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CubeSat System Reference Model (CSRM) as an OMG Specification

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ABSTRACT

This paper describes the transformation of the CubeSat Reference Model™ (CSRM™) into an Object Management Group® (OMG®) specification, as effected by the International Committee on System Engineering (INCOSE) Space System Working Group (SSWG) from 2016 to 2022.

The CSRM is a logical model of engineering artifacts used by a CubeSat mission team to build its mission-specific logical and physical models according to its individual engineering methodology. It is based on Model-Based System Engineering (MBSE) principles, is OMG System Modeling Language (SysML) compliant, is hosted on a graphical modeling tool, and is intended to foster completeness and economies of scale associated with reusability.

The OMG, an international standards organization, has a mature, worldwide, and open process for identifying the need for a specification, as well as for soliciting, developing, approving, and distributing a specification. In 2018, the OMG initiated a process to provide the CSRM as an OMG specification.

This resulted in the normative CSRM Profile Specification document, the normative CSRM Profile XMI file for import into a graphical modeling tool, and the non-normative CSRM Profile Model. Supplementing these files are the non-normative CSRM Model file and the non-normative CSRM HTML file which allows for exploration and evaluation of the CSRM without the need to acquire a graphical modeling tool and provides sufficient guidance for establishing a mission specific CSRM.

1. INTRODUCTION

The CubeSat System Reference Model (CSRM) is a collection of logical elements that make up a CubeSat space-ground system. Prior papers addressed the development and application of the CSRM [1]-[12]. This paper addresses the creation and maintenance of the OMG specification for the CSRM.

It was proposed in 2016 that the CSRM could provide the basis for an INCOSE - OMG joint development of an OMG specification. OMG, an international Voluntary Consensus Standards Body organization, has a detailed process for identification of the need for a specification followed by the solicitation, development, approval, and distribution of a specification.

Areas of collaboration included working with OMG's Space Domain Task Force and OMG's Architecture Board (AB) to develop the CSRM specification as a hybrid of a PDF document and a graphical engineering model. Traditionally, OMG specifications have always been captured in PDF documents.

This collaboration broke new ground for OMG by creating 1) Hyper Text Markup Language (HTML) file to complement PDF document and 2) XML Metadata Interchange (XMI) file as a tool agnostic version of the CSRM Specification. The XMI file was developed in collaboration with graphical modeling tool vendors.

The organization of the paper is as follows:

- CSRM Project Background
  - Origin of the CSRM
  - Development of the CSRM
  - Development of the Specification
- CSRM Configurations
  - CSRM Profile
  - Creation of the CSRM Profile Specification document based on the CSRM Profile Model. OMG CSRM Profile Setup Environment (Figures 2a, 2b, 4)
  - Creation of the CSRM Profile Model based on the CSRM Profile Specification document. Mission Modeling Environment. (Figure 6)
- Creation of Mission Model (Figures 2d, 10)
  - Development of a Mission Model in three steps starting with a CSRM Profile XMI file or reusing a Mission Profile.
  - Reuse of a logical model to bypass the first two steps.
  - Resulting four models that provide the design specifications for developing the Mission CubeSat.

The flow of figures is:

- Figure 2. Model view illustration of modeling concepts presented in this paper.
- Figure 3. The CSRM Profile contains stereotypes that provides the building blocks for creating CSRM elements which provides the building blocks for creating the CSRM logical architecture.
- Figure 4. Creating a CSRM Profile Specification document, XMI file, and XML file from a Proof-of-Concept CSRM Profile Model.
- Figure 5. Maintaining a CSRM Profile Specification document, XMI file, and HTML.
- Figure 6. Creating a CSRM Profile Model file from a CSRM Profile Specification document, XMI file, and HTML file.
- Figure 7. Extracting CSRM Profile XMI file and CSRM Profile HTML file from a CSRM Profile Model file.
- Figure 8. Model elements can be reused between projects based on the CSRM Profile.
- Figure 9. The CSRM Profile Model file cannot be an OMG specification since it is not transportable between different graphical modeling tools.
- Figure 10. Process view illustration of creating a mission specific model.

2. CSRM PROJECT BACKGROUND

Origin

Figure 1 shows the CSRM development timeline.

The CSRM has its origins in 2007 with the INCOSE MBSE Challenge Project. It was a joint MIT and Georgia Tech student project that demonstrated the application of MBSE and SysML as applied to the hypothetical FireSat system as described in Space Missions Analysis and Design (SMAD).

The project was reestablished in 2012 with the development of a CubeSat framework and its application to the University of Michigan's Radio Aurora Explorer (RAX). This included behavior modeling of state, power, and communication. A new model was developed with capability to time-step through a scenario and to capture the energy collection and usage processes as well as data collection, storage, and download processes.

Development of the CSRM

That was followed in 2015 by initiating the development of the CSRM, the logical architecture of a CubeSat space and ground system, to be used by a university team as a starting point for their mission specific logical and physical models.

The methodology used to create the CSRM draws from:

- INCOSE Systems Engineering Handbook [13]
- NASA System Engineering Handbook [14]
- Space Mission Engineering - The New SMAD [15]

Additionally, the methodology is consistent with OASIS and ISO specifications including ISO/IEC/42010 Systems and software engineering – Architecture description.

The CSRM is based on Model-Based System Engineering (MBSE) principles, is compliant with the OMG System Modeling Language (SysML) 1.6, and is hosted on a graphical modeling tool. It tracks core elements of stakeholders, technical measures, behaviors, and requirements across architecture levels of enterprise, space and ground segments, subsystems and components.

The CSRM is a repository for systems engineering artifacts. However, it is not prepopulated. That is the job of the mission team. The mission team is free to adopt a different logical architecture and modify the CSRM components to accommodate the change.

The CSRM can be applied to small satellites in general.

Development of the Specification

It was proposed in 2016 that the CSRM could provide the basis for an INCOSE – Object Management Group® (OMG®) joint development of an OMG specification. OMG, an international Voluntary Consensus Standards Body (VCSB) organization, has a detailed process for identification of the need for a specification followed by the solicitation, development, approval, and distribution of a specification.

That process as applied to the CSRM is illustrated in Figure 1 starting with the INCOSE-OMG MOU in January 2018.

The CSRM Profile Specification was endorsed by the OMG Architecture Board in September 2021 and adopted by the OMG Board of Directors (BoD) in September 2022.

3. CSRM CONFIGURATIONS

This section addresses the creation and maintenance of an OMG specification based on the CSRM. including how the specification is created to be free of implementation.

CSRM is an umbrella term for:

- CSRM Model
- CSRM Profile Model
- CSRM Profile Specification
- CSRM HTML File
- CSRM Profile XMI File

In this instance, a Model is an instantiation of SysML elements in a graphical modeling tool file captured in a graphical modeling tool. The tool-specific nature of the graphical model file means that the CSRM Model is also tool-specific.

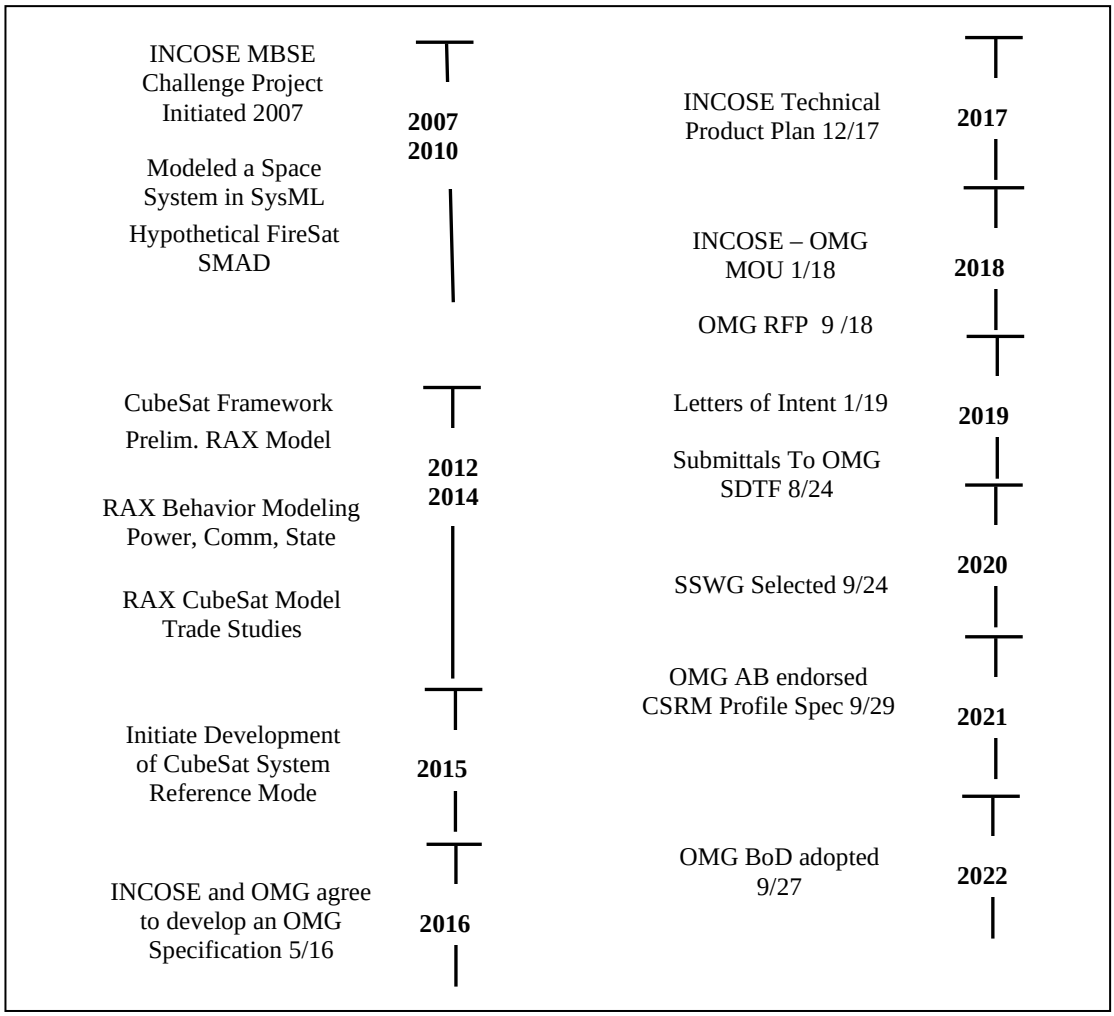

Figure 1. CSRM Development Timeline

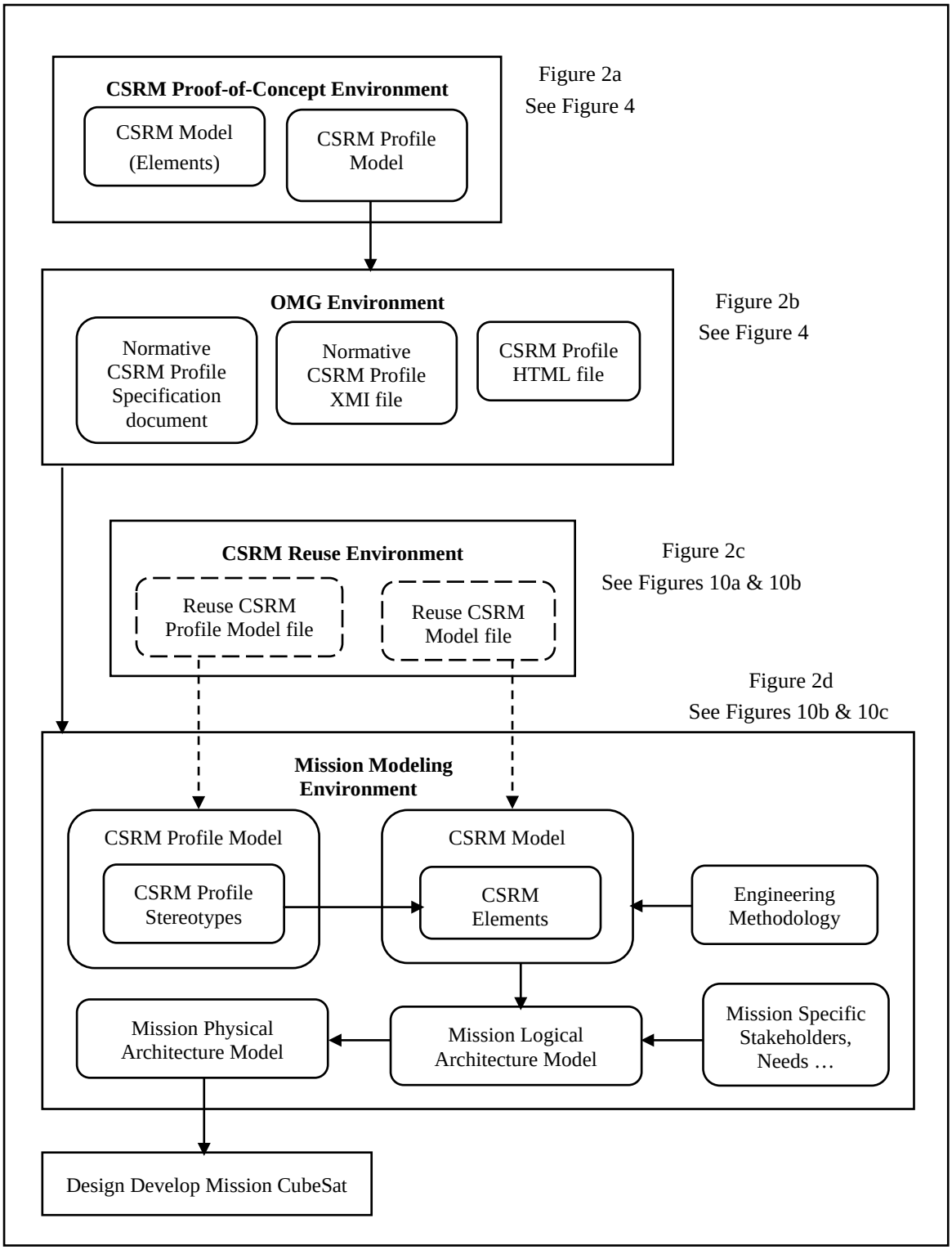

Figure 2. Model view illustration of modeling concepts presented in this paper. Environment - A grouping of objects, for example with respect to their role or physical hosting. Refer also to the section on terminology.

Up to this point in the development, the term CSRM or CSRM Model, has referred to the CSRM graphical model tool file (.mdzip) as implemented in the Cameo Systems Modeler graphical modeling tool.

An environment is a grouping of objects, for example with respect to their role or physical hosting.

An OMG specification derived from the CSRM Proof-of-Concept Environment illustrated in Figure 2a must be:

- Free of implementation, which rules out using a graphical modeling tool file.
- Document based, which does provide for OMG's rigorous configuration management processes.

The CSRM Model elements are founded on the CSRM Profile Model, a package of CSRM stereotypes.

The OMG Environment normative CSRM Profile Specification document, the normative CSRM Profile XMI file, and the CSRM Profile HTML file are derived from the CSRM Profile Model as shown in Figure 2b.

CSRM Profile

In SysML, a package is a container for model elements. A profile is a package that contains stereotypes. A stereotype defines a new kind of model element. For example, the subsystem stereotype is used to create subsystem elements such as the Communication Subsystem.

The essence of the CSRM is the CSRM Profile containing SysML stereotype definitions that provide the building blocks for creating CSRM elements which in turn provides the building blocks for creating the CSRM logical architecture. (Figures 2d and 3)

The CSRM Profile Specification document contains descriptions of the CSRM Profiles, the CSRM SysML element stereotypes used to create the CSRM elements.

The CSRM Profile XMI file and CSRM Profile Specification document are normative. A mission-specific CubeSat Model based on the Profile Specification document and Profile XMI file provides assurance to the stakeholders that the CubeSat Model is well founded. Incorporation of the CSRM Profile can be verified by inspection. The Specification itself is in accordance with OMG's definition of a Specifications.

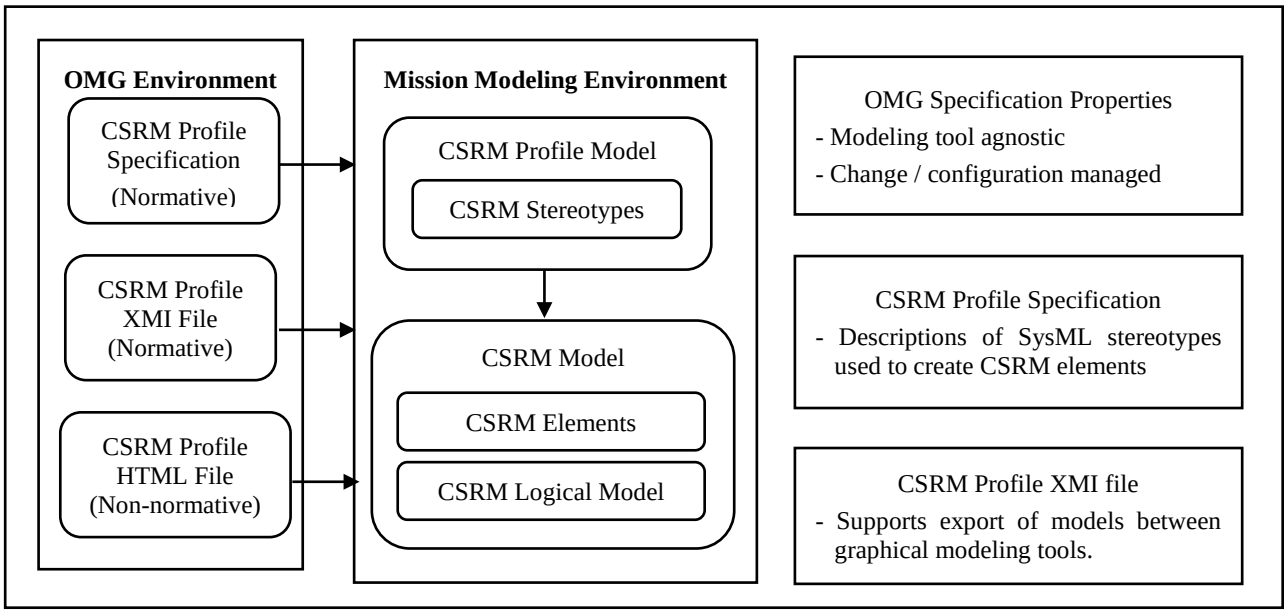

Figure 3. The CSRM Profile contains stereotypes that provides the building blocks for creating CSRM elements which provides the building blocks for creating the CSRM logical architecture.

See also Figures A1 and A2

The CSRM Profile can be exported as an implementation-free CSRM Profile XMI file and imported into another graphical modeling tool.

A user can implement the CSRM Profile and claim conformance with verification by inspection. If two users claim conformance, they can reuse each other's elements.

Creating and Maintaining CSRM Profile Specification document, XMI file, and HTML file.

Which came first, the CSRM Specification document and the XMI file OR the CSRM Model?

In our case the CSRM Model came first. The CSRM Model is the result of several years of iterative development with systems engineers working on CubeSat and smallsat missions and providing feedback to the SSWG. As the model was refined, it became possible to separate the CSRM Profile and extract it to become a normative specification.

Figure 4 illustrates the creation of a CSRM Profile Specification document and a CSRM Profile XMI file from a CSRM Profile Model file. The CSRM Profile Specification was created using a Proof-of-Concept CSRM Profile Model to populate an OMG specification template. Additionally, a CSRM Profile XMI file and a CSRM Profile HTML file were exported from the CSRM Profile Model.

The CSRM Profile HTML file is a representation of a Model generated by a graphical modeling tool that can explored/evaluated using a browser, independently from any graphical modeling tool.

Figure 5 illustrates the maintenance of the Specification document and XMI file. Updates are applied to the CSRM Profile Specification document and the CSRM Profile Model thus creating a new XMI file and HTML file.

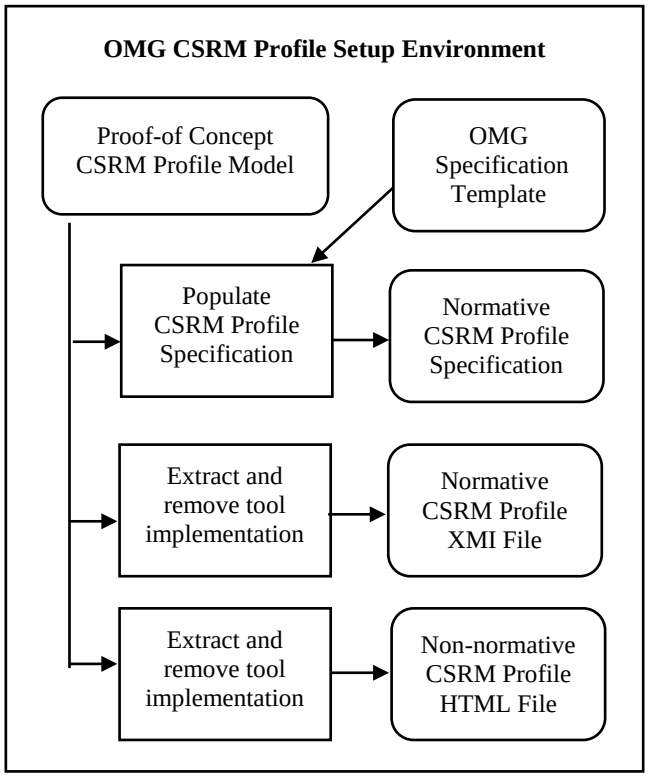

Figure 4. Creating a CSRM Profile Specification document, XMI file, and XML file from a Proof-of-Concept CSRM Profile Model. See also 2a and 2b

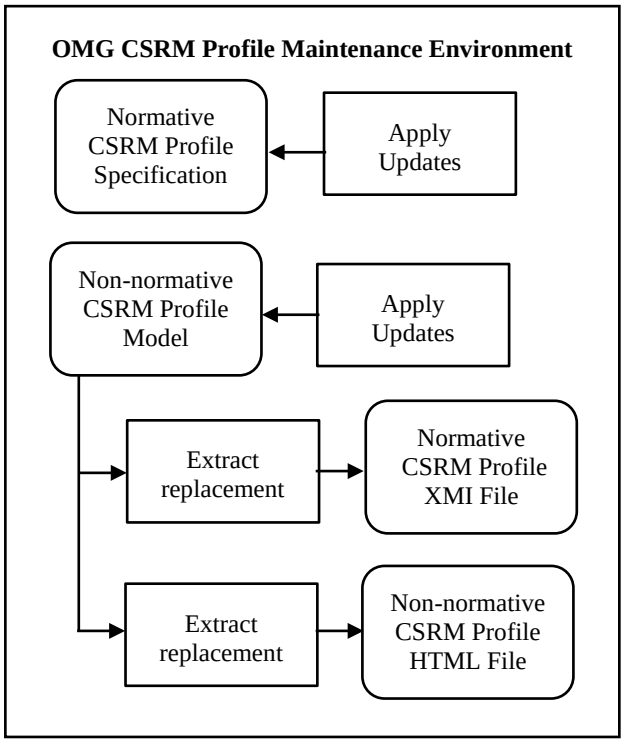

Figure 5. Maintaining a CSRM Profile Specification document, XMI file, and HTML file. See also A3

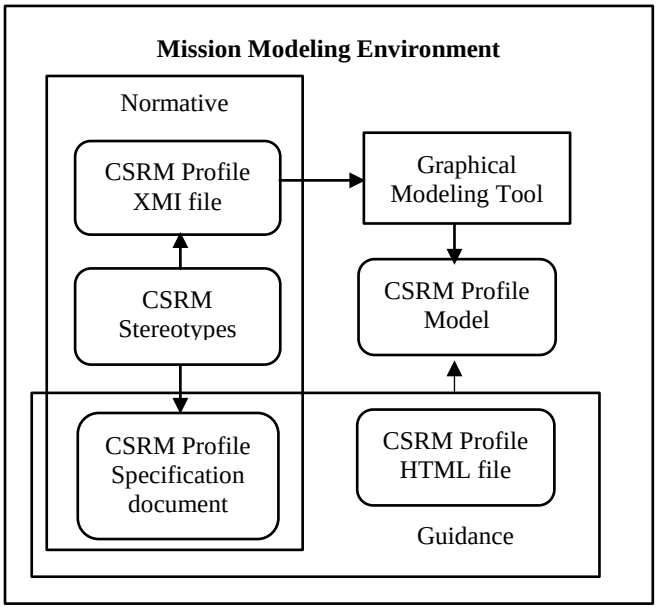

Figure 6. Creating a CSRM Profile Model file from a CSRM Profile Specification document, XMI file, and HTML file.

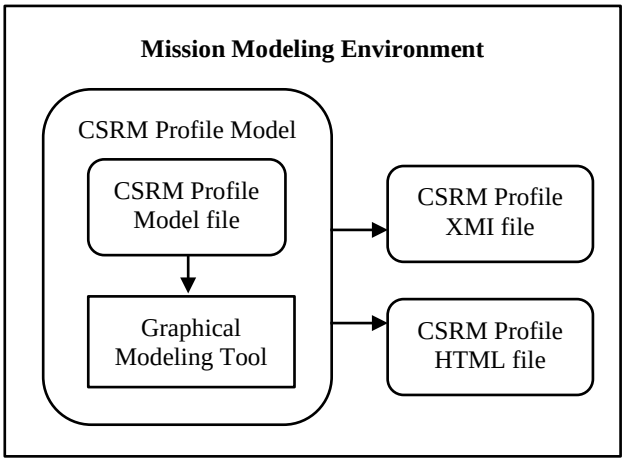

Figure 7. Extracting CSRM Profile XMI file and CSRM Profile HTML file from a CSRM Profile Model file.

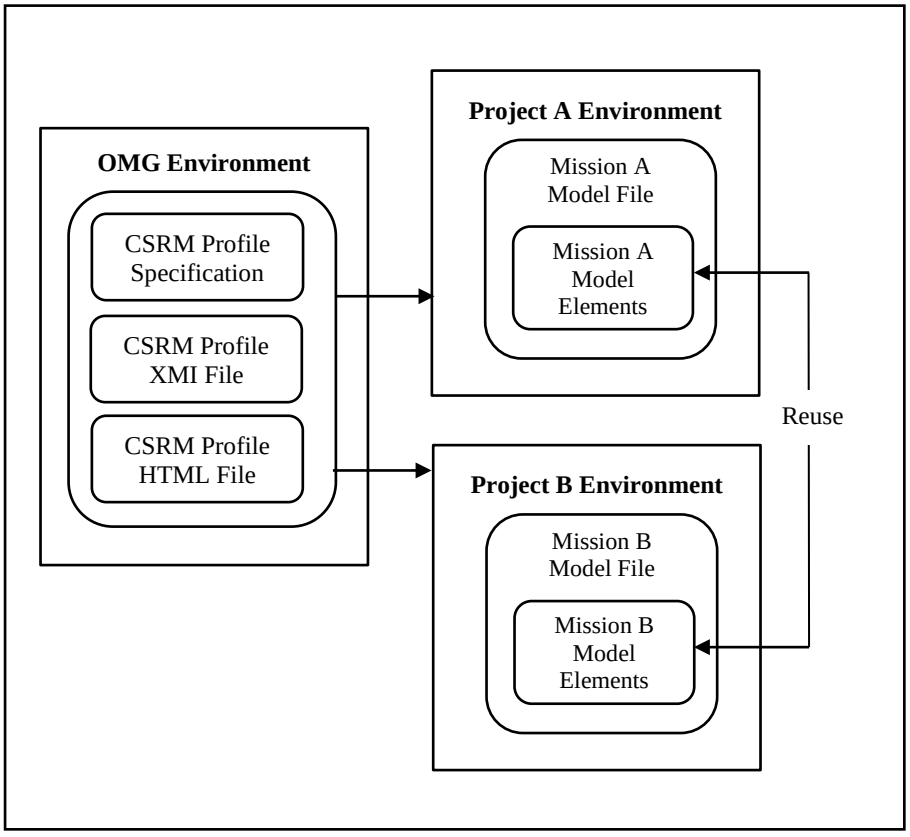

Figure 8. Model elements can be reused between projects based on the CSRM Profile.

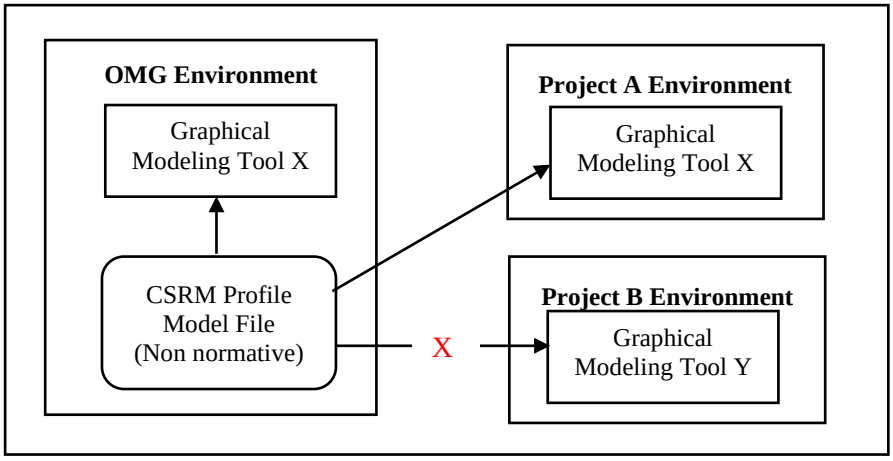

Figure 9. The CSRM Profile Model file cannot be an OMG specification since it not transportable between different graphical modeling tools.

Creating a CSRM Profile Model file from a CSRM Profile Specification document and XMI file.
The CSRM Profile Model can be created by importing the CSRM Profile XMI file into a graphical modeling tool, using the CSRM Profile Specification and CSRM Profile HTML file as guidance. (Figure 6)

Conversely, the CSRM Profile XMI file and CSRM Profile HTML file can be exported from the CSRM Profile Model. (Figure 7)

Figure 8 illustrates that model elements based on the CSRM Profile can be reused between projects.

Figure 9 illustrates why CSRM Profile Model file cannot be an OMG specification. Project A Environment is founded on Graphical Modeling Tool X, the same tool used in the Specification Environment. However, Project B Environment is founded on Tool Y thus incompatible with the CSRM Profile Model file created with Tool X.

4. CREATING A MISSION MODEL

Figure 10 illustrates creating a Mission Model in three steps starting with setting up a Profile Model from a CSRM Profile XMI File and / or reusing a Mission Profile Model. (Figure 10a)

The Profile Model is incorporated into a graphical modeling tool to set up the Mission Model. This includes creating model elements and the logical architecture according to the project engineering methodology. (Figure 10b)

The third step is to populate a mission specific logical architecture with mission specific stakeholders and needs followed with a mission specific physical architecture. (Figure 10c)

Figure 10c shows that steps 1 and 2 can be bypassed with the reuse of a Logical Architecture Model. The Project environment graphical modeling tool must be the same as used in the reuse environment.

The Mission Model, Logical Architecture Model, Logical Architecture Mission Model, and Physical Architecture Mission Model are types of specifications.

5. SUMMARY

Use of the CSRM elements and architecture levels enables common baselines for comparing and evaluating different mission-specific implementations, for assessing completeness of design, and for the sharing and reuse of design elements.

Using an OMG specification gives the user confidence that the specification is well founded and will be well maintained. It also assures the specification is transportable between different graphical modeling tools. And as an OMG specification, it adheres to OMG's rigorous configuration management process.

As part of the OMG specification process, the CSRM has been thoroughly vetted by system engineering professionals, and introduced to the CubeSat development community.

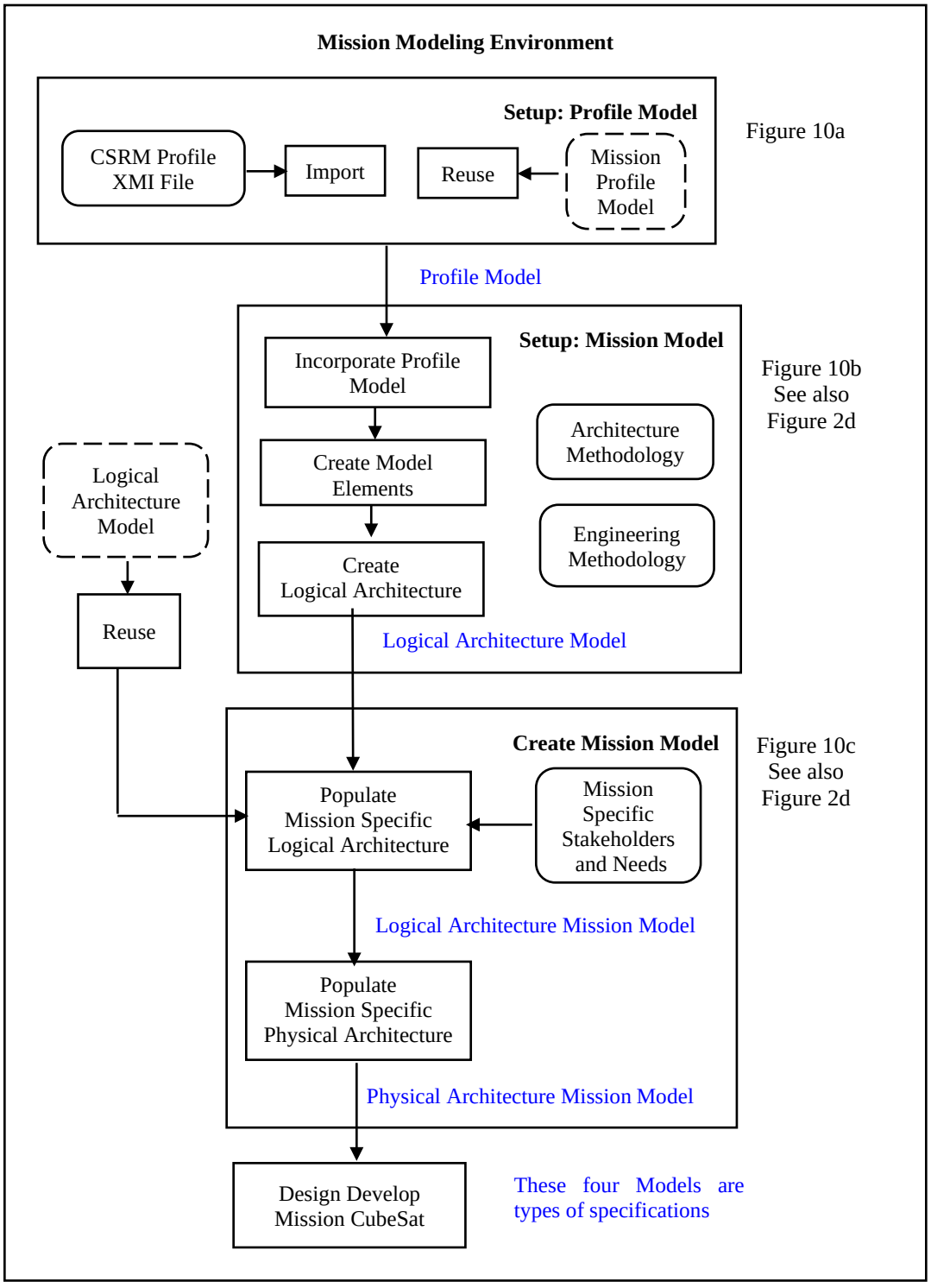

Figure 10. Process view illustration of creating a mission specific model.

APPENDICES

A. CSRM ELEMENTS AND STEREOTYPES

CSRM Exo-Structure

Figure A1 illustrates that the CSRM is an exo-structure which can be populated with mission-specific stakeholders, requirements, behaviors, architecture, and technical measures. A stakeholder is any entity that has an interest in the system. Behaviors describes the functionality of a system in terms of how it is used to achieve the goals of the stakeholders. Technical Measures are an established set of metrics based on the expectations and requirements that are tracked and assessed to determine overall system effectiveness and stakeholder satisfaction.

The CSRM provides for defining these elements, and for tracing requirements from stakeholders, behaviors, and technical measures down to subsystems and components and then to validation and verification activities. The CSRM provides a library of model elements but does not dictate a methodology. What model elements and relationships to use and how they are used should be defined by the mission's project engineering methodology.

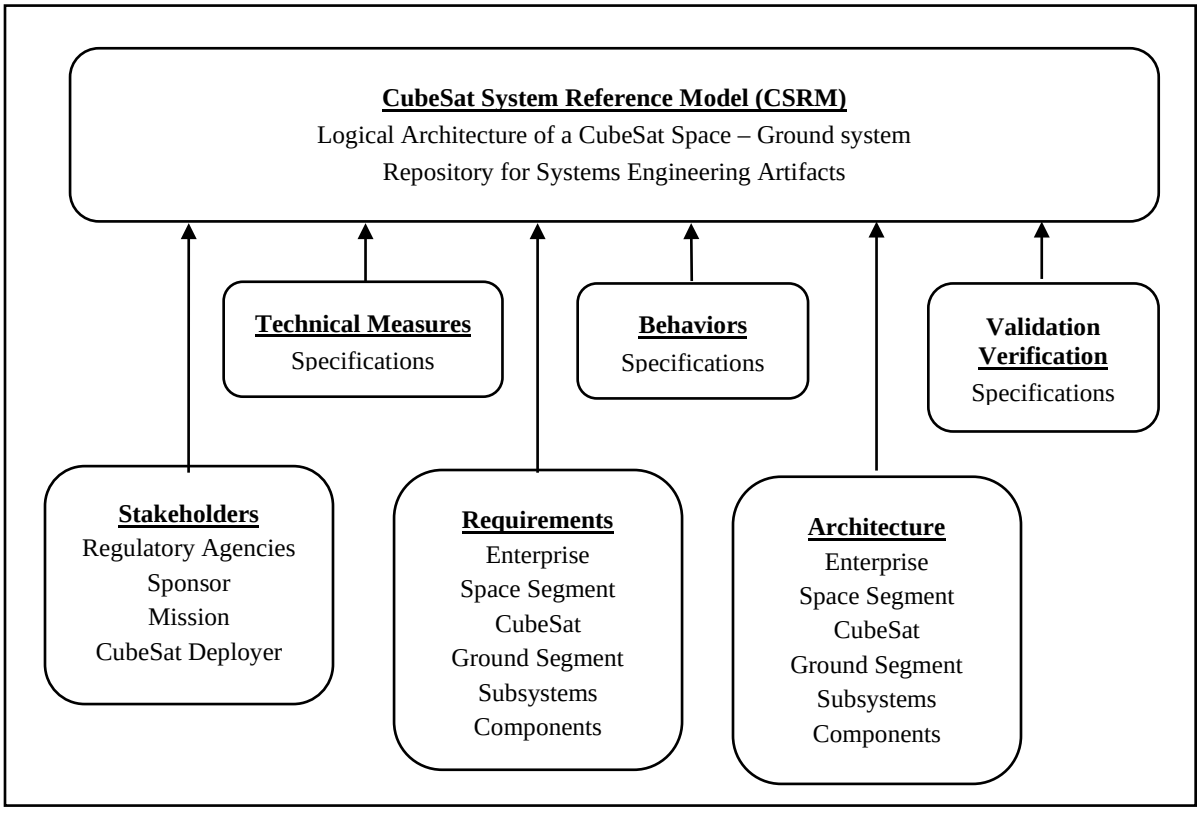

Figure A1. The CSRM is an exo-structure for population with mission-specific elements. See also Figure 3

CSRM Stereotypes

Figure A2 illustrates the CSRM is founded on the normative CSRM Profile Stereotypes with the addition of Mission Specific Stereotypes. The user can add new stereotypes, add new elements, and modify existing elements.

CSRM Profile Change Request Process

Figure A3 shows the CSRM Profile Change Request Process for a user requesting an addition or modification to a CSRM Profile stereotype.

The Change Request is submitted to the Revision Task Force to review, negotiate, and approve. The Change Request is applied with change bars to a CSRM Profile Specification for submittal to Change Management. The changes are manually applied to the Change Management CSRM Profile Specification and CSRM Profile. See also Figure 7, Maintaining a CSRM Profile Specification document and XMI file.

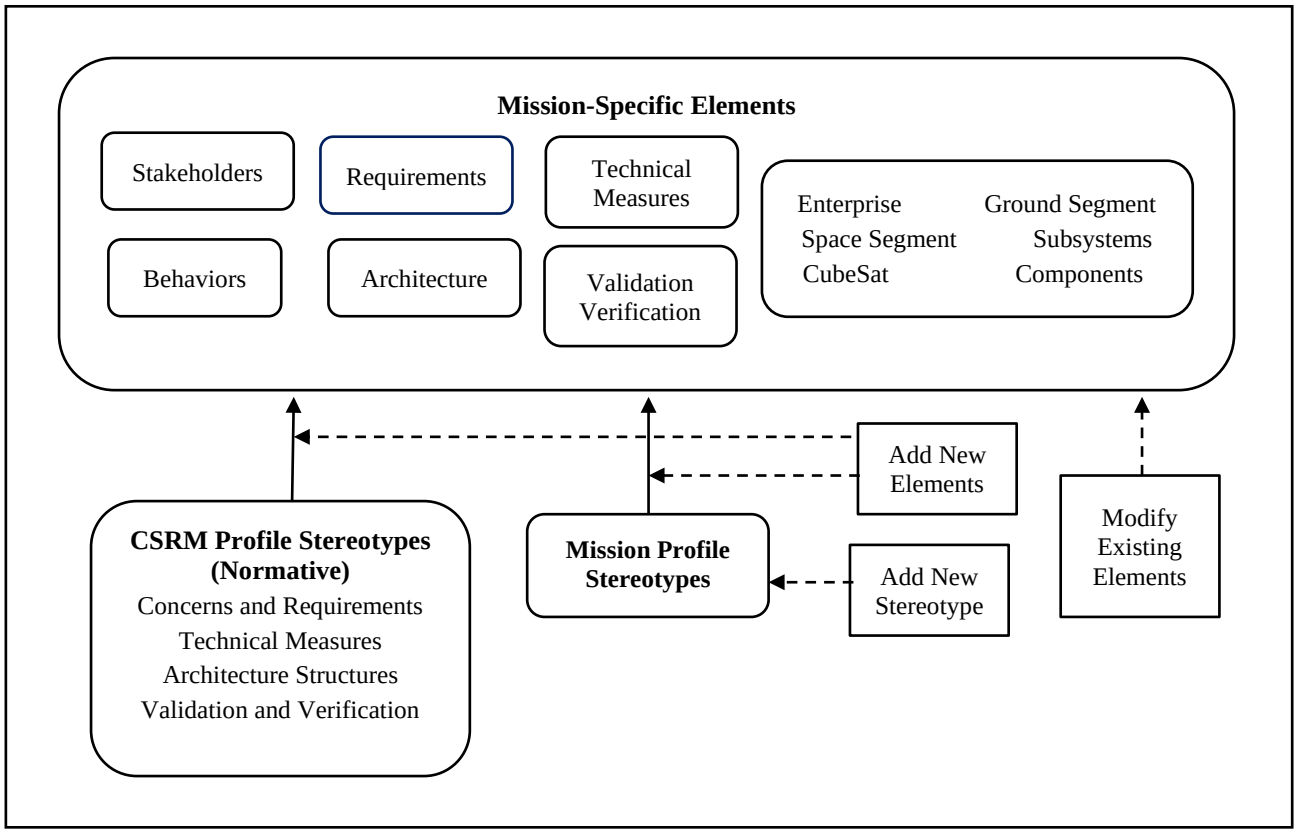

Figure A2. The CSRM is a repository of systems engineering artifacts based on stereotypes.

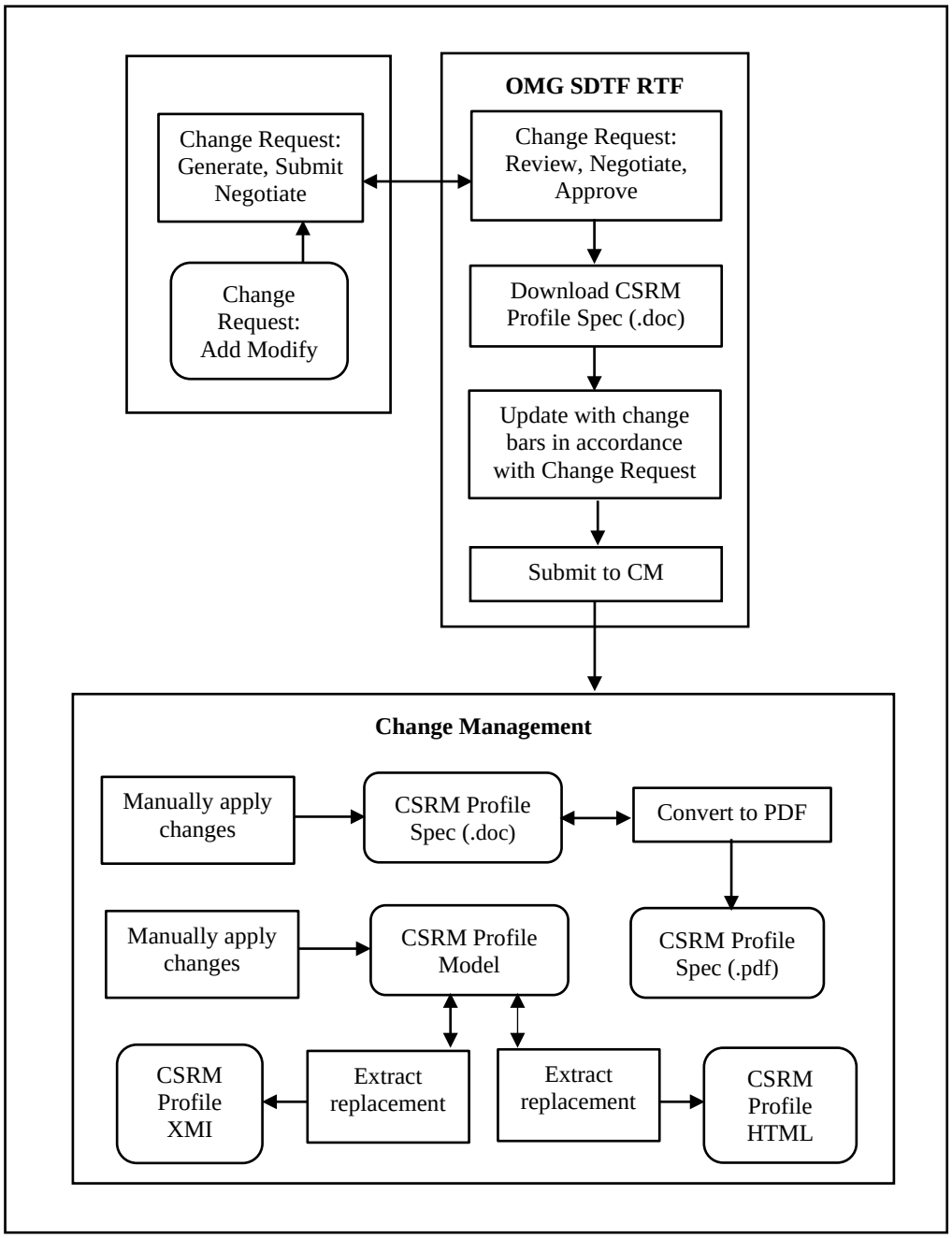

Figure A3. CSRM Profile change request process.
See also Figure 5.

B. TERMINOLOGY

OMG Specification

- OMG (Object Management Group), an international Voluntary Consensus Standards Body (VCSB) organization, has a detailed process for identification of the need for a specification followed by the solicitation, development, approval, and distribution of a specification.
- OMG specification sections can be identified normative and non-normative.

Model

- A Model contains three categories of elements: classifiers describing a set of objects, events describing a set of possible occurrences, and behaviors describing a set of possible executions. [16]
- In this instance, a Model is graphical model tool file, captured in a graphical model tool, e.g., a .mdzip file produced with Cameo Systems Modeler.

CubeSat System Reference Model (CSRM)

- The collection of logical elements that make up a CubeSat space-ground system.
- e.g., Stakeholders, technical measures, behaviors, and requirements across architecture levels of enterprise, space and ground segments, subsystems, and components.
- For use by CubeSat mission teams to build mission-specific logical and physical models
- The CSRM can be applied to small satellites in general.

CSRM Model

- CSRM as populated in a graphical modeling tool.

CSRM Proof-of-Concept Model

- The Model developed to prove out the CSRM stereotypes, elements, and architectures.
- The source of the CSRM Profile.

CSRM Profile Specification

- Normative
- A document
- Contains descriptions of the CSRM Profiles, the CSRM SysML element stereotypes used to create the CSRM elements.

CSRM Profile XMI File

- Normative
- XML Metadata Interchange (XMI) supports the export of models between graphical modeling tools. such as Cameo Systems Modeler and Enterprise Architect.

CSRM Profile HTML File

- A representation of a Model generated by a graphical modeling tool that can be explored/evaluated using a browser independently from any graphical modeling tool.

CSRM Profile Model

- CSRM Profile as described in the CSRM Profile Specification, captured in the CSRM Profile XMI file and populated in a graphical modeling tool.

Environment

- A grouping of objects, for example with respect to their role or physical hosting.

Normative

- Normative content is the prescriptive part of the specification.
- The normative content must be implemented to claim conformance with the specification.
- A Model cannot be a normative specification since it is implemented in a tool.

Package

- A package is a container for model elements.

Profile

- A profile is a package that contains stereotype definitions.

Stereotype

- A stereotype defines a new kind of model element.
- For example, the subsystem stereotype is used to create subsystem elements such as the Communication Subsystem.

Logical Architecture

- The logical architecture components are abstractions of the physical components that perform the system functionality without imposing implementation constraints.

Physical Architecture

- The physical architecture defines physical components of the system including hardware, software, persistent data, and operational procedures.

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