis, design and development, where the SysML language supports all these levels (Estefan, 2007). By adopting SysML as its implementing language, OOSEM methodology integrates smoothly with current Object-Oriented techniques. The OOSEM key objectives are the following, extracted from (Estefan, 2007):

- Capture and analysis of requirements and design information to specify complex systems;
- Integration with Object-Oriented software, hardware, and other engineering methodology;
- Support for system-level reuse and design evolution.

Three components compose the OOSEM structure:

- Systems Engineering Foundation: contains the systems engineering processes defining how requirements must be elicited;
- Common Object-Oriented System Engineering: top-down and recursive layer, it is use-case driven based on previous elicited requirements. Defines black and white box components, using Object-Oriented concepts, and is expressed with UML/SysML languages. It depends on Systems Engineering Foundation layer;
- OOSEM Unique: concerns the system activities, such as business model, context where the system is going to be deployed, system/logical decomposition, partitioning, allocation, and further system high-level activities. Is depends on Common Object-Oriented System Engineering layer.

The three previous cited key objects are unrolled into the following activities, based on the V model (Forsberg, 1991):

- Analyze stakeholder requirements;
- Define system requirements;
- Define logical architecture;
- Synthesize candidate allocated architecture;
- Optimize and evaluate design alternatives;
- Validate and verify the overall system.

2.4.4 RUP-SE

The Rational Unified Process for Systems Engineering (RUP-SE) is based on the well-know software development RUP process, incrementing it to deal with systems specification, analysis, design and development (RATIONAL, 2002). RUP is based on *content-elements*, describing what must be produced in each RUP cycle. These cycles can be represented by the well know RUP's *whale chart*.

All iterations in the RUP life cycle have seven *disciplines*: business modeling, requirements, analysis and design, implementation, test, and deployment. RUP-SE extends RUP by defining new roles, by including for example the systems engineer; new artifacts related to systems engineer non-function requirements, such as security, training, and logistics; by adding the concepts of *model level, view* and *viewpoints*. A *model level* groups model element with similar level of details – it does not group abstraction levels. RUP-SE offers more scalability due the concept of viewpoint from SysML, enabling to provide the same model with different presentation details for distinct groups of stakeholders, without replicating model elements and it offer built-in support for non-functional requirements. IBM Company through its IBM Rational Software Suite offers tool support for RUP-SE.

2.4.5 Model-Based versus Document-Centered Systems Engineering

As stated before, a Systems Engineering process encompasses some well-defined activities: requirements analysis, requirements validation, functional analysis, functional verification, synthesis, and physical verification. A process defines *how* these activities are going to be realized, thus we can imagine that there are a lot of ways of doing so, and indeed there are. Previously in this section some methodologies and processes based on models were presented, but as stated by Baker (2000), MBSE is not the current state-of-the-practice. Moreover, we can push this even nowadays, almost ten years later. Currently, companies still rely on *document-centered* processes and methodologies to have implemented their Systems Engineering process; even in AIRBUS, where we have the Model Functional Performance Requirement (MFPR) document stating the equipment simulation requirements, and partially the simulation model itself, described by the Model Interface Document (MICD) Excel sheet. In AIRBUS, only model behavior is implemented with a model-based approach, using Simulink and SCADE models, but the model architecture (or model interface) is completely document-centered. Baker (2000) made a comparison between MBSE and the *document-centered* approach, which Table 2.1 summarizes.

Table 2.1: Comparison between model-based and document-centered approaches for Systems Engineering

Characteristic	*Model-based*	*Document-centered*
Information Repository	Models	Documents
Reviews	Automated by model inspection	Manual, by reading and comparing text in natural language
Verification	Incremental (model refinements) and automated (model checker)	Manual, audited by human inspector
Communication	Consistent through model views and well-defined semantics	Ambiguous, it depends on reader's interpretation
Validation	Performed by different stakeholder's views	Text walk-through
Traceability (requirements to design verification)	Completely traceable	Accuracy depends on hard efforts
Reuse	Model repository, plug-and-play	None, only copy-and-paste
Cultural Adoption	Probably new paradigm within R&D team	*Status-quo*

Source: BAKER, 2000, p. 5.

The only “drawback” is the requirement to have tool support, but this can be easily accomplished, and several tools were presented to that. Thus, the initial effort to implement a MBSE approach probably offers an excellent Return on Investment (ROI).

2.5 Systems Engineering at AIRBUS

Systems Engineering, in a broad sense, is the use of well-defined methodology (engineering part) to design and develop products that together offer a valuable service to some user (system part). The Airbus Avionics and Simulation Department defined a System Engineering process based on a model-driven approach and SysML called OSMOSE (One Single Methodology supported by the Open Source Environment). The OSMOSE process focuses in defining equipment requirements and produces design artifacts in a more formal fashion. Within OSMOSE, a requirement specification is described with SysML. OSMOSE was created based on the EIA632 standard and on the Two Track Unified Process (2TUP).

2.5.1 Two Track Unified Process

The well know Unified Process (UP) is a development process that uses as its working language the UML. It is an iterative, incremental, and use case-driven process. Several CASE tools support it, such as IBM Rational Rose, and have a very successful history in the software development industry. The 2TUP (Roques, 2003) extends UP by adding one development branch in addition to the existing functional requirements one. The added branch deals with technical constraints that describe some operational constraints such as software specification, underlying hardware and operating environment. Thus, 2TUP also handles physical non-functional requirements. Figure 2.2 presents the 2TUP general process chart.

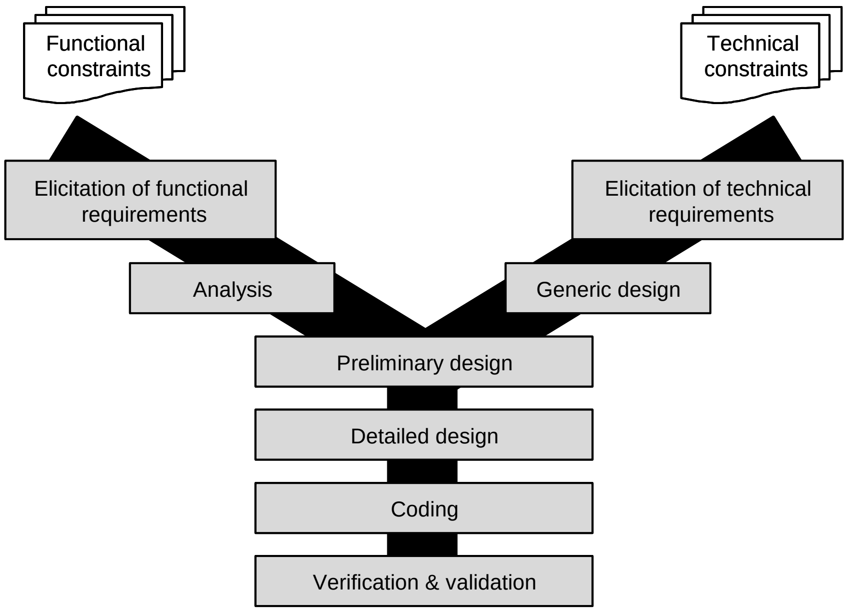


Figure 2.2: Two Track Unified Process cycle

Each Y cycle phase in 2TUP describe the abstraction level of a given specification, where the outer leaves are more abstract than the central branch and its lower level phases. The *generic design* phase intends for constructing standardized and reusable components by other system components. The *preliminary design* phase merges the functional and non-functional branches, resolving conflicts between them if any. The *detailed design* phase assesses how to create actual components from preliminary design specification. The remaining two stages concerns components construction and its proper validation. 2TUP was firstly designed to deal with Information Systems, thus the OSMOSE methodology had adapted it for Systems Engineering.

2.5.2 EIA 632 Standard

The EIA 632 standard (Martin, 1998) defines some Systems Engineering practices to improve the overall quality of a system design and development, in order to reduce time-to-market and to manage budgets initially made available to the project. This standard defines a systematic approach to engineer and/or reengineer a system, and bases itself on the following principles:

- A system is composed of one or more related products that allow end products over their life cycle to satisfy all stakeholders requirements;
- A system can be hierarchically organized;
- The successive application of a set of well-defined processes accomplishes a Systems Engineering process.

Figure 2.3 presents the EIA 632 standard processes.

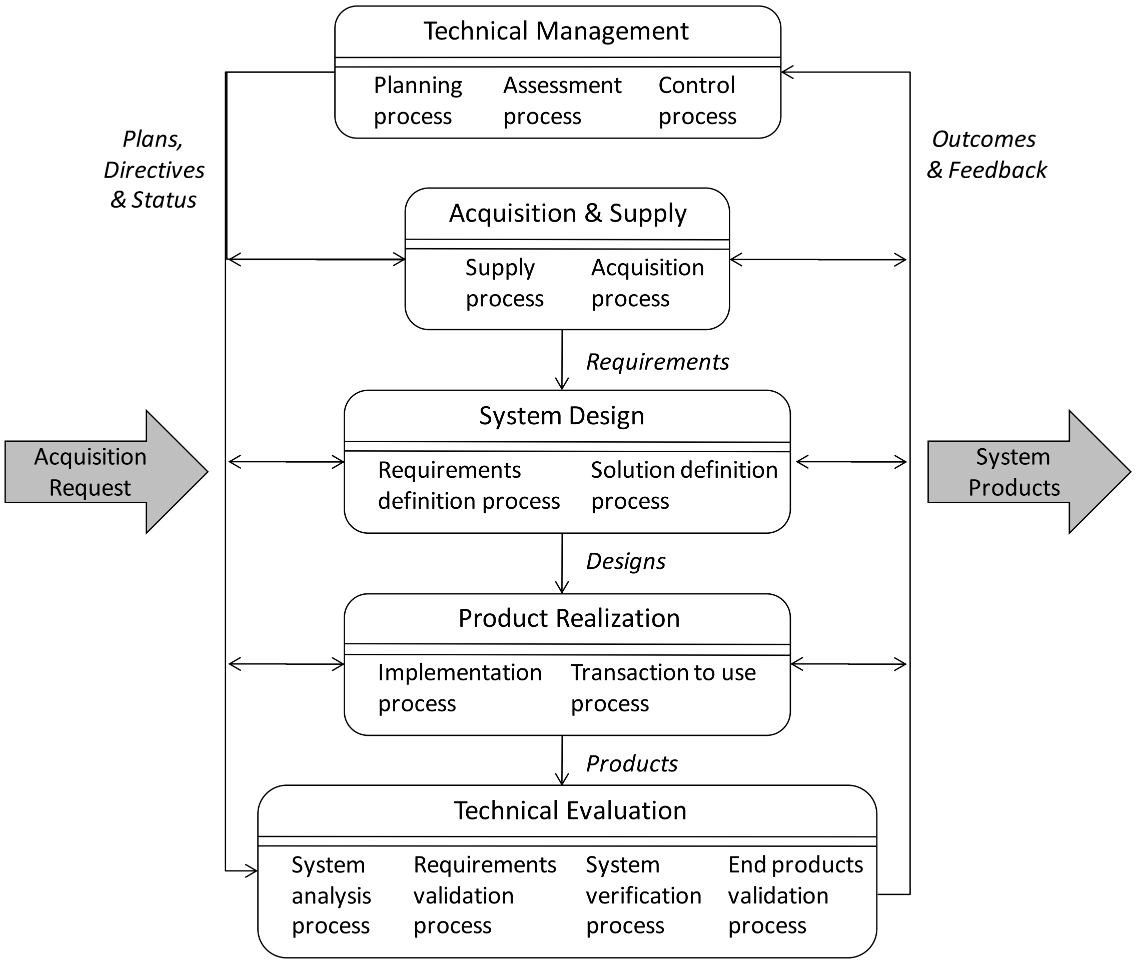


Figure 2.3: The EIA 632 process

2.5.3 OSMOSE Process

The EIA 632 defines *what to do* within an Engineering process, while 2TUP defines *how to do*. The specialization of these two processes gave rise to the OSMOSE Airbus Internal process for Avionics Systems (AIRBUS, 2007a). The OSMOSE process cycle is presented in Figure 2.4.

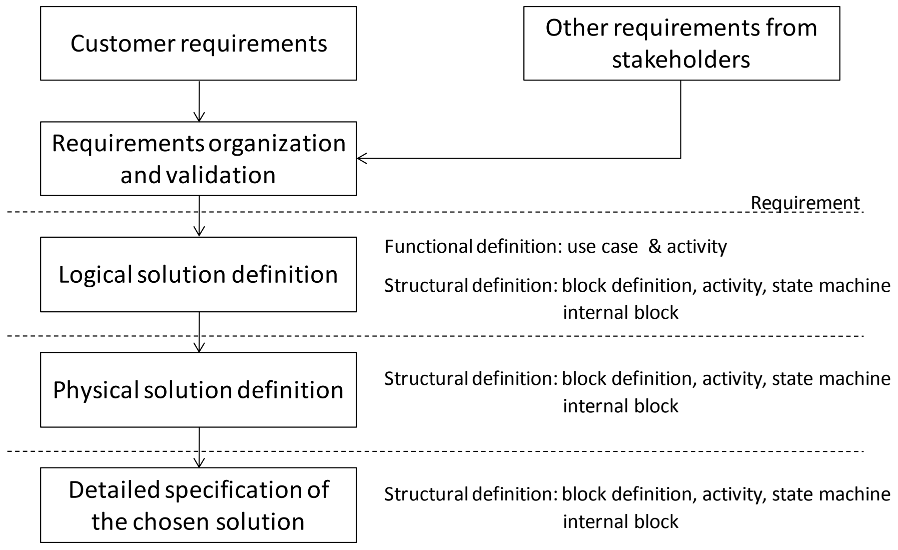

Customer requirements
Other requirements from stakeholders
Requirements organization and validation
Requirement
Logical solution definition
Functional definition: use case & activity
Structural definition: block definition, activity, state machine internal block
Physical solution definition
Structural definition: block definition, activity, state machine internal block
Detailed specification of the chosen solution
Structural definition: block definition, activity, state machine internal block

Figure 2.4: OSMOSE process cycle

As any design and development process, OSMOSE starts with requirements elicitation and specification (boxes *Customer requirements* and *Other requirements from stakeholders* in Figure 2.4). It formalizes each gathered requirement from the stakeholders according to internal Airbus specification directives. After a requirement is formalized and ratified, it is further detailed. This detailing process creates the technical specification of new equipment (box *Requirements organization and validation* in Figure 2.4). Once the requirements were gathered, ratified and the technical equipment specification was built, OSMOSE advances to the *solution definition* stage.

The *logical solution* is the realization of system objectives, services and functional architecture, while the *physical solution* is the technical implementation of the logical one based on actual hardware and software components. For each possible solution (a solution is possible when it satisfies all requirements, and a solution varies due to the several ways we can realize a set of requirements by architectural designs), an architecture must be defined, ratified, and the logical solution must be checked for requirements conformance. Based on effectiveness and risk analysis, the designer can choose a final solution. After deciding the logical and physical solutions, we create, ratify, and check the detailed subsystems specification composing the specified system.

As OSMOSE merges both design and development processes into a single life cycle, it is possible to maintain traceability between design decision and its development realization. The logical solution is a high-level product functional description; it details its main functions, objectives and provided services. Thus, each definition inside a logical solution describes the *logical structure* of the product, *i.e.* there is an association between a high-level specification and its logical structure. On the other hand, the physical structure is the actual implementation of each logical structure. This step defines the block interfaces between components, their input and output ports for data-flow and signals, creating in this way an association between the logical structure and its physical constituting blocks.

Each equipment model (the actual product that the OSMOSE process creates) is constituted by a SysML model. This SysML model has a defined package structure, where each package contains specific design model elements. The OSMOSE model package structure is presented in Figure 2.5.

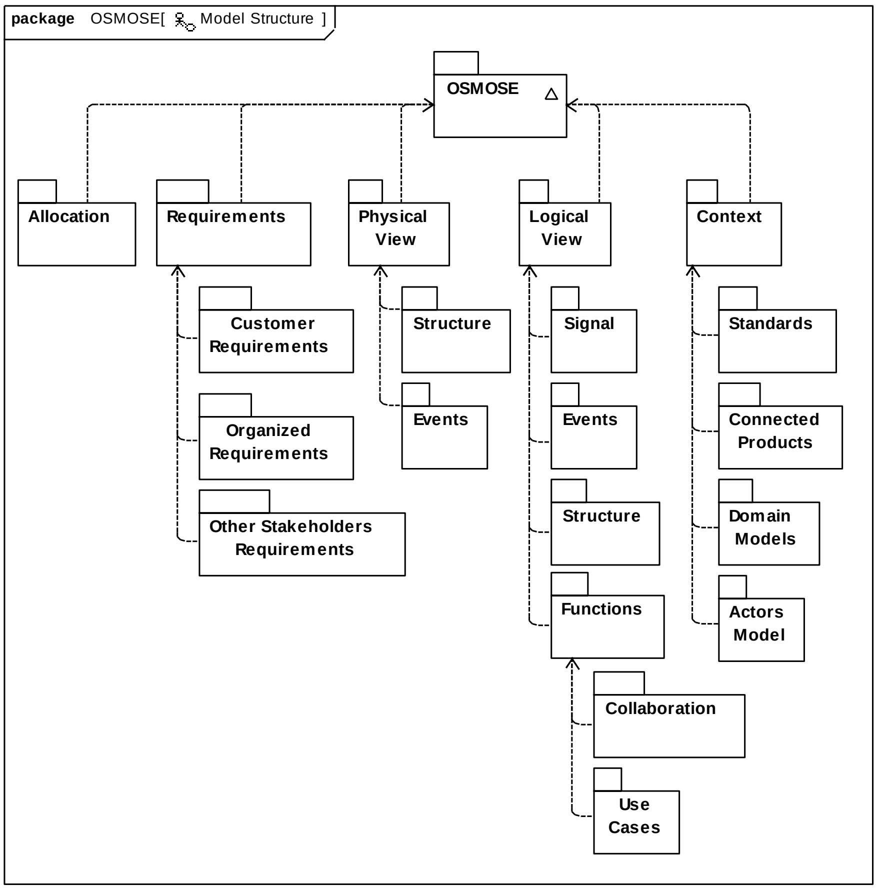


Figure 2.5: OSMOSE model package structure

The *Context* package defines the product's environment, and it is independent of the packages containing model elements defining the product. It is forbidden to create any dependency between Context and Logical View and Physical View packages. The *Context::Domain Models* package formalizes all concepts necessary to product specification, such as physical laws. *Context::Connected Products* describes all elements composing product's external structure, such as initialization files. *Context::Standards* contains standards and norms, and specifies interfaces between components and data types. *Context::Actors Model* specifies the product's interacting actors.

The *Requirements* package contains requirements specifications described with SysML requirements diagrams, as well as its inner packages *Requirements::Customer Requirements, Requirements::Other Stakeholders Requirements,* and *Requirements:: Organized Requirements.*

The *Logical View* package contains the high-level functional product (equipment) description. *Logical View::Functions* describes product objectives described in *Logical View::Function::Use Cases,* and creates within *Logic View::Function::Collaboration* the association between these objectives and product structure. *Logic View::Structure* describes product's architecture, containing mainly block elements from SysML and composition relationships between these blocks. It is worth noting that *Logic View* is both structural and behavioral system specification.

The *Physical View* package specifies the actual hardware and software product structure. *Physical View::Structure* realizes (or implements) the elements from *Logic View* packages. *Physical View* also describes ports and internal connections between actual blocks.

The *Allocation* package specifies the allocation of roles defined in *Logical View::Structure* into *Physical View::Structure* actual elements.

3 MODELING AND SIMULATION

This chapter discusses modeling and simulation (M&S) requirements, development, and deployment in organizations, particularly in AIRBUS. Section 3.1 introduces M&S, and how these activities are inserted in the development cycle. Section 3.2 presents Verification and Validation (V&V) of M&S, its basic concepts and some approaches to perform V&V applied to M&S. Section 3.2 discusses accreditation and certification, and how they connect with M&S for safe-critical domains. Section 3.4 presents the NASA standard processes for M&S, which contains the basic requirements for any safe-critical M&S activity. Finally, section 3.5 presents the AIRBUS simulation platforms, and the Systems Engineering process deployed in AIRBUS for M&S development.

3.1 Introduction to Modeling and Simulation

With the increasingly complexity of current systems, and we include here aircrafts, it is imperative to devise techniques to handle in an abstract and as formal as possible fashion this complexity. Another issue is the pressure to reduce time-to-market, what can be crucial to a new product. Just to remember the A380 delay, a €13 billion program, and its €6.3 to €7.9 billion cash shortfall due to its two years delivery delay, and the new prospects says that EADS is going to achieve investment break-even only in ten years (Clark, 2006). Therefore, in addition to handle safe-critical issues, a feasible development approach must help in respecting time development constraints and budgets. The ACARE Quality & Affordability Report discusses that, by 2020, is imperative to reduce 50% of current time in the supply-chain for aircraft production, considering both time-to-market (engineering and design time of a new aircraft) and time-to-delivery (manufacturing and delivery time to airlines), and one way of doing so is to improve Systems Engineering processes, mainly modeling and simulation (M&S) of new avionics equipment (ACARE, 2002).

The central concept in modeling is *model*. A model is a representation of something in the real world, called model *domain*. Brade (2003) defines a model as:

> "*A model is an abstract and idealized replication of a real system, which reflects all of its relevant properties with sufficient accuracy with respect to the intended purpose*"

It is possible to create a model even if the real system is still incomplete. A model usually abstracts away low-level details that are useless to the analysis we are going to conduce with the modeled system. Thus, a model can be more *tractable* because it is simpler, in the opposite of the very detailed real system. We can define model *resolution* as the perceived level of reality contained in the model. A model with high resolution is closer to the real system, while a model with less resolution is more abstract (Brade, 2003). One of the main difficulties in modeling is to define the best suitable resolution to adopt. There is no correct answer to that; adopted resolution barely depends on the system itself, it depends more on analysis and studies we will carry with the model. Different analyses (or model goals) define different model *views*, being each defined view more appropriate to one analysis and group of stakeholders as the other.

A model may contain structural and behavioral descriptions. A *structural description* consists of all model elements and their interdependencies and hierarchies. The *behavioral description* is a functional specification of how model inputs transform into model outputs, and how internal states of model elements change over time to realize the generation of outputs from inputs (Brade, 2003).

A model has three representations, depending on its purposes: conceptual, formal, and executable. A *conceptual model* presents the domain elements and their structure and behavior, and centers itself in reasoning about the modeled system. A *formal model* is a formal specification of the conceptual model, based on some adopted formalism with well-defined semantics. The *executable model* implements the formal model, and includes necessary information to be executed in a computer (Brade, 2003).

With a formal model, we can perform analysis of the produced outputs for the models inputs. When we execute the model to analyze its output, we are performing a *model simulation*. IEEE (2001) standard defines simulation as:

> *"Simulation is the execution of a model that behaves similar to the real system when provided a set of controlled inputs over time"*

The *model behavior* is the way outputs change over time during simulation. Brade (2003) presents a simulation model taxonomy:

- *Quasi-continuous vs. discrete simulation:* depending whether the state space is continuous or discrete, respectively.
- *Time-stepped vs. discrete-event simulation:* depending whether the simulation advances over a predefined time intervals, or based on triggered events in the simulation model. Time-stepped simulation supports for real-time and in-the-loop simulations, while in discrete-event usually external agents can trigger events conducing the simulation.
- *Deterministic vs. stochastic simulation:* depending whether the produced outputs depends on the inputs or not, respectively.

For more details in modeling and simulation, please refer to Brade (2003).

3.2 Verification and Validation of Simulation Models

Verification and Validation (V&V) techniques want to answer whether a model is correct, and what we can do to ensure a model is correct. *Verification* aims at ensuring that both conceptual model and its executable model are correct given the requirements specification. *Validation* informs whether an executable model results are within an acceptable range as defined in its conceptual model. V&V quite relates to model accreditation, which is concerned with building into users the confidence necessary to rely on the model, and on data it produces (Sargent, 2008). We will discuss model accreditation in the next section.

Sargent (2008) points out four approaches to conduct model V&V inside the simulation model development team:

- The model development team is itself in charge of performing V&V activities. The team makes subjective decisions based on earlier model evaluations, *e.g.* tests or model execution;
- Assuming that we have two separate teams, one dedicated to model development, and the other to model V&V, and if the development team is not too large, one of its members can help the conduction of V&V. In addition to verification, this approach increases accreditation, due to the participation of a simulation model user in its V&V process;
- The approach called Independent V&V assumes a V&V authority in charge of the decision whether V&V results proposed by the simulation model V&V team is valid or not. This approach is suitable when the simulation model development team is too large, or when it is involved in many projects with several suppliers. In this approach, an iterative refinement process between the Independent V&V authority, V&V team, and development teams occurs;
- The last approach is to use a scoring model. Scoring is conducted subjectively, based on V&V team experience. In this case, some model aspects are explicitly chosen over others, attributing a bigger score to the most important, and a smaller one to the least important.

Furthermore, Sargent (2008) describes several techniques to perform V&V in simulation models:

- *Animation:* model's behavior is presented in a step-by-step fashion, usually enabling to control what is being displayed, and how animation advances;
- *Comparison:* this technique compares the results produced by the undergoing simulation model with a similar, previously validated, simulation model. Based on an acceptance threshold, we can say that differences between the two models are acceptable or not;
- *Degenerate tests:* this tests how model degenerates when its inputs are increasingly closer to the acceptable specified limits;
- *Event validity:* compares the fidelity of simulated events or the number of model elements occurrences with real ones;
- *Extreme condition tests:* tests the robustness of the simulation model, and how it behaves in extreme values, for example, division by zero;
- *Face validity:* evaluates with a domain expert if the outputs the simulation model produces are correct, or at least seems to be correct;
- *Historical data validation:* uses previous validated data, if existing, to validate if new produced data is correct;
- *Historical methods:* divided into three sub-techniques: *rationalism* assumes that model team knows which output is correct, and uses this knowledge to assess the model; *empiricism* requires that all rational assumption to be

empirically validated; and *positive economics* assess causal relationships constructed from rationalism are empirically valid;

- *Internal validity:* only applies to stochastic models (models where outputs are independent of inputs), assess the amount of variability produced between model executions. Depending on the model domain, high variability can indicate lack of consistency;
- *Operation graphics:* V&V model team observe model behavior with graphical analysis of its generated output;
- *Sensitivity analysis:* variations in model outputs caused by perturbations in its inputs must be the same in both the real system and the simulation model;
- *Predictive validation:* V&V team uses the model to foresee the real system behavior. Usually, this model is developed before the real system, in order to conduct feasibility analysis, for example;
- *Traces:* several modeled entities have their execution traced to check if they behave properly and as expected during simulation execution;
- *Turing tests:* experts in the model domain evaluate if they can discriminate the outputs produced between simulation and real systems.

3.3 Model Simulation Accreditation and Certification

When we refer to accreditation and certification, we mean that the product under certification provides guarantees that it supports all requirements agreed by parts as being important for product's domain. Certification is necessary because, while we still continue not to use exhaustive V&V techniques (mainly due to scalability issues), we cannot be sure that our models are 100% reliable, correct, and suitable (Brade, 2003). Assuming this, we need to define the *degree of confidence* a model provides. This degree is based both on model's *depth* (it implements the correct level of details of its functionalities) and *breadth* (it implements all functionalities it needs to provide). Model *suitability* is a measure that accounts if model's depth and breadth are acceptable to model requirements. Based on these concepts, Brade (2003) defines *credibility*:

> *"The credibility of a model or simulation results is an expression of the degree to which one is convinced that a particular model or particular set of simulations results are suitable for an intended purpose and correct"*

Accreditation is the process of certification that a legal and recognized Institution or Body conducts to assert if the product (in our case simulation models) has credibility for its purpose. Balci (2001), based on the International Standardization Office (ISO), presents the definition of certification and accreditation as:

> *"Certification is a procedure by which a third party gives written assurance that a product, process or service conforms to specified characteristics"*
>
> *"Accreditation is a procedure by which an authoritative body gives formal recognition that a body or person is competent to carry out specific tasks"*

The US Department of Defense (DoD-US) defines simulation model accreditation as (Brade, 2003 *apud* DoD-US 1996).

> *"Accreditation is the official certification that a model, simulation, or federation of models and simulations is acceptable for use for a specific purpose"*

In AIRBUS, simulation is not certified yet, but with the steps beyond integrating design and simulation, in the future certifying executable simulation models may be interesting. If executable simulation models were certified, design teams and external suppliers could reuse them, reducing time-to-market and increasing credibility in the aircraft development cycle and its iterations. Considering the aeronautical domain as a *multidomain* and safe-critical, where knowledge from several disciples interconnect, certification is still complicated, being a difficult process and management issue if deciding to certify simulation models (Rodríguez-Dapena, 1999).

3.4 Modeling and Simulation Standard: NASA Approach

The three most deployed standards for M&S were proposed by three governmental agencies: the US Department of Defense (DoD-US, 2004), the Australian Department of Defence (DoD-AU, 2005), and the National Aeronautical and Space Administration (NASA, 2008). We do not see published proposals from industry to M&S, and usually companies adapt one of the three presented M&S standards (as is the case in Boeing Company, which adapts the DoD-US approach). To present the requirements involved in M&S activities, this section describes requirements from the NASA M&S standard (NASA, 2008), and as all the three standards are similar, we have a good coverage of existing requirements to develop M&S activities. NASA created this standard to tackle the following activities, which can be adopted and adapted in any organization:

- Identify best practices to ensure that knowledge from operations is captured in the user interfaces (the way users interact with models);
- Develop process for tool verification, validation, certification, reverification, revalidation, and recertification based on operational data;
- Develop standards for documentation, configuration management, and quality assurance;
- Identify any training or certification requirements to ensure proper operational capabilities;
- Provide a plan for tool management, maintenance, and obsolescence consistent with M&S environments;
- Develop a process for user feedback when results appear unrealistic or defy explanations;
- Provide a standard method to assess the credibility of the models and simulations presented to stakeholders when making critical decisions;
- Assure that model and simulation credibility meets project requirements.

The organization or group of individuals in charge of conducting M&S is called *responsible party*. The responsible party is in charge of M&S activities inside the project or program, and is responsible of requirements analysis, documents management, and the definition of objectives for all M&S activities. In the following, we present the requirements associated with each M&S activity defined in the NASA M&S standard the responsible party must perform. Note that these requirements can be adapted for each specific M&S project or program; it is not necessary to conduct all existing requirements.

Concerning M&S program management, NASA (2004) defines for the responsible party:

- Define M&S acceptance criteria and accreditation;
- Define scoring rationale to V&V activities;
- Define the intended use of M&S;
- Define metrics to assess program milestones;
- Report M&S results to support technical decisions;
- Control management of M&S (artifacts, project schedule, and processes).

Concerning model development, responsible party's activities are:

- Document design decisions in the conceptual model;
- Document model structure and behavior (*e.g.* equations);
- Document model inputs and data set to be used;
- Document units of the input data;
- Document model's limits of operation;
- Document how to use correctly the model;
- Document how to calibrate input data;
- Document model update, assigning for each different update an unique identification;
- Document criteria and date for model obsolescence;
- Provide a mechanism to enable model users to report erroneous behavior and non expected results found with the model;
- Keep models and associated documentation in control management repository.

Concerning model simulation and analysis, activities are:

- Assure that simulations occurred within the established limits, or, in case of transposing these limits, document the consequences in doing so;
- Document warning and error messages found during simulation;
- Document the version of M&S analysis results;
- Document necessary computational resources to execute the simulation;
- Document the process of constructing and publishing acquired simulation results to stakeholders;

- Document the history of M&S within the same or close applications that are useful to establish model credibility for the current M&S application;
- Document the evaluation if performed simulation and analysis are useful to the current M&S application;
- Document any decision concerning simulation and analysis configuration.

Concerning model V&V, activities are:

- Document which V&V techniques were used;
- Document numerical estimation errors, convergence, precision for the results;
- Document current status of model V&V;
- Document metrics used to validate the model and its inputs;
- Document any studies conducted with the simulation results.

Finally, concerning model credibility, activities are:

- Identify model credibility based on criteria established for the project;
- Justify assigned credibility for all used criteria;
- Sum up scores and assign overall model credibility score;
- Publish results to stakeholders;
- Include warnings in the final report when: some acceptance criteria was not met, violation of any model's premises, violation in model operational limits, execution errors and warning messages thrown, unfavorable results from the analysis of simulation results.

3.5 Model Simulation at AIRBUS

3.5.1 System Simulators

Simulation has three branches at AIRBUS: *engineering*, which is used to test and to validate aircraft equipments during the development of aircraft systems, and is very useful to test flight parameters on ground in order to guide equipments design: *training*, which is used to train aircraft crew, in this case AIRBUS delivers to Full Flight simulators manufacturers the core simulation systems; and *research*, which is independent of an aircraft program and is used to carry tests on new concepts and designs, and architectural proposals. In general, system simulation is very important to reduce development time.

Inside AIRBUS, there is the Simulation Products Department (EDYYS), which is in charge of functional simulation activities, being the AIRBUS centre of competence on real-time simulation. The EDYYS has expertise on aircraft system simulation and is deeply involved on the aircraft development process. It has expertise also on electronics, flight simulation methods and architectures. Its main missions are: to design, develop and integrate simulation hardware and software components into simulators, as well as to assure their maintenance within the Company; to design electronic interfaces for engineering simulators; to develop software simulation packages for every new aircraft program started; to guarantee that training simulators will be available before the new aircraft entries into service; to facilitate the development of low cost and high quality training devices; and to develop commercial business simulators together with the airlines and with training centers.

Figure 3.1 jointly presents the AIRBUS aircraft development and simulation cycles. The simulation and development cycles at AIRBUS take the form of a standard V development cycle (Forsberg, 1991), where it is possible to note that a *simulation platform* (white boxes) is associated for every development phase (gray boxes). In this way, simulation is highly coupled with the development, enhancing quality for the later development phases quite early in the development cycle.

The following simulators compose the simulation platform at AIRBUS:

- EPOPÉE *(Etude Prospective pour l'Organisation d'un Poste d'Equipage Ergonomique)*: this simulator corresponds to the first simulation platform of Figure 3.1. It helps the development teams to choose new design concepts and techniques before a new aircraft program is launched, assessing control laws, cockpit ergonomics and crew workload;

- OCASIME *(Outil de Conception Assistée de Simulation Multi-Equipements)* : this simulator is dedicated to system design, hosting software simulating the flight loop and other programs used to validate and test aircraft logics and equipments specification;

- A/C -1: this simulator is specific for a given aircraft program, and provides a representative system simulation used to test and to improve control laws, to assess cockpit ergonomics and crew workload. It represents most of the elements on the cockpit and some buttons are operational through touch screens.

- System Integration *Test Rigs*: after complete equipment definition and development, we integrate single equipment on functional test rigs connected to simulation platforms. These platforms host simulation packages simulating some aircraft systems such as the Flight Warning System (checks the aircraft integrity) and the Control and Display System (displays the cockpit information).

- A/C 0: this simulator, also called *Iron Bird*, integrates all actual equipments before their deployment on the final aircraft. It needs the most representative environments, and is composed of a real cockpit, all on-board computers, a reproduction of electrical and hydraulics wiring, aircraft actuators, and environment system simulation (simulates real world atmosphere conditions, such as rain, snow, hot, and so on), and aircraft physics (flight mechanics).

3.5.2 Development, Integration and Validation of Simulation Models

The current AIRBUS process for developing, integrating, and validating simulation models is the AP2633 (AIRBUS, 2008). When we say simulation model, actually we refer to an *AP2633 Compliant Simulation Model*. Thus, a simulation model must comply with AP2663 process directives to be deployable in the system simulators presented in the last section. The AP2633 process is a standard V cycle, and is divided in four phases: definition, development, evolution, and maintenance.

Definition contains all activities related to identifying simulation model requirements. *Development* contains all activities supporting the development of simulation models to reach their deliveries with the full requested functionalities, *i.e.* stable requirements as well as their development and validation. *Evolution* contains activities in charge of making corrections in simulation models to make them AP2633 compliant, as well as model updates to follow A/C systems evolution before Aircraft Entry Into Service (EIS).

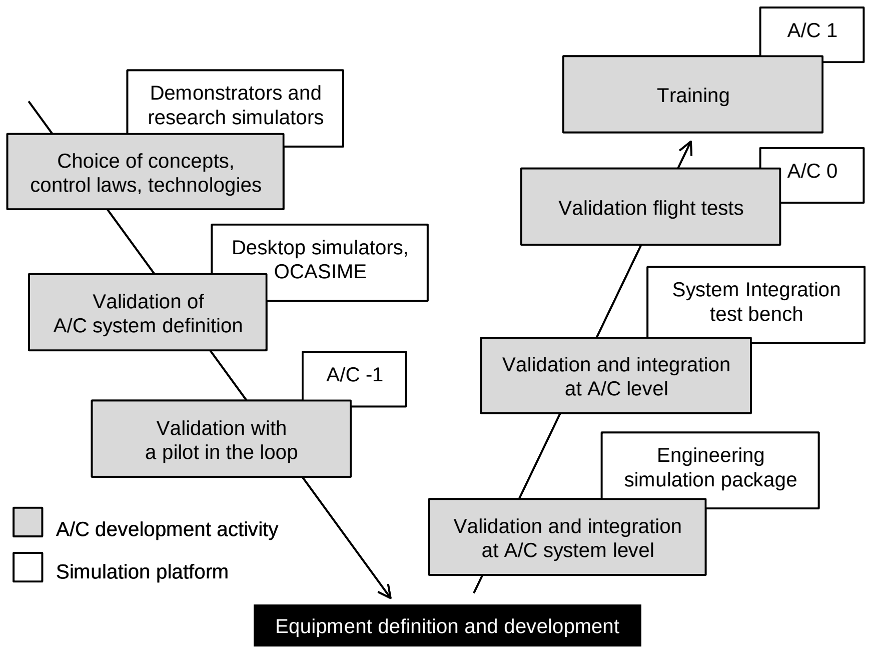

A/C 1
Training
Demonstrators and research simulators
Choice of concepts, control laws, technologies
A/C 0
Validation flight tests
Desktop simulators, OCASIME
System Integration test bench
Validation of A/C system definition
A/C -1
Validation and integration at A/C level
Validation with a pilot in the loop
Engineering simulation package
A/C development activity
Simulation platform
Validation and integration at A/C system level
Equipment definition and development

Figure 3.1: AIRBUS aircraft development and simulation cycles

The Simulation Model Life Cycle is presented in Figure 3.2. The sub-processes presented in Figure 3.2 are as follows:

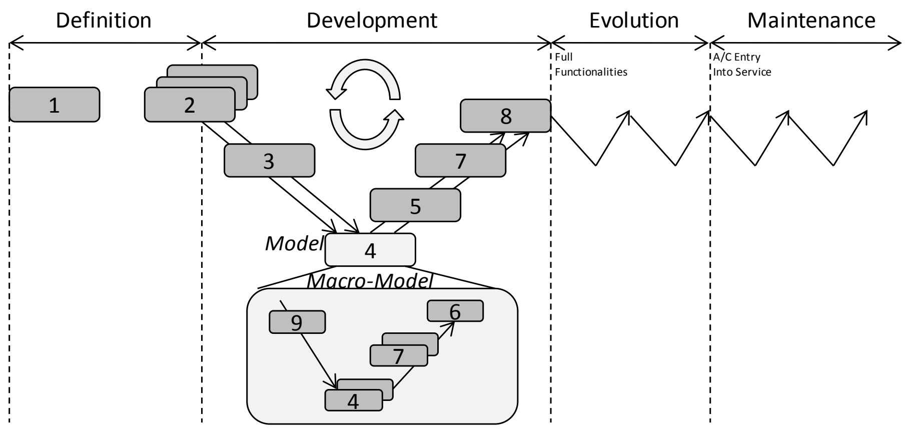


Figure 3.2: Simulation model life cycle.

At A/C program level, sub-process 1: Identify General Simulation Models Needs. At model/macro-model level 2: Define Model Functional and Performance Requirements; 3: Plan Simulation Model(s) Development; 4: Develop Shared Simulation Model; 5: Perform Delivery Preliminary Acceptance; 6: Define Integration and Validation Plan; 7: Integrate (Model/Macro-Model); 8: Validate (Model/Macro-Model); and 9: Define Macro-Model Verification Plan. This work applies to the fourth activity in the simulation model life cycle.

4 PROPOSED SOLUTION

This chapter presents the proposed solution to the problems discussed in the first chapter, section 1.2. Section 4.1 presents the requirements and the artifacts we need to produce and trace, while section 4.2 presents the low-level design flow detailing all proposed activities.

4.1 Solution Artifacts and Requirements

Considering the development V-cycle presented in section 3.5, Figure 3.1, this work is focused in the OCASIME simulator, despite of its applicability in other development stages. Figure 4.1 presents the design and simulation interactions occurring in this development cycle.

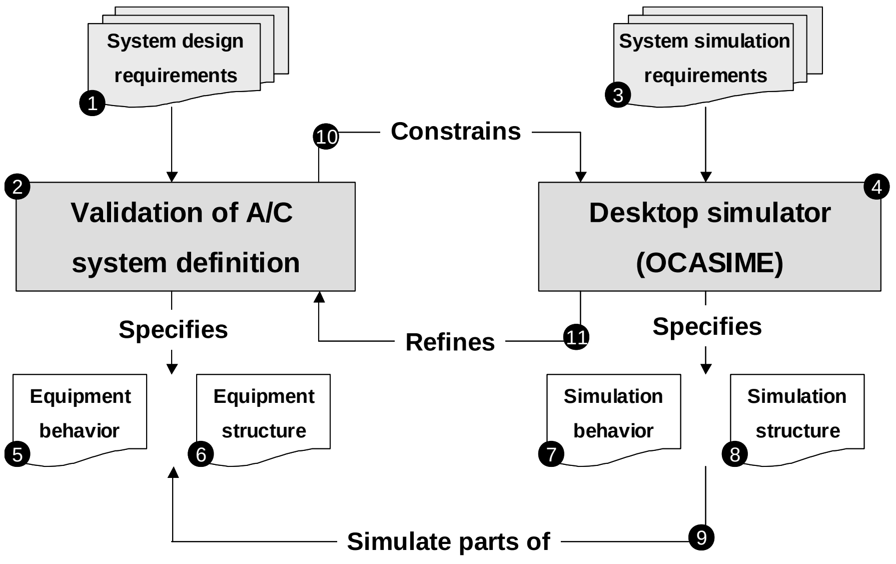


Figure 4.1: Design and simulation interactions and artifacts

Design (box 2) and simulation (box 4) start with a set of requirements (box 1 and 3, for design and simulation, respectively). The design purpose is to provide a specification of an avionics equipment structure (box 6) and behavior (box 5). In the same way, the purpose of a simulation is also to provide structure (box 8) and behavior (7), but for a simulation of some avionics equipment. As simulation artifacts simulate a set of design artifacts (arrow 9), we can say that these design elements (and the decisions around them) *constrains* the simulation requirements and elements (arrow 10). As we use simulation knowledge to advance and improve design, we can say that simulation *refines* design (arrow 11).

To develop a simulation model, we can identify three activities: system design, simulation requirements analysis, and simulation design. System design is concerned with avionics equipment design (Figure 4.1, box 2). Simulation requirements analysis specifies what must be simulated based on the constraints from design (Figure 4.1, boxes 3 and 4). Finally, Simulation Design is the construction of both simulation structure and behavior (Figure 4.1, boxes 7 and 8), implementing the simulation requirements (Figure 4.1, box 3), which simulate equipment behavior and structure (Figure 4.1, arrow 9). Figure 4.2 presents these three activities and the current and proposed artifacts flow.

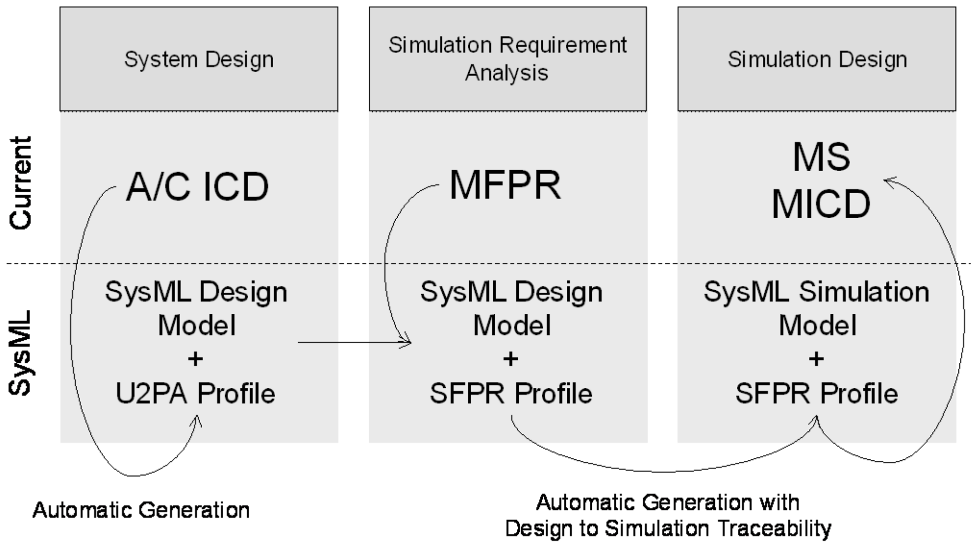

System Design
Simulation Requirement Analysis
Simulation Design
Current
A/C ICD
MFPR
MS MICD
SysML
SysML Design Model + U2PA Profile
SysML Design Model + SFPR Profile
SysML Simulation Model + SFPR Profile
Automatic Generation
Automatic Generation with Design to Simulation Traceability

Figure 4.2: Design and simulation activities and artifacts of simulation development

The problem is that both A/C ICD and MICD are very rudimentary documents, in the sense of Information Systems. The former is a Comma Separated Text (CSV) file, while the latter is an Excel sheet. Naming conventions and semi-automated document production create the modeling coherences between A/C ICD, MFPR, MS and MICD. Regarding MICD, there is an Excel Visual Basic Script called MICD Studio that generates these coherences guided by commands given by the Simulation Model Designer. One example of unstructured constructs existing in MICD is sheet naming. If some expected sheet by the MICD Studio does not follow the naming convention, it throws an error. This kind of consistency checking based only on naming convention dates back before databases management systems, and research proved this as being a bad approach for data management (Silberschatz, 2001).

Another issue, as explained earlier, is the difficulty in handling traceability between design and simulation elements with the current approach. Figure 4.2 *current* upper band shows listed artifacts and their use and/or production during equipment simulation.

4.2 Proposed Design Flow based on SysML

To improve equipment simulation, this work proposes the adoption of SysML as the means of representing design and simulation constructs and as the simulation structural language. Thus, this approach unifies in only one modeling language design and simulation activities, while maintaining simulation design traceability between design and simulation models, as well as between simulation model refinements. The proposed design flow is presented in Figure 4.2 in *SysML* lower band.

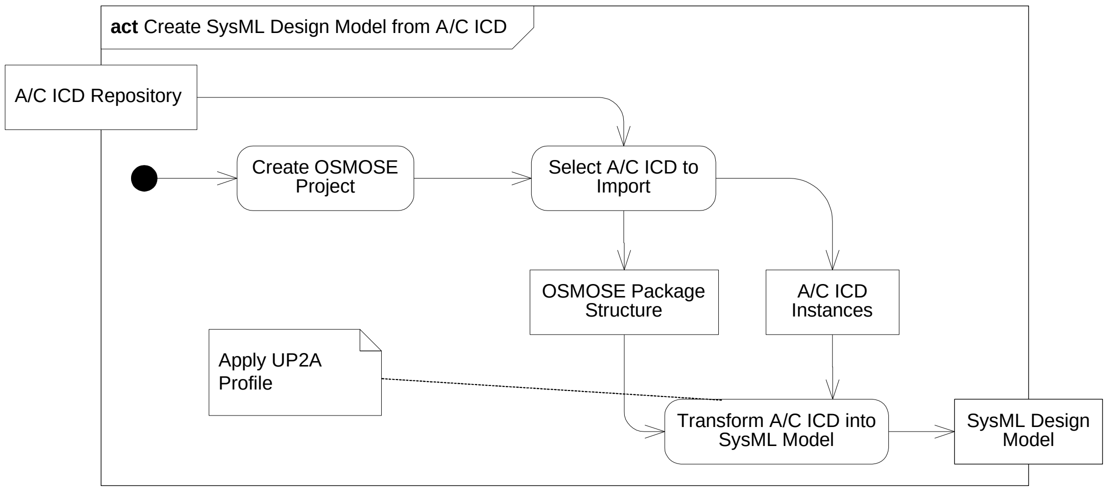


Figure 4.3: SysML design model generation from A/C ICD

Figure 4.3 presents the activity representing *System Design*. A *SysML Design Model* is created from an A/C ICD repository, and the UML Profile for AIRBUS AP2633 is used to encapsulate parsed A/C ICD data.

From the generated SysML Design Model and with the MFPR documents, it is possible to create the *SysML Simulation Model*. A simulation considers the UML Profile for Simulation Functional and Performance Requirements (SFPR) as its driving process. Figure 4.4 presents this process, and implements the *Simulation Requirements Analysis* in Figure 4.2.

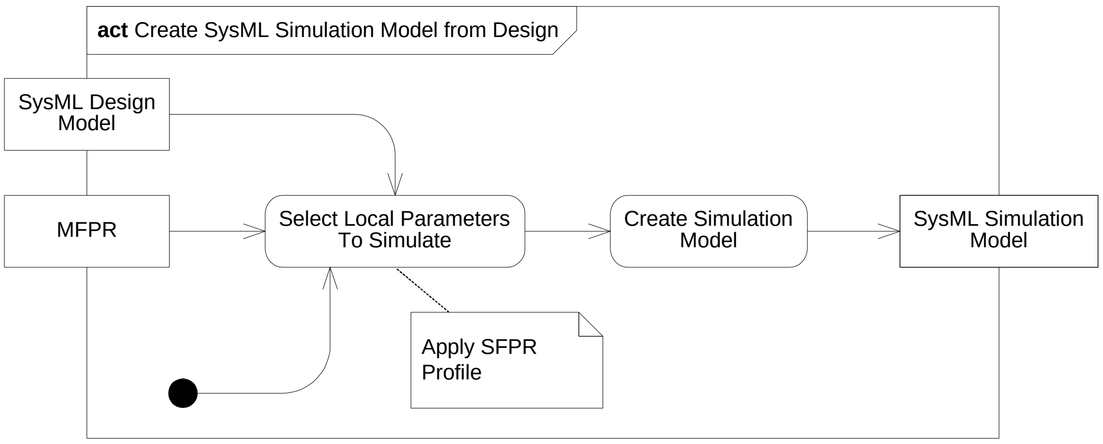


Figure 4.4: SysML simulation model generation from design model and from MFPR analysis and requirements document

After creating the SysML Simulation Model from the SysML Design Model, and refining simulation to meet MFPR functional and non-functional requirements, the Simulation Designer exports the final SysML Simulation Model to the Model Interface Control Document (MICD). MICD is a Microsoft Excel sheet describing how each model element is connected to build up the equipment. The MICD creation ends the simulation process for the simulated system. This step is the *Simulation Design* in Figure 4.5.

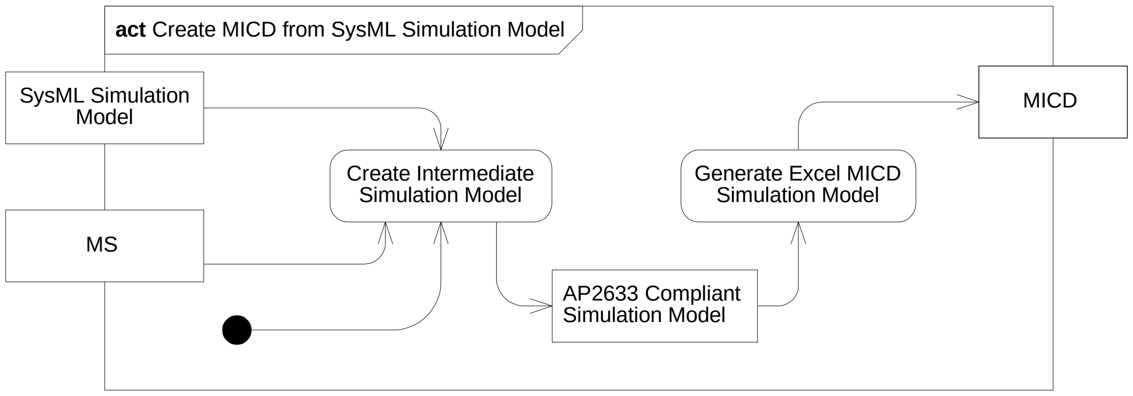

act Create MICD from SysML Simulation Model
SysML Simulation Model
MS
Create Intermediate Simulation Model
AP2633 Compliant Simulation Model
Generate Excel MICD Simulation Model
MICD

Figure 4.5: MICD generation from AP2633 compliant SysML simulation model

Figure 4.6 presents the complete Integrated Model-Based Design and Simulation process, with all its required and produced artifacts, and its internal activities described above. This approach leverages simulation and design by putting them together with a unified modeling language, instead of several different documents. As we automatically generate all SysML models, we have modeling style consistency between the Simulation Model Design team, as well as human errors reduction. In addition, this approach contributes to leverage the simulation process, enabling in the future the SysML Simulation Model be completely executed, given that we can assume a SysML subset to be executable by some model interpretation engine. We have performed real design and simulation experiments from the A380 aircraft program in order to validate this approach, and section 5 presents and discusses the results.

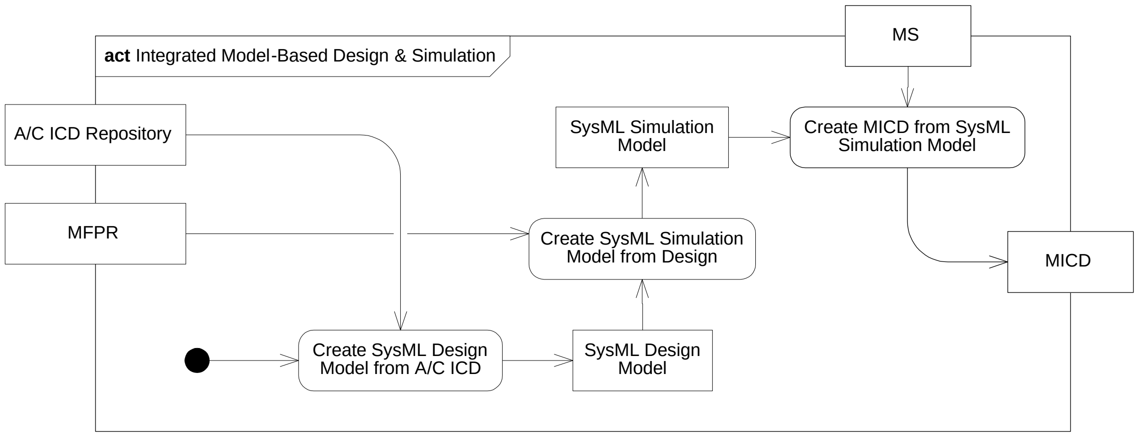

act Integrated Model-Based Design & Simulation
MS
A/C ICD Repository
MFPR
SysML Simulation Model
Create MICD from SysML Simulation Model
Create SysML Simulation Model from Design
MICD
Create SysML Design Model from A/C ICD
SysML Design Model

Figure 4.6: Complete integrated model-based design and simulation design flow

After creating the simulation model, the next step is simulation code production based on the simulation model interface. The Simulation Model Designer creates a SCADE or Simulink model implementing the model behavior, using simulation variables declared in the MICD document. After specifying all SCADE and Simulink models, the designer creates a state machine implementing the high-level behavior (or functions) the simulation model must perform. In this work, we propose to model this state machine with the UML State Machine, and to generate the simulation C code for this state machine calling the generated C code from SCADE or Simulink models. Figure 4.7 presents the design flow of simulation code production from UML.

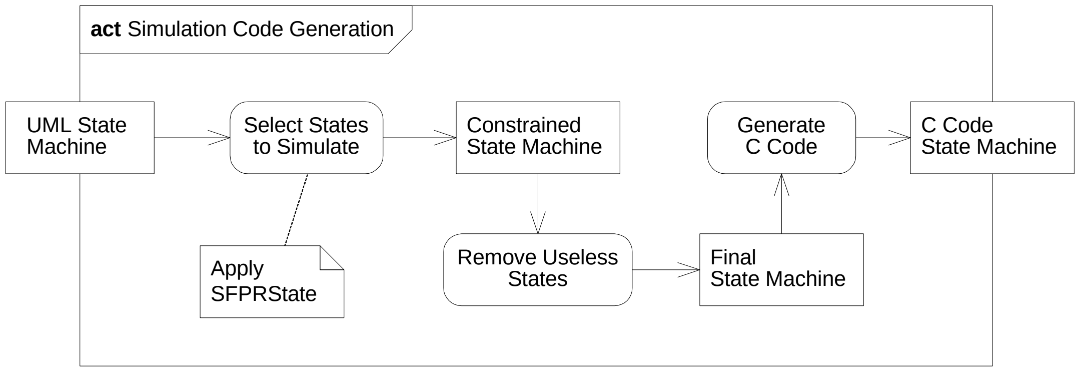


Figure 4.7: Simulation state machine code generation from UML State Machine describing equipment behavior

5 CASE STUDIES

This chapter presents the case studies we have performed to validate our proposal. It presents the approach from its user perspective. Section 5.1 presents the A380 navigation system, and the generation of its specification to SysML Design Models, as well as the MICD production from SysML Simulation Models. Section 5.2 presents the Primary Flight Control Computer and the code generation process for its UML Equipment State Machine.

5.1 A380 Navigation System

5.1.1 Navigation System Probes Embedded Avionics

The A380 navigation system, which the ATA 34 chapter regulates, is composed of 33 equipment occurrences, as follows:

- Two Automatic Direction Finders (ADF) occurrences. ADF is one of the simplest, but very useful, navigation equipment used when flying by instruments. The ADF points a navigator (it can be an arrow or digital earth coordinates) in the direction of a tuned radio frequency emitter;
- Three Air Data Inertial Reference Unit (ADIRU) occurrences. ADIRU is composed of two applications, Air Data Reference (ADR) and Inertial Reference System (IRS). ADR provides air data information concerning airspeed, angle of attack, altitude, and IRS provides the aircraft position and attitude. These data are available to both the pilots and the aircraft;
- One Air Data Switching (ADS) occurrence;
- One Autotrim Heading Angle (ATT-HDG) occurrence. It enables to set (autotrim) an aircraft inclination based on the aircraft's nose (heading angle)
- Two Distance Measuring Equipment (DME) occurrences. DME provides the aircraft distance to the ground station. UHF waves sent from ground stations are caught by DME, and based on the time needed to these ground stations acknowledging the reception of waves sent back by the aircraft, DME can calculate the aircraft distance from ground;
- Two Integrated Standby Instrument System (ISIS) occurrences. ISIS displays airspeed, altitude, Mach, attitude, and vertical speed;
- Six *Prise de Pression Statique* (ISP) occurrences. It also calculates air data based on wind static pressure;

- Three Multi-Function Probes (MFP) occurrences. It reads air data information, but instead of using pneumatic movements to publish this data to the aircraft navigation systems, it uses an ARINC 429 digital bus;
- Two Multi-Mode Receiver (MMR) occurrences. It is used to perform aircraft landing based on microwave, instead of instrument or GPS landing.
- Two Outside Air Temperature (OAP) probes. It gets the outside temperature and sends it to the navigation systems;
- One Pitot standby probe. It calculates airspeed based on wind dynamic pressure that gets inside it.
- Two Pitot Static probes. It is also used to calculate aircraft speed, Mach, and altitude based on wind pressure inside the *Pitot* probes, making pneumatic movements in the aircraft equipment;
- Three Radar Altimeter (RA) occurrences. It calculates the aircraft distance from ground, *i.e.* it measures the altitude between the plane and the ground directly below the aircraft;
- Three SSA occurrences.

Figure 5.1 presents the *Pitot* and static pressure probes; we can find in the A330 aircraft, which are very similar in the A380 one.

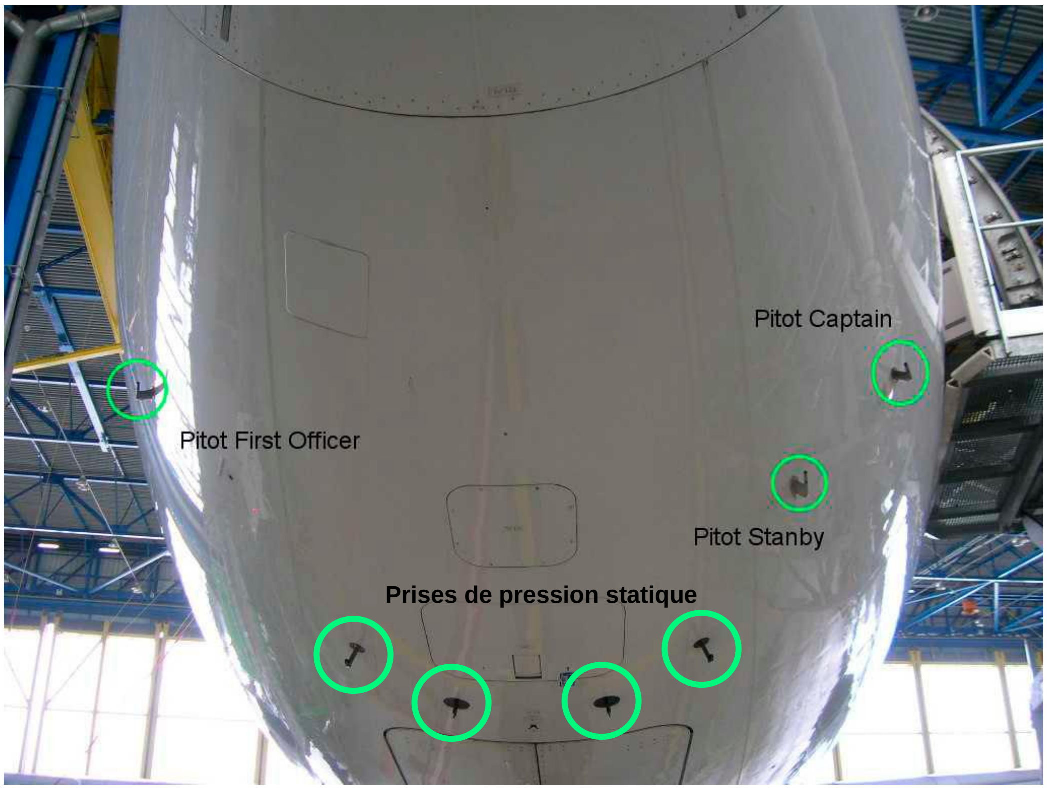
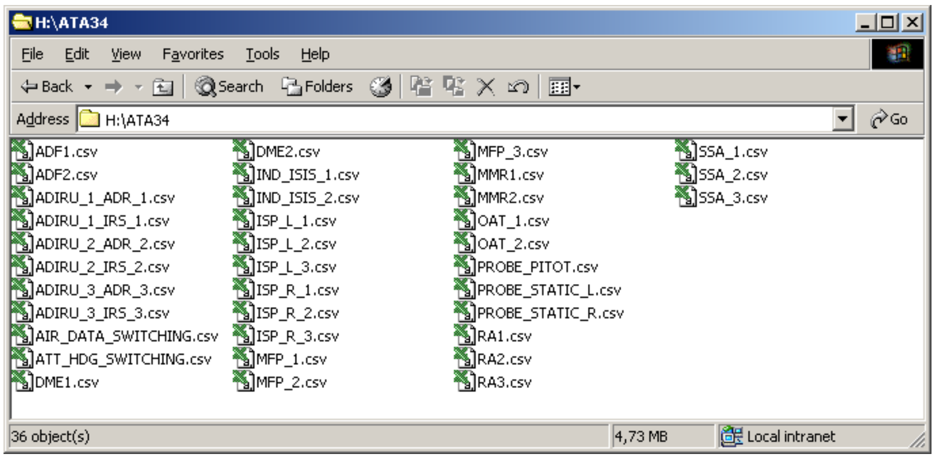


Figure 5.1: A330 external navigation probes

5.1.2 SysML Design and Simulation and MICD Generation

Each equipment occurrence has an A/C ICD describing its interfaces, thus, the A380 navigation system is composed of 33 A/C ICDs. Figure 5.2 lists these files.



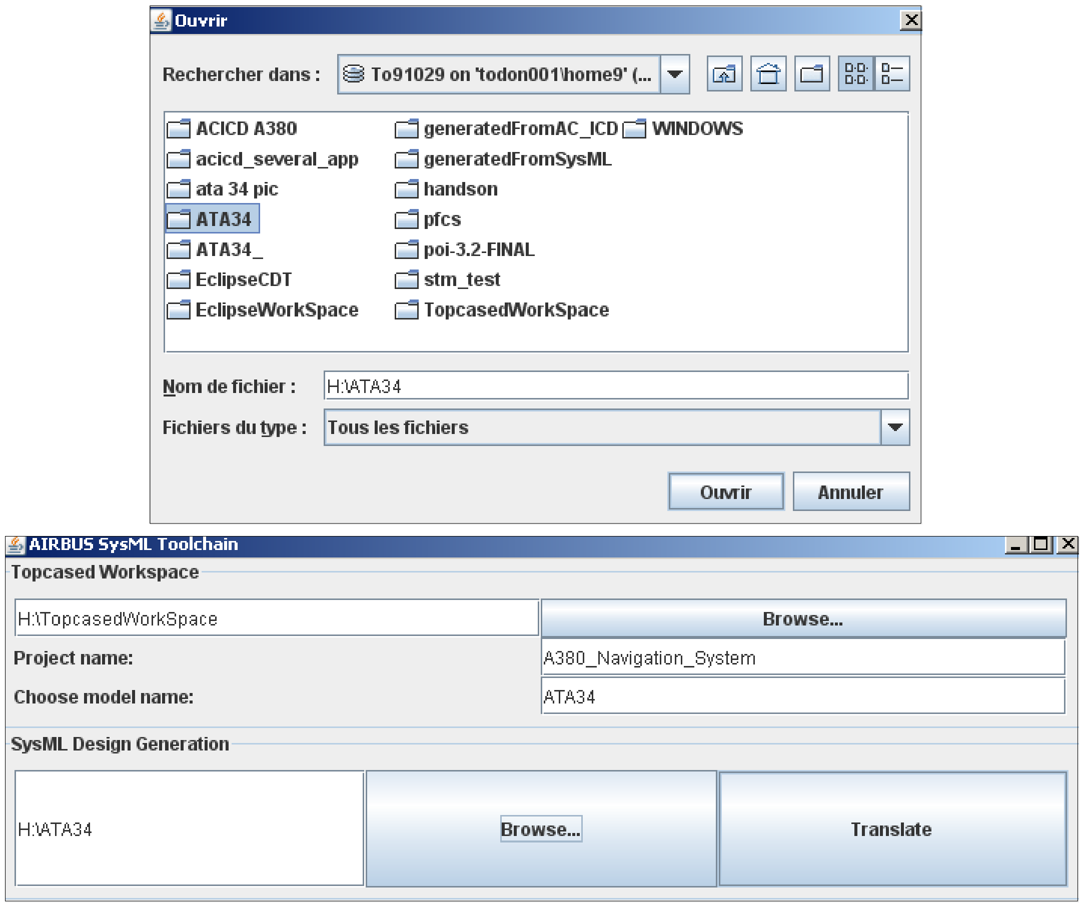
H:\ATA34

ADF1.csv
ADF2.csv
ADIRU_1_ADR_1.csv
ADIRU_1_IRS_1.csv
ADIRU_2_ADR_2.csv
ADIRU_2_IRS_2.csv
ADIRU_3_ADR_3.csv
ADIRU_3_IRS_3.csv
AIR_DATA_SWITCHING.csv
ATT_HDG_SWITCHING.csv
DME1.csv
DME2.csv
IND_ISIS_1.csv
IND_ISIS_2.csv
ISP_L_1.csv
ISP_L_2.csv
ISP_L_3.csv
ISP_R_1.csv
ISP_R_2.csv
ISP_R_3.csv
MFP_1.csv
MFP_2.csv
MFP_3.csv
MMR1.csv
MMR2.csv
OAT_1.csv
OAT_2.csv
PROBE_PITOT.csv
PROBE_STATIC_L.csv
PROBE_STATIC_R.csv
RA1.csv
RA2.csv
RA3.csv
SSA_1.csv
SSA_2.csv
SSA_3.csv

36 object(s) | 4,73 MB | Local intranet

Figure 5.2: A380 navigation systems' A/C ICDs

The first step is to generate the SysML Design Models from the A/C ICD repository presented in Figure 5.2. With our tool prototype, we just select this folder and click on *Generate*. Figure 5.3 presents this process.



Rechercher dans : To91029 on 'todon001\home9' (...

ACICD A380
acicd_several_app
ata 34 pic
ATA34
ATA34_
EclipseCDT
EclipseWorkSpace
generatedFromAC_ICD
generatedFromSysML
handson
pfcs
poi-3.2-FINAL
stm_test
TopcasedWorkSpace
WINDOWS

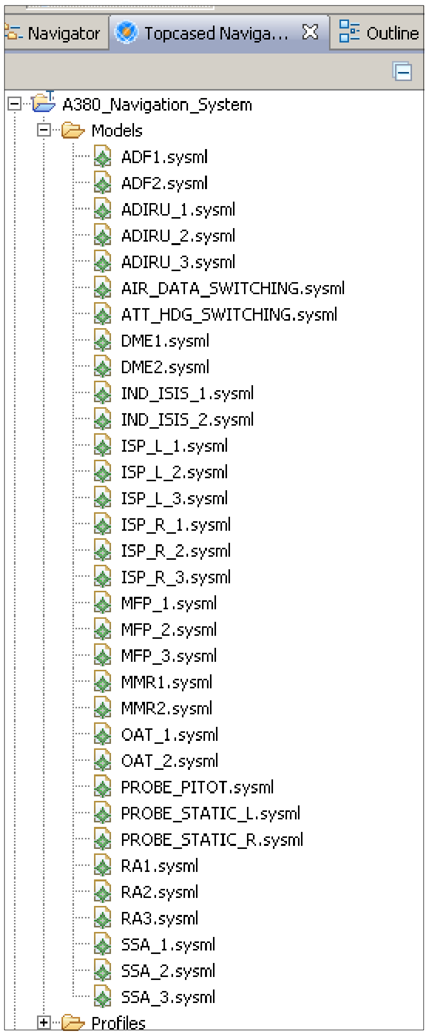
Nom de fichier : H:\ATA34
Fichiers du type : Tous les fichiers

Topcased Workspace
H:\TopcasedWorkSpace
Project name: A380_Navigation_System
Choose model name: ATA34

SysML Design Generation
H:\ATA34

Figure 5.3: SysML generation from A/C ICD performed with our tool prototype

After the translation process from A/C ICD using the algorithms we have devised, we have the following SysML Design Model organization, presented in Figure 5.4.

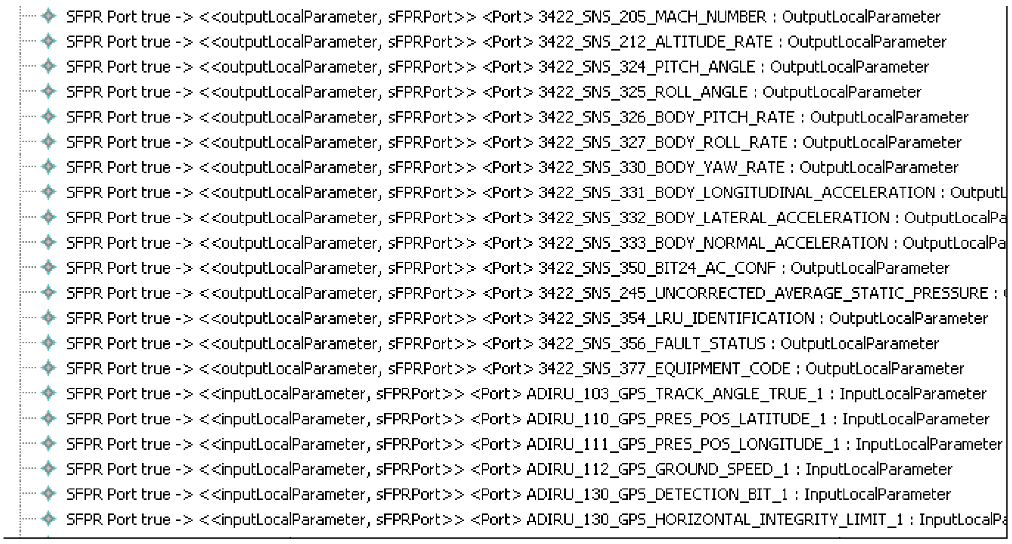


Navigator | Topcased Naviga... | Outline

```
A380_Navigation_System
  Models
    ADF1.sysml
    ADF2.sysml
    ADIRU_1.sysml
    ADIRU_2.sysml
    ADIRU_3.sysml
    AIR_DATA_SWITCHING.sysml
    ATT_HDG_SWITCHING.sysml
    DME1.sysml
    DME2.sysml
    IND_ISIS_1.sysml
    IND_ISIS_2.sysml
    ISP_L_1.sysml
    ISP_L_2.sysml
    ISP_L_3.sysml
    ISP_R_1.sysml
    ISP_R_2.sysml
    ISP_R_3.sysml
    MFP_1.sysml
    MFP_2.sysml
    MFP_3.sysml
    MMR1.sysml
    MMR2.sysml
    OAT_1.sysml
    OAT_2.sysml
    PROBE_PITOT.sysml
    PROBE_STATIC_L.sysml
    PROBE_STATIC_R.sysml
    RA1.sysml
    RA2.sysml
    RA3.sysml
    SSA_1.sysml
    SSA_2.sysml
    SSA_3.sysml
  Profiles
```

Figure 5.4: Generated A380 navigation systems SysML Design models

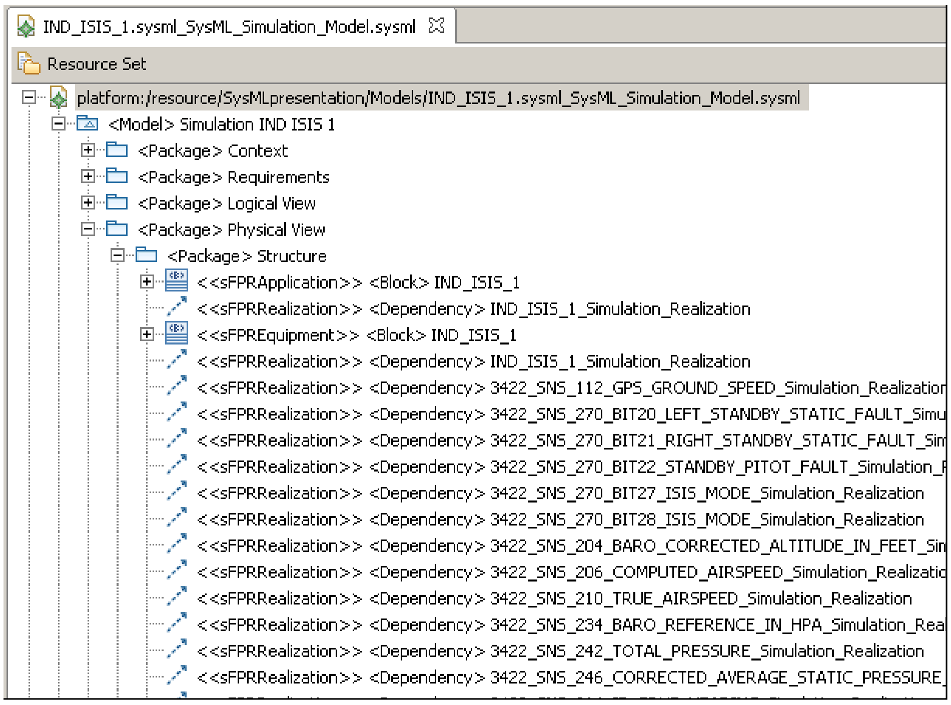
. After generating the SysML Design Models, we have to select which application local parameters we are going to simulate. Figure 5.5 presents some local parameters of the ISIS first occurrences, where all local parameters are going to be simulated.



```
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_205_MACH_NUMBER : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_212_ALTITUDE_RATE : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_324_PITCH_ANGLE : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_325_ROLL_ANGLE : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_326_BODY_PITCH_RATE : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_327_BODY_ROLL_RATE : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_330_BODY_YAW_RATE : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_331_BODY_LONGITUDINAL_ACCELERATION : OutputL
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_332_BODY_LATERAL_ACCELERATION : OutputLocalPa
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_333_BODY_NORMAL_ACCELERATION : OutputLocalPa
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_350_BIT24_AC_CONF : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_245_UNCORRECTED_AVERAGE_STATIC_PRESSURE :
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_354_LRU_IDENTIFICATION : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_356_FAULT_STATUS : OutputLocalParameter
SFPR Port true -> <<outputLocalParameter, sFPRPort>> <Port> 3422_SNS_377_EQUIPMENT_CODE : OutputLocalParameter
SFPR Port true -> <<inputLocalParameter, sFPRPort>> <Port> ADIRU_103_GPS_TRACK_ANGLE_TRUE_1 : InputLocalParameter
SFPR Port true -> <<inputLocalParameter, sFPRPort>> <Port> ADIRU_110_GPS_PRES_POS_LATITUDE_1 : InputLocalParameter
SFPR Port true -> <<inputLocalParameter, sFPRPort>> <Port> ADIRU_111_GPS_PRES_POS_LONGITUDE_1 : InputLocalParameter
SFPR Port true -> <<inputLocalParameter, sFPRPort>> <Port> ADIRU_112_GPS_GROUND_SPEED_1 : InputLocalParameter
SFPR Port true -> <<inputLocalParameter, sFPRPort>> <Port> ADIRU_130_GPS_DETECTION_BIT_1 : InputLocalParameter
SFPR Port true -> <<inputLocalParameter, sFPRPort>> <Port> ADIRU_130_GPS_HORIZONTAL_INTEGRITY_LIMIT_1 : InputLocalPa
```

Figure 5.5: *SFPRPort* simulation local parameters selection

After the selection of which local parameters are going to be simulated, we can generate the SysML Simulation model. The SysML simulation model has the same information as the Design one, but the transformation blocks, and their internal structure. Figure 5.6 shows ISIS first occurrence simulation model, as well as some dependencies to trace the simulation elements into design ones.

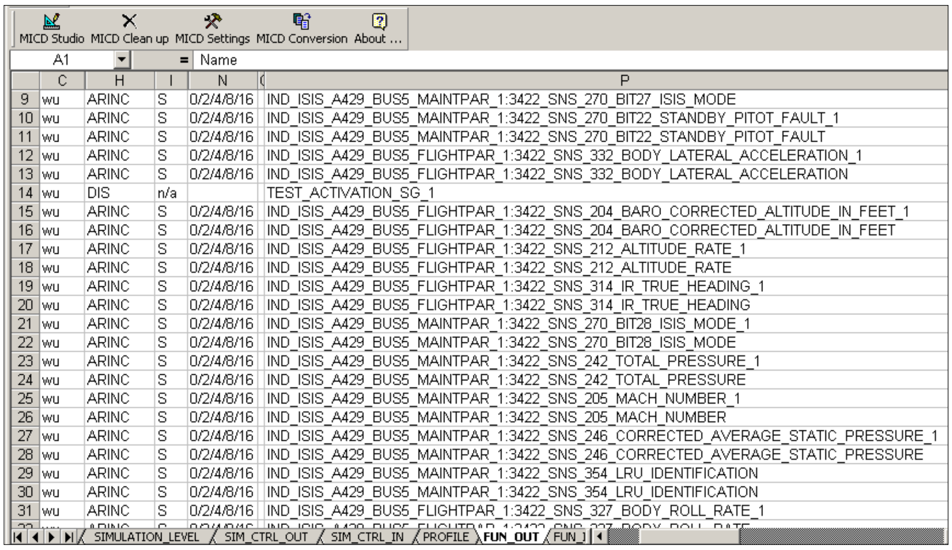

IND_ISIS_1.sysml_SysML_Simulation_Model.sysml

Resource Set

- platform:/resource/SysMLpresentation/Models/IND_ISIS_1.sysml_SysML_Simulation_Model.sysml
  - <Model> Simulation IND ISIS 1
    - <Package> Context
    - <Package> Requirements
    - <Package> Logical View
    - <Package> Physical View
      - <Package> Structure
        - <<sFPRApplication>> <Block> IND_ISIS_1
        - <<sFPRRealization>> <Dependency> IND_ISIS_1_Simulation_Realization
        - <<sFPREquipment>> <Block> IND_ISIS_1
        - <<sFPRRealization>> <Dependency> IND_ISIS_1_Simulation_Realization
        - <<sFPRRealization>> <Dependency> 3422_SNS_112_GPS_GROUND_SPEED_Simulation_Realization
        - <<sFPRRealization>> <Dependency> 3422_SNS_270_BIT20_LEFT_STANDBY_STATIC_FAULT_Simu
        - <<sFPRRealization>> <Dependency> 3422_SNS_270_BIT21_RIGHT_STANDBY_STATIC_FAULT_Sim
        - <<sFPRRealization>> <Dependency> 3422_SNS_270_BIT22_STANDBY_PITOT_FAULT_Simulation_F
        - <<sFPRRealization>> <Dependency> 3422_SNS_270_BIT27_ISIS_MODE_Simulation_Realization
        - <<sFPRRealization>> <Dependency> 3422_SNS_270_BIT28_ISIS_MODE_Simulation_Realization
        - <<sFPRRealization>> <Dependency> 3422_SNS_204_BARO_CORRECTED_ALTITUDE_IN_FEET_Sim
        - <<sFPRRealization>> <Dependency> 3422_SNS_206_COMPUTED_AIRSPEED_Simulation_Realizatio
        - <<sFPRRealization>> <Dependency> 3422_SNS_210_TRUE_AIRSPEED_Simulation_Realization
        - <<sFPRRealization>> <Dependency> 3422_SNS_234_BARO_REFERENCE_IN_HPA_Simulation_Rea
        - <<sFPRRealization>> <Dependency> 3422_SNS_242_TOTAL_PRESSURE_Simulation_Realization
        - <<sFPRRealization>> <Dependency> 3422_SNS_246_CORRECTED_AVERAGE_STATIC_PRESSURE_

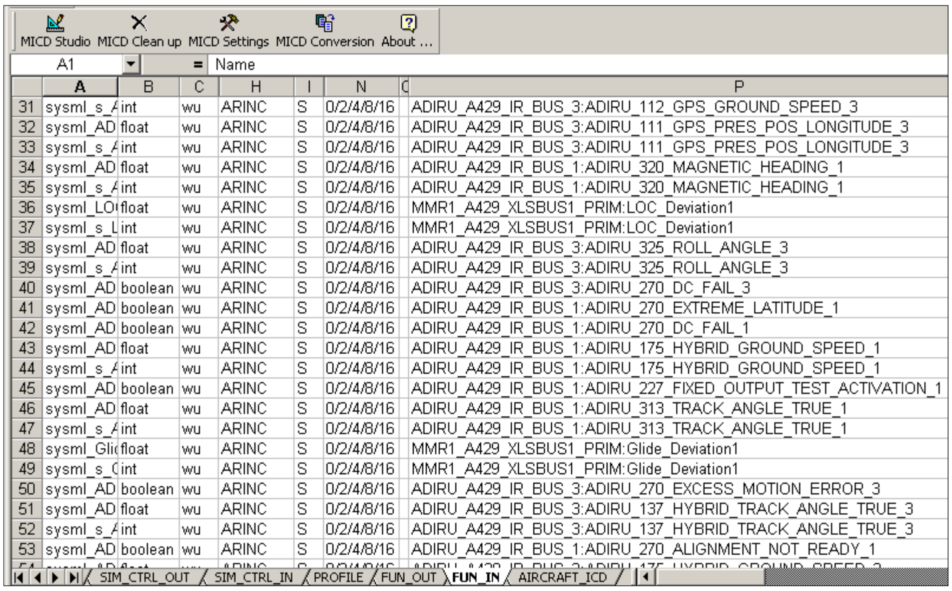
Figure 5.6: ISIS SysML simulation model and generated SFPR dependencies

The last step is the MICD generation from SysML Simulation models. This process is automatic, not requiring human intervention. Figure 5.7 presents an extract of the generated output signals and Figure 5.8 the input ones of the MICD to the ISIS first occurrence.



	C	H	I	N	P
9	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_270_BIT27_ISIS_MODE
10	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_270_BIT22_STANDBY_PITOT_FAULT_1
11	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_270_BIT22_STANDBY_PITOT_FAULT
12	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_332_BODY_LATERAL_ACCELERATION_1
13	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_332_BODY_LATERAL_ACCELERATION
14	wu	DIS	n/a		TEST_ACTIVATION_SG_1
15	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_204_BARO_CORRECTED_ALTITUDE_IN_FEET_1
16	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_204_BARO_CORRECTED_ALTITUDE_IN_FEET
17	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_212_ALTITUDE_RATE_1
18	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_212_ALTITUDE_RATE
19	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_314_IR_TRUE_HEADING_1
20	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_314_IR_TRUE_HEADING
21	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_270_BIT28_ISIS_MODE_1
22	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_270_BIT28_ISIS_MODE
23	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_242_TOTAL_PRESSURE_1
24	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_242_TOTAL_PRESSURE
25	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_205_MACH_NUMBER_1
26	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_205_MACH_NUMBER
27	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_246_CORRECTED_AVERAGE_STATIC_PRESSURE_1
28	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_246_CORRECTED_AVERAGE_STATIC_PRESSURE
29	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_354_LRU_IDENTIFICATION
30	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_MAINTPAR_1:3422_SNS_354_LRU_IDENTIFICATION
31	wu	ARINC	S	0/2/4/8/16	IND_ISIS_A429_BUS5_FLIGHTPAR_1:3422_SNS_327_BODY_ROLL_RATE_1

Figure 5.7: ISIS MICD output variables and their generated joining keys



A1 = Name

	A	B	C	H	I	N	O	P
31	sysml_s_A	int	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_112_GPS_GROUND_SPEED_3
32	sysml_AD	float	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_111_GPS_PRES_POS_LONGITUDE_3
33	sysml_s_A	int	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_111_GPS_PRES_POS_LONGITUDE_3
34	sysml_AD	float	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_320_MAGNETIC_HEADING_1
35	sysml_s_A	int	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_320_MAGNETIC_HEADING_1
36	sysml_LO	float	wu	ARINC	S	0/2/4/8/16		MMR1_A429_XLSBUS1_PRIM:LOC_Deviation1
37	sysml_s_L	int	wu	ARINC	S	0/2/4/8/16		MMR1_A429_XLSBUS1_PRIM:LOC_Deviation1
38	sysml_AD	float	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_325_ROLL_ANGLE_3
39	sysml_s_A	int	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_325_ROLL_ANGLE_3
40	sysml_AD	boolean	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_270_DC_FAIL_3
41	sysml_AD	boolean	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_270_EXTREME_LATITUDE_1
42	sysml_AD	boolean	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_270_DC_FAIL_1
43	sysml_AD	float	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_175_HYBRID_GROUND_SPEED_1
44	sysml_s_A	int	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_175_HYBRID_GROUND_SPEED_1
45	sysml_AD	boolean	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_227_FIXED_OUTPUT_TEST_ACTIVATION_1
46	sysml_AD	float	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_313_TRACK_ANGLE_TRUE_1
47	sysml_s_A	int	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_313_TRACK_ANGLE_TRUE_1
48	sysml_Gli	float	wu	ARINC	S	0/2/4/8/16		MMR1_A429_XLSBUS1_PRIM:Glide_Deviation1
49	sysml_s_G	int	wu	ARINC	S	0/2/4/8/16		MMR1_A429_XLSBUS1_PRIM:Glide_Deviation1
50	sysml_AD	boolean	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_270_EXCESS_MOTION_ERROR_3
51	sysml_AD	float	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_137_HYBRID_TRACK_ANGLE_TRUE_3
52	sysml_s_A	int	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_3:ADIRU_137_HYBRID_TRACK_ANGLE_TRUE_3
53	sysml_AD	boolean	wu	ARINC	S	0/2/4/8/16		ADIRU_A429_IR_BUS_1:ADIRU_270_ALIGNMENT_NOT_READY_1

Figure 5.8: ISIS MICD input variables and their generated joining keys

We can see in Figure 5.8 that ISIS's inputs from the MMR equipment, as well as the IRS application provided by ADIRU. In Figure 5.7 we can see ISIS's outputs, such as computed Mach and lateral acceleration. This information is later displayed by ISIS equipment screen. Figure 5.9 presents the ISIS equipment display.

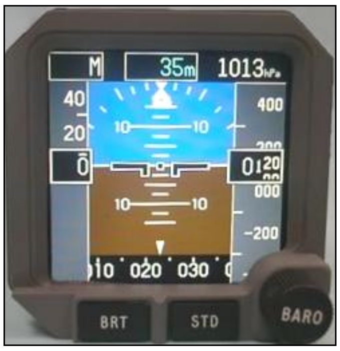


Figure 5.9: ISIS equipment screen

5.2 Primary Flight Control Computer

In this section, we present the UML Equipment State Machine process and code generation to the Primary Flight Control Computer. As we have presented the SysML process using theA380 Navigation Systems, and for any model the process is the same, in this section this is not going to be repeated.

5.2.1 A340 Flight Control Computer Organization

The flight control computer is the interface between pilot's sidestick and aircraft sensors and actuators, implementing the Fly-By-Wire (FBW) system. The A340 aircraft has five flight control computers: three Primary Flight Control Computers (PRIM) and two Secondary Flight Control Computers (SEC) (A320 has two PRIMs and three SECs) (Flight International, 1991). The SEC computers act as a backup to PRIM. In case of failure or disagreement on results between the three PRIM computers, the SEC computers take the responsibilities of computation.

The AIRBUS FBW system operates under three control laws (Flight International, 1991):

- *Normal:* Auto-flight systems active, computer accepts pilot's input in the sidestick, but the FBW system overrides pilot inputs in order to respect the Flight Envelop (FEP). The FEP specifies the security margins the aircraft must be operated. In normal control law, in the case the pilot pulls the sidestick to its limits, the FBW overrides this command to the maximum allowed value as specified in the FEP. FEP acts in three commands: pitch, roll, and angle-of-attack (preventing aircraft stalling);
- *Alternate:* Auto-flight systems are inactive, computer accepts pilot's input in the sidestick, but the FBW system overrides pilot's inputs in order to respect FEP. Alternate law is activated when two or more failures that are critical occur in the PRIM computers.
- *Direct:* Both auto-flight systems and FEP protection are turned off. There is no computer intervention between the pilot and the FBW system. SEC computers operate this control law, activated by failures in all three PRIM computers are inoperative, or their outputs are not reliable.

During 99% of a flight, the aircraft stays in the normal control law managed by the autopilot/auto-flight systems (Flight Daily News, 2009). For a demonstration of the A320 FBW system being pushed to its limits, readers are recommended to watch (Discovery Channel, 2009).

Both PRIM and SEC were designed to be hardware and software fault-tolerant. PRIM and SEC are designed by different providers, Aerospatiale (now Thales) and Sextant (now Honeywell), respectively. PRIM adopts Intel 80386 architecture, while SEC adopts Intel 80186. This avoids errors and provides fault-tolerance concerning hardware architecture design. In addition, the software running embedded in PRIM and SEC are design by different teams, providing better fault-tolerance due to flawed algorithms and hidden errors (Brière, 1993).

The flight control computer has two functions: *computation*, which is the computing of normal and alternate control laws. In this case, the pilot does not directly intervenes; the computer drive the control surface to best implement the pilot's commands; and *execution*, which is elaborating electrical signals for surface deflection (Flight International, 1991).

For more details of the FBW system, refer to (Traverse, 2004), and for details of the Flight Control Computer, refer to (Brière, 1993).

5.2.2 Primary Flight Control Computer Equipment UML State Machine

The UML Equipment State Machine describes the states and the functions performed in each state the equipment is. Figure 5.10 presents the PRIM UML Equipment State Machine.

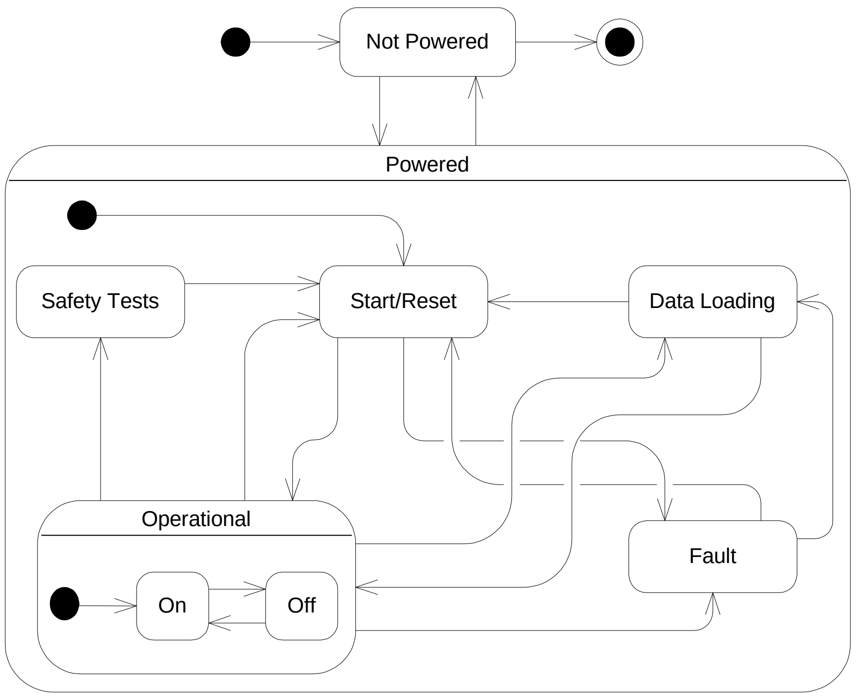


Figure 5.10: Primary Flight Control Computer UML Equipment State Machine

The PRIM Equipment UML State Machine is created by hand in the PRIM SysML Design Model, all transitions and *ChangeEvents* necessary to trigger state transitions. After creating and specifying the UML State Machine, the Simulation Model Designer applies the SFPR profile and selects which states he is going to use to perform the simulation he is creating. Figure 5.11 presents the SFPR profile application, as well as some simulated (white states) and not-simulated states (gray shaded states). Note that it is not shown in Figure 5.11, but both *On* and *Off* states have the *SFPRState* stereotype, suppressed to improve presentation.

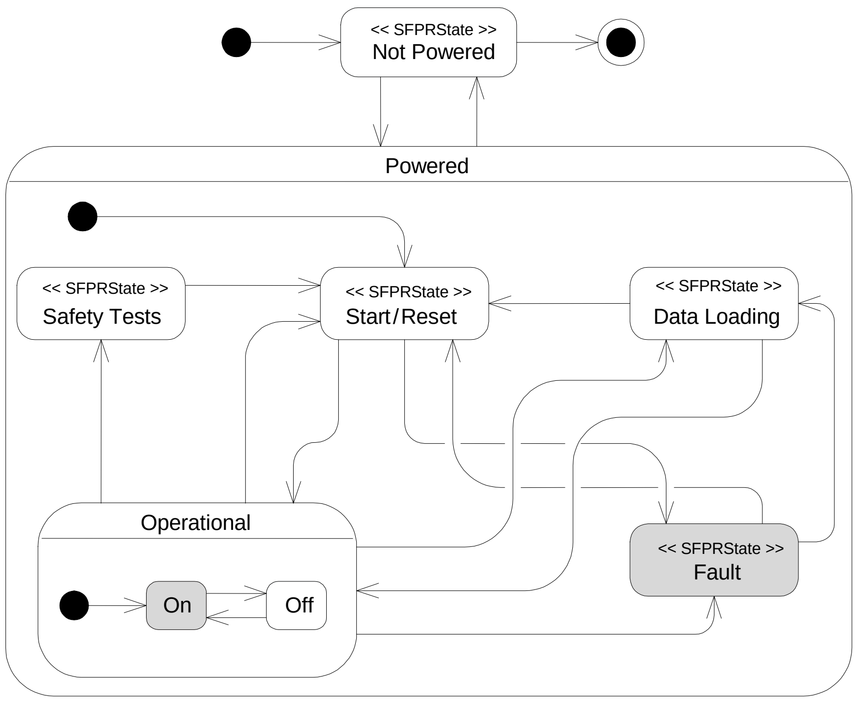


Figure 5.11: SFPR state selection

Note that the state selection is performed by setting to *true* the *SFPRState* tagged value *simulated*. After selecting the states that are going to be simulated, we remove all useless states (states not reachable from some start pseudostate). Figure 5.12 presents the final simulation Equipment UML State Machine.

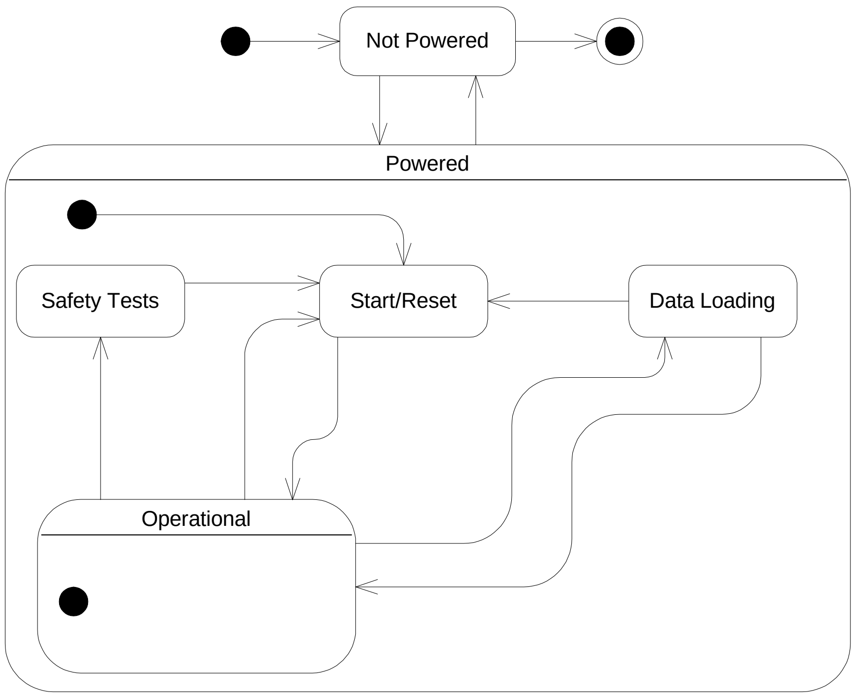


Figure 5.12: Final UML Equipment State Machine after useless state removal

Note that we have removed the *Off* state because without the *On* state (removed because it was not selected to be simulated), *Off* is unreachable from the start pseudostate inside the *Operational* state. Although after useless state removal the *Operational* state has no inner behavior, it is not removed because maybe the Simulation Designer had set its *before* action to contain some behavior. Thus, even without inner states, the *Operational* state can still be useful.

Finally, with the state machine presented in Figure 5.12, we can generate the simulation code. The generated C code for the Equipment UML State Machine presented in Figure 5.12 is shown below.

STM_UTILS.H

```
#ifndef STM_UTILS_H_
#define STM_UTILS_H_
#define TRUE 1
#define FALSE 0
#define STATE struct state
#define PARAM struct formal_parameter
#define CHANGE_EVENT struct change_event
struct formal_parameter
{
        int integer_value;
        float float_value;
        char *param_name;
};
struct state
{
        STATE *composite_state;
```

```c
        void (*do_action)(PARAM *);
        STATE *(*evaluate_transition)(void);
        CHANGE_EVENT *change_event_pool;
        void (*init_state)(void);
};
struct change_event
{
        int happens;
        void *past_value;
        void *current_value;
};
#endif /* STM_UTILS_H_ */
```

PRIM_STM.C

```c
#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>
#include "stm_utils.h"
void next_state(STATE *current);
void evaluate_event(CHANGE_EVENT *pool);
STATE *evaluate_st_notpowered(void);
STATE *evaluate_st_powered(void);
STATE *evaluate_st_start_reset(void);
STATE *evaluate_st_safetytests(void);
STATE *evaluate_st_dataloading(void);
STATE *evaluate_st_operational(void);
void st_notpowered_do_action(PARAM *params);
void st_powered_do_action(PARAM *params);
void st_start_reset_do_action(PARAM *params);
void st_safetytests_do_action(PARAM *params);
void st_dataloading_do_action(PARAM *params);
void st_operational_do_action(PARAM *params);
void st_finalstate1_do_action(PARAM *params);
STATE *st_current;
STATE *st_notpowered;
STATE *st_powered;
STATE *st_start_reset;
STATE *st_safetytests;
STATE *st_dataloading;
STATE *st_operational;
STATE *st_finalstate1;
int main(void)
{
        init();
        next_state(st_current);
        return EXIT_SUCCESS;
}
void next_state(STATE *current)
{
        do
        {
              current->do_action(NULL);
              if(current->composite_state != NULL)
                    next_state(current->composite_state);
              current = current->evaluate_transition();
        }
        while( current != NULL );
}
void init(void)
```

```c
{
       st_notpowered  = (STATE *) malloc(sizeof(STATE));
       st_powered     = (STATE *) malloc(sizeof(STATE));
       st_start_reset = (STATE *) malloc(sizeof(STATE));
       st_safetytests = (STATE *) malloc(sizeof(STATE));
       st_dataloading = (STATE *) malloc(sizeof(STATE));
       st_operational = (STATE *) malloc(sizeof(STATE));
       st_finalstate1 = (STATE *) malloc(sizeof(STATE));
       initialize_st_notpowered();
       initialize_st_powered();
       initialize_st_start_reset();
       initialize_st_safetytests();
       initialize_st_dataloading();
       initialize_st_operational();
       initialize_st_finalstate1();
       st_current = st_notpowered;
}
void initialize_st_notpowered(void)
{
       st_notpowered->evaluate_transition = &evaluate_notpowered;
       st_notpowered->composite_state = NULL;
       st_notpowered->do_action = &st_notpowered_do_action;
       st_notpowered->change_event_pool =
                   (CHANGE_EVENT *)malloc(sizeof(CHANGE_EVENT)*2);
}
void initialize_st_powered(void)
{
        st_powered->evaluate_transition = &evaluate_powered;
        st_powered->composite_state = st_start_reset;
        st_powered->do_action = &st_powered_do_action;
        st_powered->change_event_pool =
                   (CHANGE_EVENT *)malloc(sizeof(CHANGE_EVENT));
}
void initialize_st_start_reset(void)
{
     st_start_reset->evaluate_transition = &evaluate_start_reset
     st_start_reset->composite_state = NULL;
     st_start_reset->composite_state = NULL;
     st_start_reset->do_action = &st_start_reset_do_action;
     st_start_reset->change_event_pool =
                   (CHANGE_EVENT *)malloc(sizeof(CHANGE_EVENT));
}
void initialize_st_safetytests(void)
{
     st_safetytests->evaluate_transition = &evaluate_safetytests;
     st_safetytests->composite_state = NULL;
     st_safetytests->do_action = &st_safetytests_do_action;
     st_safetytests->change_event_pool =
                   (CHANGE_EVENT *)malloc(sizeof(CHANGE_EVENT));
}
void initialize_st_dataloading(void)
{
     st_dataloading->evaluate_transition = &evaluate_dataloading;
     st_dataloading->composite_state = NULL;
     st_dataloading->do_action = &st_dataloading_do_action;
     st_dataloading->change_event_pool =
                   (CHANGE_EVENT *)malloc(sizeof(CHANGE_EVENT));
}
void initialize_st_operational(void)
{
    st_operational->evaluate_transition = &evaluate_operational;
    st_operational->composite_state = NULL;
    st_operational->do_action = &st_operational_do_action;
    st_operational->change_event_pool =
                (CHANGE_EVENT*)malloc(sizeof(CHANGE_EVENT)*4);
}
void initialize_st_finalstate1(void)
{
    st_finalstate1->evaluate_transition = NULL;
    st_finalstate1->composite_state = NULL;
    st_finalstate1->do_action = &st_finalstate1_do_action;
    st_finalstate1->change_event_pool = NULL;
}
void st_notpowered_do_action(PARAM *params)
{
    // TODO: call Simulink/SCADE external code
}
void st_powered_do_action(PARAM *params)
{
    // TODO: call Simulink/SCADE external code
}
void st_start_reset_do_action(PARAM *params)
{
    // TODO: call Simulink/SCADE external code
}
void st_safetytests_do_action(PARAM *params)
{
    // TODO: call Simulink/SCADE external code
}
void st_dataloading_do_action(PARAM *params)
{
    // TODO: call Simulink/SCADE external code
}
void st_operational_do_action(PARAM *params)
{
   // TODO: call Simulink/SCADE external code
}
void st_finalstate1_do_action(PARAM *params)
{
   exit(EXIT_SUCCESS);
}
void evaluate_event(CHANGE_EVENT *pool)
{
   // TODO: handle change event based on current and past values
}
STATE *evaluate_st_notpowered(void)
{
      evaluate_event(st_notpowered->change_event_pool);
      if(st_notpowered->change_event_pool[0].happens == TRUE)
            return st_finalstate1;
      if(st_notpowered->change_event_pool[1].happens == TRUE)
            return st_powered;
      return NULL;
}
STATE *evaluate_st_powered(void)
{
      evaluate_event(st_powered->change_event_pool);
      if(st_powered->change_event_pool[0].happens == TRUE)
            return st_notpowered;
      return st_start_reset;
```

```
166. }
167. STATE *evaluate_st_start_reset(void)
168. {
169.       evaluate_event(st_start_reset->change_event_pool);
170.       if(st_start_reset->change_event_pool[0].happens == TRUE)
171.            return st_fault;
172.       if(st_start_reset->change_event_pool[1].happens == TRUE)
173.            return st_operational;
174.       return NULL;
175. }
176. STATE *evaluate_st_safetytests(void)
177. {
178.       evaluate_event(st_safetytests->change_event_pool);
179.       if(st_safetytests->change_event_pool[0].happens == TRUE)
180.            return st_start_reset;
181.       return NULL;
182. }
183. STATE *evaluate_st_dataloading(void)
184. {
185.       evaluate_event(st_dataloading->change_event_pool);
186.       if(st_dataloading->change_event_pool[0].happens == TRUE)
187.            return st_start_reset;
188.       return NULL;
189. }
190. STATE *evaluate_st_operational(void)
191. {
192.       evaluate_event(st_operational->change_event_pool);
193.       if(st_operational->change_event_pool[0].happens == TRUE)
194.            return st_dataloading;
195.       if(st_operational->change_event_pool[1].happens == TRUE)
196.            return st_safetytests;
197.       if(st_operational->change_event_pool[2].happens == TRUE)
198.            return st_start_reset;
199.       if(st_operational->change_event_pool[3].happens == TRUE)
200.            return st_fault;
201.       return NULL;
202. }
```

The first generated file, “STM_UTILS.H”, defines the data structures we use in the state machine code. In this file, we have the declaration of a Simulink/SCADE formal parameter that is going to be passed to their functions (lines 8-13). From line 14 to 21, we have the declaration of a state of the state machine. In line 17, there is the function pointer to the Simulink/SCADE code, in line 18 there is the next state evaluation function based on state’s change events, in line 19 there is the set of change events a state has subscribed, and in line 20, there is the state memory initialization function. The *change_event* structure contains the data needed to declare a change event. The *happens* variable (line 24) contains the evaluation of a Boolean expression declaring the event itself; *current_value* and *past_value* are the computed values by the Simulink/SCADE function pointed by the function pointer in line 17. The change event is triggered when these two values are different (they are an AND clause in the change event Boolean expression).

The second generated file, “PRIM_STM.H”, contains the specified state machine from Figure 5.12. From line 34 to 44 it is the next state function. It firstly calls the action defined for the current state (line 38) and then calls next state recursively to inner states (in case of the current be a composite state). In line 41 the state machine evaluates the next state to branch. It keeps executing until the evaluated next state is NULL (line 43), or some of the evaluation functions exits the program.

From line 45 to 62 there is the state memory allocation function, each state structure initialization and, lastly, the assignment of the initial state (line 61). In the case of the state machine presented in Figure 5.12, this state is the *NotPowered* one (remember that an initial node in a UML State Machine is a pseudostate; there is no associated actions with them. Initial states are only decorative, to graphically represent the actual initial node).

From line 63 to 118 there is the memory and action state initialization for each specific state of the state machine. These functions set the STATE struct points to enable the *next_state* (line 38) function to execute state behavior independent of a specific state. Note the *change_event_pool* initialization. This field is an array of change events, and the array's length is equal to the number of state's outgoing edges. For example, in line 69 we have the *NotPowered* state *change_event_pool* initialization, and the number of elements to be allocated is two (one for the outgoing edge going to the *Powered* state, and the other to the *FinalState*).

From line 119 to 150 we have the specific *do_action* for each state, calling the external Simulink/SCADE code. Due to time restriction, we could not implement the external code call, but it is straightforward. The *do_action* for each UML state has as its implementation the *empty activity*, which has an *opaque action*. The Simulink/SCADE function call is written in the opaque action's *body* parameter by hand. The code generator only gets this specified function call and writes in the *do_action* body code specific to each state.

6 ASSESMENT AND CONCLUSIONS

This chapter presents in section 6.1 the technical evaluation of every aspect discussed in this work, highlighting their problems and advantages. In section 6.2, we discuss further research to continue this work and our proposed approach.

6.1 Technical Evaluation

6.1.1 Model Transformations

6.1.1.1 Understanding

In the beginning, the focus of this work was to perform only the transformation between A/C ICD and the SysML Design Model. Concerning this transformation, in my opinion the most critical one, some aspects remain unclear.

Despite the fact of A/C ICD being broadly adopted and well know in AIRBUS, there are some aspects unclear about its specification. Worst, some aspects of A/C ICD specification are not described in its specification document (*e.g.* how to treat some corner cases on variables types). We still have some flaws when translating A/C ICD into SysML, for example, when we have a message in the A/C ICD, but its local parameter field is empty; or yet, when we use some buses not declared in the A/C ICD (both cases have happened in the ADIRU A/C ICD presented in section 5.1).

Maybe these cases are due to A/C ICD maturity, but there is no document specifying which constructs can happen (or are missing) for a given maturity level. I suggest defining this document, relating the three A/C ICD maturity level and the constructs an A/C ICD compliant to some level must have.

6.1.1.2 Completeness

A/C ICD is quite complete given its purpose, i.e. specifying how an embedded application interfaces with its equipment. With the new A/C ICD version near to its publishing this description is going to be even more detailed, containing, for example, the equipment power supply. A/C ICD completeness made easy its transformation to SysML. I think that all A/C ICD constructs were well translated into SysML Design Model, without any prejudice to its data or completeness.

6.1.1.3 Specification

As this work was refined as time has passed, growing fast in complexity, size, and target domains, we have defined transformation rules in an ad hoc fashion. In my opinion this was the best way to follow, given the exploratory bias of this work; we did not want to have a final, closed product, we wanted a research prototype that could show us the potentials, flaws, and feasibility of a model-based approach to simulation design of embedded avionics equipment instead. Now that the transformation rules are consolidated, I suggest specifying them in a more formal fashion (see implementation for a discussion on that).

6.1.1.4 Implementation

We have implemented the transformation rules in pure Java, summing around 27.000 lines of code entirely written by hand. Java was chosen because in the beginning the work was small, but, as said before, its size has increased a lot. Currently, given the size of this work, as well as the complexity of the transformation rules, and the metamodels used, Java is far from being suitable to a more end-product version. The Java code is too big, complex, and its legibility is not good. We have not defined code conventions, prejudicing its manageability. Finally, as Java is not targeted to model transformations, the transformation rules are hidden in Java code, making very difficult their understanding.

I suggest implementing a new version of our prototype with ATL (ATLAS Transformation Language). ATL was designed to handle model transformations, has a concise notation to that, making quite evident the transformation rules between metamodels. I think that our tool quality, manageability, and understanding would dramatically increase with this new coding in ATL. In addition, using ATL makes our tool closer to both TOPCASED and MDE (Model-Driven Engineering) communities.

6.1.2 SysML Design and Simulation Models

6.1.2.1 Understanding

Both SysML Design and Simulation models were very understandable to everybody that was in contact with them. It contains clear and simple concepts, and in my opinion, this was achieved due to the definition of both the UP2A and SFPR profiles. The separation of design and simulation architectural levels was very clear, and how we trace both levels. The internal mapping structure between messages, signals, and local parameters is straightforward too. As we have adopted a block-oriented fashion to specify in SysML the A/C ICD constructs, and everybody in the simulation department has notions of Simulink/SCADE, both SysML Design and Simulation models understanding is straightforward.

Concerning the empty activity and the UML Equipment State Machine we have received a feedback from a team member of the AMISA project saying that the interaction with the simulation platform scheduler was not clear, and how and when the *do_action* is executed. This is easily fixed just defining new stereotypes in the UP2A profile to represent the simulation scheduler, but it is not needed to do so. As soon as these rules are coded in the code generator, and the Simulation Designer creating the UML State Machine is aware of them, they are useless, being only a notational overhead decreasing model legibility and conciseness.

6.1.2.2 Abstraction

Both SysML Design and Simulation models have an adequate level of abstraction, but the internal mapping structure between messages, signals, and local parameters. These mapping structure contains several blocks, connectors, flow ports that, in my opinion, does not need to be in the model. As discussed internally, we see the simulation being performed in terms of application variables (or local parameters), not anymore in terms of signals and messages. Assuming that this work is targeted for long-term research, I think we can be more *aggressive* and get rid this information off the model. If this information is necessary for some analysis, a tool could retrieve it from a database. Thus, in this approach we only need to connect the model elements in the SysML models with its internal structure stored in the database. This database approach is suitable, in my opinion, because SysML models are good at system specification, but are quite bad in information storage. Putting the mapping structure in the SysML model is the wrong way of dealing with them. I think that this clear separation of modeling data and design data is the biggest impeditive of adopting model-based techniques in industry today, and I do not see any solution to integrate models with a relational database. This is another research direction that can be conducted in the frame of INSIDE or even AMISA.

6.1.2.3 Implementation

I have the same considerations as presented in section 6.1.1.4. We should implement the transformation rules in ATL, not in Java. In the TOPCASED project there is available a set of APIs to handle SysML models, and they can be easily integrated with ATL, as TOPCASED already does. Nevertheless, I think that it is best to use a text-to-model tool to generate SysML from A/C ICD CSV files. Unfortunately, these tools are not widespread available in the community, they are rather incubated projects yet.

6.1.3 MICD and Simulation Code Generation

6.1.3.1 Understanding

The MICD generation is straightforward, and its specification is good. Again, it fails in specifying corner cases, but it is possible to infer these cases. As MICD are broadly adopted, there is no problem of understanding how it is generated from SysML models.

Concerning code generation, we have not closed how to specify when and how a state branches to other, thus, affecting code generation. A better specification and algorithms that are more detailed are left as future work.

6.1.3.2 Completeness

The MICD code generation supports only the minimum features to pass validation in the MICD Studio. Other data that we have in the A/C ICD may not be generated in the MICD due to this point. As we wanted to reconstruct only the joining keys to create a proof-of-concept, this is fine to our objectives.

Concerning simulation code generation, it is missing how to evaluate the next state based on declared change events, and the connection with Simulink/SCADE. The former it lacking the formalization of change events specification, and the latter is just a matter of gluing the code inserted on the opaque action’s body field. In addition, it is needed to declare the MICD variables in the generated C code, which is quite straightforward too.

6.1.3.3 Implementation

I have implemented everything in Java, and, in the case of MICD generation, I think this is the best way of doing so right now. We have used the APACHE POI API to generate the Excel file, being very abstract and easy to use. Using such an API avoids the problem of byte serialization and compliance with the Microsoft Excel binary format. I do not recommend using a model-to-text transformation in this case.

Regarding simulation code generation, I suggest using Acceleo tool to do that. It is very easy and high level, being perfect to code generation from well-defined metamodels. Unfortunately, C code generation from UML State Machines is not complete in Acceleo, but, in our case, we have a very simple code generation process, not requiring the implementation of all UML metamodel constructs related to state machines.

6.1.4 Integrated Model-Based Design and Simulation Process

6.1.4.1 Understanding

The idea of integrating design and simulation in a more formal fashion (based on SysML models in our approach) received an excellent reception from AIRBUS engineers, both from the Design Office and the Avionics Simulation Products Department. Both departments recognize the lack of formalism in integrating design and simulation artifacts, and recognize the bad outcomes associated with it. Thus, this approach is completely feasible in the middle or long-terms.

AIRBUS is a strong supporter of SysML and TOPCASED, so there is somehow a broad knowledge of it in the company; SysML is not seen as black magic or an unfeasible academic proposal. In this way, a model-based approach using SysML has the potential to decrease the adoption barrier and resistance to changes in *status quo*. Certainly, it will be necessary to provide training on SysML and the new process, and highlight that more formalism is beneficial to the aeronautic domain, helping engineers to make their jobs better and more reliable.

I suggest organizing meetings with AMISA team to discuss common problems and solutions. AMISA has common problems and solution to INSIDE and this discussion can be very beneficial. In addition, it is the perfect opportunity to integrate design and simulation from the beginning with SysML.

6.1.4.2 Completeness

In this work, we have approached the process of importing current design artifacts into SysML, and selecting the ones we want to simulate, and, finally, generating the current simulation artifact from SysML. We have not approached how requirements engineering could be integrated in this approach, or event testing of the created models. Current tools for requirements engineering, *e.g.* Telelogic DOORS, support SysML models, creating requirement version management, as well as model artifacts. Nonetheless, it is still necessary to adopt how simulation requirements would be described with such an approach. Clearly, this is completely feasible. Regarding testing, it could be performed over the generated or hand written code from the SysML model, or over the SysML model, through the UML Profile for Testing or OCL constraints.

The Cockpit Group in the Design Office (EDYAK) already uses Telelogic DOORS to handle requirements, and they have some integration with SysML models. It could be interesting to discuss with them how their process is. Testing with UML/SysML model is still an open research problem, and there is no close solution to that. For me it seems interesting to express consolidated test procedures with OCL representing structural constraints that the model must respect, and exploratory test procedures with the UML Profile for Testing. From this profile, we could generate unit tests to test the generated code. Another open problem is how to integrate Simulink/SCADE models with these testing procedures.

6.1.4.3 Suitability

An integrated approach for design and simulation is completely suitable and necessary with the increase in aircraft design complexity. Current techniques based on textual documents, and *ad hoc* communication and traceability is far from efficiently manage this complexity. Any approach integrating design and simulation in a more formal fashion is more than desirable, it is essential.

In our approach, the bottleneck is clearly two: the internal mapping from messages to signals and local parameters, and the CASE tool we have adopted (TOPCASED). As discussed before, the internal mapping is an overhead on abstraction not desirable when systems are getting more complex, thus, making this mapping even more obfuscated in SysML. Concerning TOPCASED, it is an excellent experimentation tool, and should be used in AIRBUS research projects, given its flexibility due to its open-source nature, but I think that it cannot be used yet in production. The environment is very unstable, with many beta tools working together, and the modeling area and properties panels' sizes are not good to modeling (we can solve that using two monitors side-by-side). AMISA has adopted Telelogic Rhapsody as its CASE tool, and I think this is a good choice. It is completely integrated with DOORS, very robust, being in the market for year. Again, I recommend TOPCASED for R&T projects, while Rhapsody for production.

6.2 Contributions and Future Work

Our contributions are:

- An approach enabling integrated design and simulation in a model-based fashion. With our approach, all simulation and design elements are traced, enabling further impact analysis between these two architectural levels. In addition, our approach removes all redundancies between simulation and design, given that a SysML model can be reused by other model, always referencing the source one;
- Transformation and representation of aircraft design and simulation data in a more convenient formalism, moving from textual-based to model-based representations through the SysML Design and Simulation models, as well as the UP2A and SFPR UML profiles;
- Separation and better understanding of simulation model and simulation platform responsibilities, in specific the simulation scheduler and the AP2633 state machine;
- Definition and first algorithms for simulation code generation from SysML Simulation models and its integration with Simulink/SCADE, through the mechanism of change events;

- Development of a tool prototype to perform and show the feasibility of our approach. One of the main difficulties to introduce new technology and to break *status quo* is to convince people that the new way of doing things is better, and with a tool prototype, this was easier.

Another contribution is the further research and development this work opens:

- Full simulation code generation from SysML Simulation models and its further integration with Simulink/SCADE. It is needed to define the change events semantics, its relation with the AP2633 state machine, and the best way to call Simulink/SCADE code. It would be interesting to use Acceleo to implement the code generator;
- Implementation of the model-to-model transformation (A/C ICD-AP2633 to SysML Design Model, then to SysML Simulation Model) rules in ATL, the text-to-model transformations (A/C ICD CSV file to A/C ICD-AP2633 metamodel), and model-to-text transformations (SysML Models to MICD Excel sheet). This would improve our tool, making easier to perform evolution, manageability, testing, and production;
- Integration of relational databases with SysML models, enabling to store low-level data into databases, improving the abstraction of the SysML models. This is important to avoid using the SysML model as a data repository, and to improve impact analysis and engineering with SysML;
- Full SysML Simulation model execution in SysML to enable exploratory modeling, reducing the simulation design cycle by performing partial simulations before OCASIME. It is necessary to define the subset of SysML we are going to use, and to code its virtual machine;
- Devising design and simulation process for requirements management, and artifacts control integrated with OSMOSE.

REFERENCES

ADVISORY COUNCIL FOR AERONAUTICS RESEARCH IN EUROPE. : Strategic Research Agenda 1. Volume 2, [S.l.], 2002.

AIRBUS SAS. **M2633 Module 2:** Shared Simulation Models Design Rules. Draft 4. Toulouse, 2009.

AIRBUS SAS. **AP2633:** Develop, Integrate and Validate Shared Simulation Models. Issue C. Toulouse, 2008.

AIRBUS SAS. **X0WD0805765:** Project INSIDE : INtegrated Simulation Into DEsign. R&T Project Agreement. Toulouse, 2008b.

AIRBUS SAS. **RP0816448:** AMISA Method – Technical Report. Toulouse, 2008c.

AIRBUS SAS. **UG0600603:** OSMOSE Guide méthodologique outils : métier équipement. Issue 3. Toulouse, 2007a.

AIRBUS SAS. **V00RP0716320:** A350 ISCD Policy. Issue 1. Toulouse, 2007b.

AIRBUS SAS. **509.0025/2003:** AP2633 Model ICD Guideline. Technical Report. Toulouse, 2006.

AIRBUS SAS. **L00ME0315182:** How to Fill the Column "Aircraft Signal Name" in Model ICD. Memorandum. Toulouse, 2003.

AIR TRANSPORT ASSOCIATION. **99100P:** Spec 100: Manufacturers' Technical Data. Revision 1999. Washington, 1999.

BAKER, L.; CLEMENTE, P.; COHEN, B.; PERMENTER, L.; PURVES, B.; SALMON, P. **Foundational Concepts for Model Driven System Design:** INCOSE Model Driven System Design Workgroup. [S.l.], 2000.

BALCI, O. A Methodology for Certification of Modeling and Simulation Applications. **ACM Transactions on Modeling and Computer Simulation.** New York: ACM Press, 2001, v. 11, n. 4, p. 352-377.

BRADE, D. **A Generalized Process for the Verification and Validation of Models and Simulation Results.** 2003. 239 f. Thesis (Doctor rerum naturalium) – Fakültat für Informatik, Universität der Bundeswehr München, Munich, Germany.

BRIÈRE, D.; TRAVERSE, P. AIRBUS A320/330/340 electrical flight controls – A family of fault-tolerant systems. In: THE TWENTY-THIRD INTERNATIONAL SYMPOSIUM ON FAULT-TOLERANT COMPUTING (FCTS'93). **FCTS 1993 Digest of Papers.** Los Alamitos: IEEE Computer Society Press, 1993, p.616-623.

CLARK, N. Next Delay for A380: A Decade Before Break-Even. **The New York Times.** 2006, 19th October, Business Section. http://www.nytimes.com/2006/10/19/ business/worldbusiness/19iht-airbus.3222866.html. Accessed on July 2009.

CRAIG, I. D. **Object-Oriented Programming Languages: Interpretation.** Undergraduate Topics in Computer Science (UTCS) Series. 1st edition. Heidelberger, Germany: Springer-Verlag, 2007.

DEPARTMENT OF DEFENCE OF AUSTRALIA. : Simulation Verification, Validation and Accreditation Guide. Canberra, 2005.

DEPARTMENT OF DEFENSE OF UNITED STATES. **MG101:** Improving the Composability of Department of Defense Models and Simulations. Santa Monica, 2004.

DISCOVERY CHANNEL. http://www.youtube.com/watch?v=IKBABNL-DDM. Accessed on July 2009.

ESTEFAN, J. A. **Survey of Model-Based System Engineering (MBSE) Methodologies:** INCOSE MBSE Focus Group. Revision A. [S.l.], 2007.

FERREIRA, R.; BRISOLARA, L.; MATTOS, J.; SPECHT, E.; COTA, E.; CARRO, L. **Engineering Embedded Software: from Application Modeling to Software Synthesis.** In: GOMES, L.; FERNANDES, J. (Org.). Behavioral Modeling for Embedded Systems and Technologies: Applications for Design and Implementation. Hershey: IGI Publishing Group, 2009.

FLIGHT DAILY NEWS. Paris Air Show: Perception By Wire. **Flight Daily News.** 2009. http://www.flightglobal.com/articles/2009/06/08/327191/paris-air-show-perception- by -wire.html, Accessed on July 2009.

FLIGHT INTERNATIONAL. A340 Described: Architecture Refinement for A340 FBW. **Flight International Magazine.** [S.l.] : [S.n.], n.5, 11 June, 1991.

FORSBERG, K.; MOOZ, H. The Relation of System Engineering to the Project Cycle. In: JOINT CONFERENCE OF THE NATIONAL COUNCIL ON SYSTEMS ENGINEERING (NCOSE) AND THE AMERICAN SOCIETY FOR ENGINEERING MANAGEMENT (ASEM) (ASEM'91). **Proceedings of the 1991 ASEM.** Chattanooga, TN, USA: ASEM Press, 1991, p. 1-12.

IEEE COMPUTER SOCIETY. **IEEE Std 1516.2-2000:** IEEE Standard for Modeling and Simulation (M&S) High Level Architecture (HLA) – Object Model Template (OMT) Specification. Std 1516.2-2000. New York, 2001.

IEEE COMPUTER SOCIETY. **IEEE Std 1220-2005:** IEEE Standard for Application and Management of the Systems Engineering Process. Std 1220-2005 (Revision of IEEE Std 1220-1998). New York, 2005.

LARMAN, C. **Applying UML and Patterns: An Introduction to Object-Oriented Analysis and Design and Iterative Development.** 3rd edition. New Jersey, USA: Prentice Hall, 2004.

MARTIN, J. N. Overview of the EIA 632 Standard: Processes for Engineering a System. In: 17th DIGITAL AVIONICS SYSTEMS CONFERENCE (DASC'98). **Proceedings of the 17th AAIA/IEEE/SAE DASC.** [S.l.]: IEEE Computer Society Press, 1998, v.31, n.1, p. B32 1-9 vol. 1.

MURPHY, C. A. The Definition and Potential Role of Simulation Within an Aerospace Company. In: 2001 WINTER SIMULATION CONFERENCE (WSC'01). **Proceedings of the IEEE WSC 2001.** [S.l.]: IEEE Computer Society Press, 2001, v. 1, p. 829-837.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. **NASA-STD-7009:** Standard for Models and Simulations. 07-11-2008. Washington, 2008.

OBJECT MANAGEMENT GROUP. **formal/06-01-01:** Meta Object Facility (MOF) Core Specification. Version 2.0. [S.l.], 2006a.

OBJECT MANAGEMENT GROUP. **formal/2008-04-03:** Meta Object Facility (MOF) 2.0 Query/View/Transformation Specification. Version 1.0. [S.l.], 2008a.

OBJECT MANAGEMENT GROUP. **ormsc/2001-07-07**, [S.l.], 2001.

OBJECT MANAGEMENT GROUP. **formal/06-05-01:** Object Constraint Language. Version 2.0. [S.l.], 2006b.

OBJECT MANAGEMENT GROUP. **formal/2008-11-02:** OMG Systems Modeling Language (OMG SysML^{TM}). Version 1.1. [S.l.], 2008b.

OBJECT MANAGEMENT GROUP. **formal/2009-02-04:** OMG Unified Modeling Language^{TM} (OMG UML), Infrastructure. Version 2.2. [S.l.], 2009a.

OBJECT MANAGEMENT GROUP. **formal/2009-02-02:** OMG Unified Modeling Language^{TM} (OMG UML), Superstructure. Version 2.2. [S.l.], 2009b.

RATIONAL SOFTWARE. **TP 165A:** Rational Unified Process® for Systems Engineering: RUP® SE1.1. Version 5/02. Cupertino, 2002.

RODRÍGUEZ-DAPENA, P. Software Safety Certification: A Multidomain Problem. **IEEE Software.** Los Alamitos : IEEE Computer Society Press, 1999, v. 16, n. 4, p. 31-38.

ROQUES, P.; VALLÉE, F. **De l'analyse des besoins à la conception en Java.** 2^{éme} édition. Paris : Éditions Eyrolles, 2003.

SARGENT, R. G. Verification and Validation of Simulation Models. In: 2008 WINTER SIMULATION CONFERENCE (WSC'08). **Proceedings of the 39th IEEE/ACM WSC 2008.** Piscataway: IEEE Computer Society Press, 2007, p. 124-137.

SILBERSCHATZ, A.; KORTH, H. F.; SUDARSHAN, S. **Database Systems Concepts.** 4th ed. New York: McGraw-Hill Science/Engineering/Math, 2001.

TRAVERSE, P.; LACAZE, I.; SOUYRIS, J. Airbus Fly-By-Wire : A Total Approach To Dependability. In: 18th WORLD COMPUTER CONGRESS (WCC'04). **Proceedings of the IFIP WCC 2004**. Toulouse: Springer Boston, v. 156/2004, p. 191-212.

TOPCASED Modeling and Simulation CASE Tool. **The Open-Source Toolkit for Critical Systems.** Version 2.5, http://www.topcased.org. Accessed on July 2009.

VOAS, J. Certifying Software for High-Assurance Environments. **IEEE Software.** Los Alamitos: IEEE Computer Society Press, 1999, v. 16, n. 4, p. 48-54.

WEILKIENS, T. **Systems Engineering with SysML/UML: Modeling, Analysis, Design**. 1st ed. Amsterdam: The Morgan Kaufmann/OMG Press, 2008.