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A review on spacecraft modeling, simulation, verification, and validation towards use in Integration Readiness Levels

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Abstract. *The Integration Readiness Levels (IRL) aims to address the limitations of the Technology Readiness Levels (TRL) scale to assess the integration of elements of a system. IRL has been evolving, and research is being conducted on whether modeling and simulation (M&S) could be used to comply with IRL. The objective is to review the literature on spacecraft modeling, simulation, verification, and validation. A bibliometric analysis showed key organizations and countries. The main subjects and their correlation were mapped through keyword analysis. A qualitative analysis covered special topics on spacecraft verification and validation, model-based systems engineering, digital engineering, and M&S credibility and maturity. This paper contributes to discuss ongoing research on M&S and IRL and may be useful to other researchers on related subjects.*

Keywords: Integration Readiness Levels; Modeling; Simulation; Verification; Validation.

1. Introduction

Although the Technology Readiness Levels (TRL) has been used for decades to support decision-making on the introduction of technologies in complex systems development, it has limitations related to the representation of integration between the technological elements of a system. The Integration Readiness Levels (IRL) scale aims to address these limitations, to represent risk levels associated with the readiness of integration between two or more technological elements of a system. It has been evolving over the past fifteen years and is expected to be an emerging system engineering best practice. However, IRL does not explicitly guide whether modeling and simulation (M&S) could comply with IRL dedicated to verification and validation (V&V) (JESUS; CHAGAS JUNIOR, 2021).

M&S play many roles in the systems engineering and project management effort (JESUS *et al.*, 2020). The advancement of digital technologies and high-fidelity digital models reduces physical models' need to verify complex systems as spacecraft. Model-based system engineering practices and digital twins topics correlate with this discussion. The reuse of technologies and systems to reduce the costs and schedule of a space mission strengthens the importance of assessing systems integration risks using verification by analysis and simulation, instead of verification by test (JESUS; CHAGAS JUNIOR, 2021).

Initial research was done to identify the possible roles of M&S in assessing IRL for spacecraft. M&S roles were identified as essential or supporting to achieve each IRL and could play an essential role at IRL 4 to 7. Future studies should investigate whether and at which conditions the simulation results could be accepted to accomplish IRL (JESUS; CHAGAS JUNIOR, 2021). This paper shows a literature review conducted to support these future studies.

The objective is to review the literature on spacecraft modeling, simulation, verification, and validation.

2. Method

The first step was to perform a bibliometric analysis using Scopus (2021) and the following search: "TITLE-ABS-KEY ((model OR simulat*) AND (spacecraft OR satellite OR "space system") AND (verification OR validation)) AND (LIMIT-TO (SUBJAREA , "ENGI"))". The search found 6.329 results. The most recent 2.000 results were used in VOSViewer (2021) to perform keyword analysis in the title and abstract of the publications.

Section 3.1 shows the above results. Sections 3.2 to 3.5 show a qualitative analysis of special topics related to the research: Spacecraft V&V, Model-Based Systems Engineering (MBSE), digital engineering, and the credibility and maturity of modeling and simulation.

3. Results and Discussion

3.1. Bibliometric analysis

A growing trend of publications on the subject was observed. The country of origin of the publications was predominantly the USA, followed by China, Germany, other European countries, Japan and India. The institutions that published the most were the European ESTEC, DLR, and CNES, NASA JPL, Goddard, and Langley centers, the Chinese Academy of Sciences, JAXA. The company Airbus Defence and Space was the seventh in the rank.

By filtering publications by organizations, it was possible to identify some specific applications they developed. For example, Aglietti *et al.* (2019) described a Virtual Shaker Testing developed at ESA and mentioned a Design & Validation method from NASA to validate the spacecraft design for a launcher. By filtering book and chapter publications, a more comprehensive book on the topic of interest was identified (EICKHOFF, 2009).

Figure 1 provides an overview of the analysis of terms in the titles and abstracts of publications. The size of the circles indicates their relative frequency. The lines indicate the relative frequency that the terms appeared together. The colors represent clusters of the most correlated terms with each other. Figure 1 focuses on the cluster in red, as another cluster focused on remote sensing applications. The terms in Figure 1 were used to refine the search. For example, by focusing on the term "Verification", the main search was modified, replacing the code "(verification OR validation)" with "verification". The result was similar, but the most cited author was J. Eickhoff, who was in eighth place in the original search.

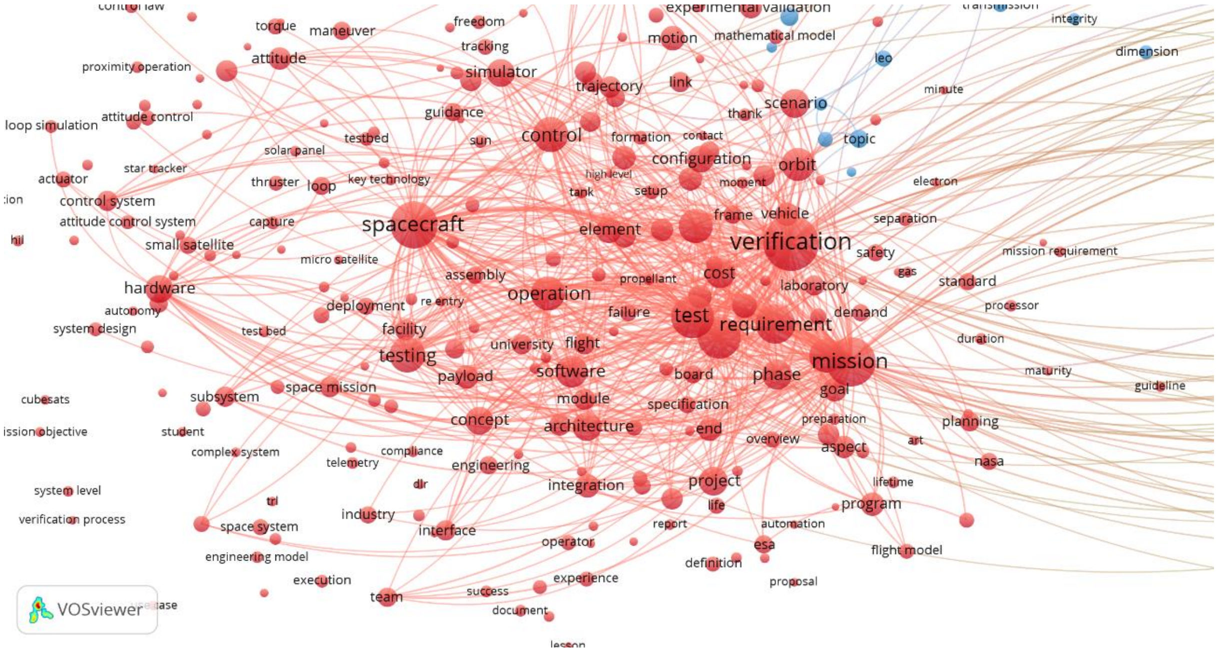

Figure 1. Keyword analysis in publications title and abstract (VOSVIEWER, 2021).

3.2. Spacecraft verification and validation

There are often major differences in how verification and validation efforts are organized and described (SELLERS *et al.*, 2009). From a process point of view (NASA, 2017a), the product verification and Product validation processes may be similar, but the objectives are fundamentally different.

Verification tests refer to the set of approved requirements and may be performed at different stages of the product lifecycle. Validation relates to the operations concept document. Validation tests are performed under realistic conditions (or simulated conditions) of end products to determine the effectiveness and suitability of the product for use in mission operations by typical users. Validation may be performed at each development phase using phase products (for example, models) and not just on delivery using end products. M&S can be used to increase the level of detail and support the product verification process and is an effective tool for performing verification, either at the early or later stages of the lifecycle. M&S are also important validation tools (NASA, 2017a).

At ESA, verification is defined in ECSS-E-ST-10-02C (2018).

The life cycle of a model or simulation has stages such as development and operation (NASA, 2016; SARGENT, 2020), and undergo V&V. There are more than one hundred methods proposed for modeling and simulation V&V (JAIN; MCLEAN, 2011). Accreditation is the official certification that a model, simulation, or federation of models and simulations and their associated data are acceptable for use for a specific application (SARGENT, 2020).

3.3. Model-Based Systems Engineering

Research (HULDT; STENIUS, 2019) indicates that one of the main obstacles to introducing a model-based approach is the lack of adopted and clear organizational structures and the understanding of conditions and needs at the management level. Current management methods and frameworks are designed for document-based systems engineering, and research indicates that there is a need for further development for the MBSE approach, supporting how to manage a successful implementation rather than improving its execution. The maturity and breadth of SysML language applications are still limited. However, there are efforts in systems engineering communities, such as INCOSE, to increase their applicability, such as integrating architectural models with simulation, analysis, and visualization.

Research conducted by NASA (KNIZHNIK *et al.*, 2020) interviewed many organizations and pointed out that: MBSE may be beneficial, but benefits are difficult to measure. Cultural issues represent the main challenge. MBSE is in its infancy, twenty-five percent of the organizations consulted adopted MBSE.

Model-based systems engineering does not affect the process but will allow the opportunity for better overall quality, lower cost, and lower risk for various reasons according to NASA (2017b). One reason is that there may be greater consistency of all products, as any design information can be expressed with authority in a single location that can later be referred to by others for decisions, derivations, or artifact formation. Another reason is that there may be better visibility of the salient characteristics of a system because several views may be created that succinctly address specific stakeholder concerns. The use of MBSE may reduce the schedule for preparing reviews, as in many cases review products can be automatically generated directly from the system model (NASA, 2017c).

The European Space Agency (ESA) increased MBSE deployment in ESA missions and MBSE-related R&D activities and progressed in establishing collaborative efforts across the European Space Industry as the MB4SE Advisory Group. Many initiatives and R&D are under development, such as the ESA MBSE Solution for a common approach, TASTE, Digital Engineering Hub Pathfinder, Overall Semantic Modelling for Systems Engineering (OSMoSE), SAVOIR Electronic Data Sheets (SEDS), and MBSE Engineering Hub. Much of these efforts are in the downward of a systems engineering “V” model, relating to requirements, architecture, and design definition. Initiatives in the “V” upward, as for verification, are still preliminary (WHITEHOUSE, 2021).

Examples of current application domains in ESA are discipline modeling for system design, software, avionics, ground segment, AIT, and FDIR. Modeling applications go beyond system engineering, and MBSE technology spans disciplines and the development life cycle, such as auto code, avionics, operation, AIT, dependability, verification, and reviews. Connect data models shall enable digital threads, and semantic interoperability is the next key challenge to address. MBSE is one of the enablers of a Digital Spacecraft and supports ESA to implement the Agenda 2025, where: "ESA will therefore digitalise its full project management, enabling the development of digital twins, both for engineering by using Model-Based System Engineering, and for procurement and finance, achieving full digital continuity with industry.” (TERRAILLON, 2021).

3.4. Digital Engineering

According to Zimmerman et al. (2019), DoD's current engineering approach to system acquisition is largely a linear process that can take years to conceive, design, and deliver a system. Moreover, the acquisition process is based on documents, in which a large amount of data used in acquisition activities and decisions is communicated and stored separately in disjointed and static forms (such as diagrams, spreadsheets, text documents, and two-dimensional drawings) across organizations, tools, and environments.

The DoD established the digital engineering initiative to transform these traditional practices. This initiative incorporates existing model-based principles such as Model-Based Engineering (MBE), Model-Based Systems Engineering (MBSE), digital thread (DT), digital twin (DTw), and other model-based approaches. Digital engineering is defined as “an integrated digital approach that uses authoritative sources of systems’ data and models as a continuum across disciplines to support lifecycle activities from concept through disposal”. By developing, integrating, and using models to connect data at every stage of the lifecycle using computer-based methods, processes, and tools, and innovations such as artificial intelligence and advanced analytics, digital engineering efforts have been implemented in sectors such as transportation, healthcare, finance, and manufacturing, to drive accessibility, agility, quality, and efficiency. The initiative has five objectives: Formalize the development, integration, and use of models to inform enterprise and program decision making; Provide an enduring authoritative source of truth; Incorporate technological innovation to improve the engineering practice; Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders; Transform a culture and workforce that adopts and supports digital engineering across the lifecycle (ZIMMERMAN *et al.*, 2019). A guide on digital engineering is being developed.

Digital engineering approaches require systems engineering digital models to be kept in repositories and certified as an authorized source of truth, enabling model reuse, qualification, and collaboration. Digital models need to be evaluated, verified, and validated to be certified as authorized, or credible (CARROLL; MALINS, 2020). In digital engineering, an Authoritative Source of Truth (AST) is required, which captures consistent data and models across disciplines of an evolving system, providing access in the form of specific views for stakeholders. NASA/JPL's open-source Model-Based Engineering Environment (MBEE) (KARBAN *et al.*, 2020) was used as an AST implementation. The results showed documents based on models generated with a library of views, supporting multi-party collaboration stakeholders accessing consistent data without a modeling background required and enabling a more efficient engineering process with faster design iterations (KRUSE; BLACKBURN, 2019).

Many research efforts in the U.S. are being made to transform systems engineering through digital engineering. The DoD Systems Engineering Research Center (SERC) researches several streams to support the digital engineering strategy implementation. One of these streams is on model integrity to develop and evaluate confidence in model forecasts and simulations. Some topics of high-performance computing were evaluated at Sandia laboratory (BONE *et al.*, 2019).

In this same research stream, a group at MIT researches human-model interaction and decision-making, and model curation. A framework has been created that can serve to guide model curation in the context of digital engineering, which includes model composition, transparency, adherence practices, model evaluation practices, trust in the model, and other topics (RHODES *et al.*, 2019).

SERC developed a framework of competencies to be developed to implement digital engineering. Competencies were split into groups: data engineering, modeling and simulation, digital engineering and analysis, systems software, and digital enterprise environment. In the Digital Engineering and Analysis Competency Group, digital verification and validation is the process to determine whether a product meets established requirements or specifications, using digital models and artifacts for testing and verification. The importance of this process is to ensure that digital practices correlate well with your real-world projects (BAKER *et al.*, 2021).

INCOSE's Model-Based Capability Matrix (MBCM) (HALE; HOHEB, 2020) is a tool to help organizations that have decided to implement digital engineering or model-based capabilities to evaluate and then plan for the development of these capabilities comprehensively and coherently. There are five stages of development for each capacity identified.

At NASA, a digital engineering environment is expected to help enable collaborative digital engineering while integrating stakeholders with authoritative decentralized sources of data and models seamlessly across organizations and disciplines supporting life-cycle activities from concept through disposal (NASA, 2020). NASA Digital Engineering Acquisition Framework Handbook (2020) supports the digital engineering environment by guiding on contractual language for work statements and data requirements descriptions, model-based data definition, digital data collaboration, architecture, standards interoperability, and other guidelines. The framework details activities that can be developed in a model-based engineering (MBE) approach throughout the entire life cycle of a space mission. Data delivery format maturity levels are defined in four levels: traditional paper, digital document, XML data objects, and EXTL application/database.

ESA established five objectives in the Agenda 2025 to benefit from space activities considering the new space market and current massive challenges to the space sector. One of the objectives is to complete the ESA transformation, to boost its effectiveness and attractiveness. ESA projects have heavy engineering efforts from geographically dispersed teams in ESA and industry. Digital continuity throughout the life cycle of projects should substantially reduce cost, errors, and schedules. ESA shall digitalize its full project management, developing digital twins for engineering by using MBSE, and for procurement and finance, to achieve full digital continuity with industry. The development of IT tools and the creation of modern workplace culture should support this objective (ESA, 2021).

3.5. Credibility and maturity of modeling and simulation

Computational models that simulate real-world physical processes are playing an increasing role in engineering and physical sciences (NRC, 2012). To support this reality, advances in the foundations of mathematical sciences of verification, validation, and quantification of uncertainties are important (MEHTA *et al.*, 2016; NRC, 2012).

According to a NASA report edited by Mehta (2016), decision-makers and other simulation users need to know the quantified credibility of simulation to make critical simulation-based decisions and effectively use simulations. The credibility of a simulation is quantified by its accuracy in terms of uncertainty, and some frameworks support a general assessment of credibility and communication to decision-makers and stakeholders (BLATTNIG *et al.*, 2008; MEHTA *et al.*, 2016).

NASA developed a method for assessing the credibility of M&S (MEHTA *et al.*, 2015; NASA, 2016), considering that the credibility of M&S-based results is not something that can be directly assessed, but that the main credibility factors can be assessed more directly. There are eight factors grouped into three classes: M&S Development (Data Pedigree, Verification, Validation); M&S Use (Input Pedigree, Uncertainty Characterization, Results Robustness); Supporting Evidence (M&S History, M&S Process/Product Management), which may span all aspects of an M&S. This method details and defines five levels for each factor described above. It is proposed to define what would be the acceptable limit level for each factor, and then compare it with the evaluation results.

In the first versions of the Predictive Capability Maturity Model (PCMM) developed at the Sandia laboratory (OBERKAMPF *et al.*, 2007), M&S maturity levels were linked to appropriate applications at the four defined levels, respectively to support: conceptual design, preliminary design, and qualification or final design, or when qualification of a system's performance, safety, and reliability is based primarily on M&S. The factors evaluated were: Geometric representation and fidelity, physics and fidelity of the material model, code verification, solution verification, model validation, and uncertainty quantification and sensitivity analysis.

In new versions of the PCMM (HILLS *et al.*, 2013), which are not fully published, the adequacy of the application is separate from the evaluation, and the desired level for each factor should be established, as well as in the NASA (2016) model.

Another proposal (HARMON; YOUNGBLOOD, 2005) defined a validation process maturity model structured in six levels, to successively increase the objectivity of the validation process and improve the quality of the validation.

The credibility of MBSE models should also be assessed, due to the high complexity of many systems (CARROLL; MALINS, 2020). These authors presented twenty-five questions to start research on this subject in the Sandia laboratory.

Kraft (2020) proposed the Digital Surrogate Model Readiness Level (DSMRL) scale. The argument is that in the digital engineering strategy, metrics will be needed that bring information about the performance of the system, for risk-based decision making, and the TRL and IRL scales do not yet provide this information. The nine-level DSMRL scale would reflect the evolution of the digital model towards lower quantified uncertainty, evolving along with the TRL scale and having a relationship with the PCMM model. However, this scale predicts that physical tests would update the digital model in an application more focused on the digital twin, and not that the digital model could be an alternative to the physical model. For example, when arriving at TRL 6, tests with the physical model would lead to a recalibration of the digital model.

Research projects sought to understand the many facets of human decision-making in digital engineering environments, grounded on theory and interview workshops, and to propose innovations. Many sociotechnical factors influence decision-maker trust and perception of models in model-centric decision-making. While technical factors were cited as limiting effective model-centric decisions, the majority of limitations were related to social and cultural factors. Considering that model-centric engineering enterprises will need specialized competencies and leadership, model curation was defined as lifecycle management, control, preservation, and active enhancement of models and associated information to ensure value for current and future use, as well as repurposing beyond initial purpose and context. Model credibility within the context of model curation is being researched, as enterprises begin to develop large model repositories in search of digital maturity (RHODES, 2020; RHODES *et al.*, 2019).

4. Conclusion

The objective was accomplished. The research reviewed the literature on spacecraft modeling, simulation, verification, and validation. A bibliometric analysis showed key organizations, countries, and relevant references. A keyword analysis mapped the main subjects and their correlation. Results showed a qualitative analysis of special topics on spacecraft V&V, MBSE, digital engineering, and M&S credibility and maturity.

This paper contributes to discuss ongoing research towards the use of M&S to comply with IRL and may be useful to other researchers on related subjects.

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