Journal of Knowledge Learning and Science Technology
ISSN: 2959-6386 (Online)
2024, Vol. 3, No. 4, pp. 49 - 56
DOI: https://doi.org/10.60087/jklst.v3.n4.p49

Review

Model-Based Systems Engineering: Pioneering a New Era in Astrophysics Mission Design

Sayak Moulic[1], Sahil Arora[2], Adhiraj Agarwala[3], Trisha Agarwal[4], Sannidhya Ghosh[5], Oviya Shree V[6], Anirudh Sahu[7]

[1]Kalyani Central Model School, Kalyani, Nadia, India

[2]Emerald Valley Public School, Yercaud Foothills, Salem, India

[3]La Martiniere for Boys School, 11 Loudon Street, Kolkata, India

[4]Chatrabhuj Narsee School, Kandivali East Mumbai, India

[5]Phoenix Greens School Of Learning, Kokapet, Hyderabad, India

[6]Sri Chaitanya College, Hyderabad, Telangana, India

[7]Bonnie Foi School, Ayodhya Bypass Road, Bhopal, Madhya Pradesh, India

Abstract

Model-based systems engineering (MBSE) is a model in which the relationships between system components are specified and integrated. MBSE has become essential in various scientific applications, as it helps ensure that systems work well across different areas by improving team collaboration at work and by making the design process more efficient. However, the main role of MBSE lies in its use in astrophysical missions and overall physical and engineering missions. Traditional methods of modeling often struggle to provide a completely diverse view of complex systems because of their limited scope. MBSE with systems modeling language (SysML), on the other hand, offers significant advantages in these domains in lieu of the onion model of its systems, where the model is developed and completed in layers. This study explores in depth how MBSE and SysML can improve astrophysical and physical missions by thoroughly examining their biases and their use in previous missions, as well as discussing their potential challenges and plausible solutions. This study identifies and reviews the critical metrics for measuring success in astrophysical missions and suggests the factors that should be considered when reviewing scientific data. Furthermore, by examining case studies from previous missions by NASA, ESA, etc., this study aims to demonstrate the clear advantages of using MBSE for designing, testing, and validating complex astrophysical systems for broader applications in the field and beyond.

Keywords

Model-Based Systems Engineering, Systems Modeling, Astrophysics, National Aeronautics and Space Administration

*Corresponding author: Adhiraj Agarwala

Email addresses:

sayakmoulic@gmail.com (Sayak Moulic), sahilarora2378@gmail.com (Sahil Arora), adhirajagarwala2007@gmail.com (Adhiraj Agarwala), trishaagarwal2809@gmail.com (Trisha Agarwal), sannidhya.ghosh@yahoo.com (Sannidhya Ghosh), oviyashree06@gmail.com (Oviya Shree V), renudilip19@gmail.com (Anirudh Sahu)

Received: 16-00-2024; **Accepted:** 27-08-2024; **Published:** 25-12-2024

Journal of Knowledge Learning and Science Technology
ISSN: 2959-6386 (Online)
2024, Vol. 3, No. 4, pp. 49 - 56
DOI: https://doi.org/10.60087/jklst.v3.n4.p49

1. Introduction

Model-based system engineering is a relatively new approach to systems engineering that moves away from the traditional approach and instead focuses on modeling the relationships between system components, including hardware components, functional software, system requirements, and verification artifacts. The MBSE approach is very effective at minimizing errors and helping engineers develop a complete and consistent system. Rather than simply a change in approach, MBSE focuses on completely removing the old document-centric systems engineering and moving to a model-centric system to design, verify, and validate systems [1].

Using the MBSE approach, the requirements development, behavior analysis, architecture development, and verification and validation information are all determined and completed before proceeding down to the next layer. This approach is a powerful way to break large, complex systems into more manageable pieces [1]. Various authors have focused on aspects of model-based verification and how MBSE can be used to guide requirements verification in a meaningful way. Astronomical instrumentation systems, whether ground-based or space-based, often contain multiple interdependent subsystems and must balance multiple novel scientific objectives against constraints, including cost, timelines, and environmental factors [2].

Understanding SysML is highly relevant in understanding the context of MBSE, as it provides a structured and systemized approach for developing complex models. SysML (Systems Modeling Language) is a standardized modeling language especially designed for systems engineering. SysML uses the extension UML (Unified Modeling Language), and it is designed to support the analysis, design, verification, and validation of complex systems. In the case of MBSE, SysML plays an important role in providing a unified modeling framework for representing systems. Its diagrams and notations improve communication among stakeholders. SysML ensures that all requirements are met and that all changes are managed effectively; it attempts to resolve issues early through analysis and verification. Its tool system makes it a very efficient system for engineering across various domains.

Given these capabilities, systems modeling language (SysML) offers essential tools for organizing relationships between data objects in graphical diagrams and executing behaviors in a model as simulations. SysML is used for requirement diagrams to visualize and organize requirements, structure diagrams are used to define the hierarchical decomposition of the system and the interfaces between components, activity diagrams are used to define block behaviors, and interface specification tables and allocation matrices are used to support model execution [2].

Traditional approaches in systems engineering include document-centric systems engineering, which involves creating and managing a vast array of documents, such as requirement specifications, design explanations, test plans, and verification reports, which are too complex to maintain when the documents are interrelated. The waterfall method was obtained where every phase is performed through a linear and sequential approach, and returning to the previous phases is difficult, as each phase must be completed before the next phase begins, which makes it a rigid structure to follow when there are changes that can be included. The verification and validation processes rely on manual and extensive testing, and their disadvantages are that they are time-consuming and prone to error. Hence, a shift was made to MBSE using SysML models where these issues were addressed, which included enhanced

*Corresponding author: Adhiraj Agarwala

Email addresses:

sayakmoulic@gmail.com (Sayak Moulic), sahilarora2378@gmail.com (Sahil Arora), adhirajagarwala2007@gmail.com (Adhiraj Agarwala), trishaagarwal2809@gmail.com (Trisha Agarwal), sannidhya.ghosh@yahoo.com (Sannidhya Ghosh), oviyashree06@gmail.com (Oviya Shree V), renudilip19@gmail.com (Anirudh Sahu)

Received: 16-00-2024; **Accepted:** 27-08-2024; **Published:** 25-12-2024

collaboration and improved verification and validation. MBSE improved efficiency and decision-making while also catching up with innovation. MBSE's approach provides a future where complex astrophysical systems can be handled.

MBSE has already proven immensely beneficial at NASA by creating a single, centralized model of the entire system, capturing all relevant information. The 7-step interface management (Identify, Capture, Define, Allocate, Verify, Comply, and Integrate) used in several NASA flight projects also became a part of MBSE [3]. MBSE can detect potential problems early in the design process, which can save time and work. MBSE is also used throughout the project's lifecycle, which ensures that design, planning verification, and validation considerations are met. MBSE also improves communication where everyone has access to the latest information.

The OSIRIS-REx Science Processing and Operations Center (SPOC) is at the heart of the process of characterizing the asteroid and collecting the sample. The SPOC team has chosen an MBSE approach to facilitate the development of the OSIRIS-REx ground system and, more specifically, the SPOC. This formally applies modeling to support system requirements, design, analysis, verification, and validation activities [1]. In the Europa mission, the resulting plan called for the MBSE environment to be in place and ready to support the project team. By leveraging the existing infrastructure and a modest additional investment, striking advances in the capture and analysis of designs using MBSE were achieved. The modeling artifacts quickly became the single source of authoritative information once the capture phase was completed [4].

There are five main problem areas identified by NASA's Jet Propulsion Laboratory (JPL), which is common to many large complex system projects. (1) Mission complexity is growing faster than our ability to manage it. (2) System design emerges from the pieces, not from an overarching architecture. (3) Knowledge is lost at the boundaries of project lifecycle phases. (4) Knowledge and investment are lost between projects. (5) Technical and programmatic aspects of projects are poorly coupled. Ontologies and conceptual modeling provide a well-defined vocabulary for system engineers to capture information with a precise meaning. This creates consistency and correctness across modeling artifacts and engineering domains for analysis, design, and the resulting documentation for the integration of a multiplicity of system views and models and reuse across projects. Model transformation is a key technology that promotes the single source of the truth paradigm and uses the same information consistently for different purposes [5].

The challenges in MBSE and SysML have made systems much more complex and have increased the intensity of calculations. This would require the training of astronauts and space scientists, which would lead to enormous investments [1]. Additionally, SysML and MBSE data can be inefficient if complex data are produced in large volumes, which restricts their ability to maintain efficiency and consistency. This would also require a large workforce to process and analyze these data.

The purpose of this study is to show the extensive applications of SysML and Model-Based Systems Engineering approaches and their methodologies to ensure the best success in NASA missions with the integration of SysML and Model-Based Systems Engineering approaches, best practices, and finding solutions to problems. This study is also intended to highlight the challenges faced in NASA missions when traditional approaches are used and the quality of data, efficiency, and overall mission performance. Requirement analysis is first used to check the requirements of mission items via SysML. The design phase uses model navigation, as well as various table and diagram types, to advance system design. In the developmental phase, the focus will be on how SysML helps in the development of mission requirements and architecture and reduces gaps between the two. The study will also examine how SysML supports the verification process by tracking user details such as date, sponsor, state, and UID. Finally, this research addresses the challenges and limitations of adopting SysML and MBSE for NASA missions and evaluates the performance and outcomes of these approaches [6].

2. Discussion

2.1. Metrics and parameters for success

The assessment of mission success in astrophysics is fundamentally linked to specific metrics and parameters that gauge the effectiveness of space missions. Understanding these metrics is crucial for optimizing mission design and ensuring that objectives are met. This section outlines key metrics, including scientific data quality, mission lifetime, and instrument performance, which serve as benchmarks for evaluating the success of astrophysics missions.

Scientific Data Quality: The quality of scientific data collected by a space mission is a critical metric for measuring success. The key factors to consider include resolution, which is the ability to resolve small details in the data. Sensitivity: The capacity to detect small signals or changes in the data. Field of view: The area of the sky that the telescope can observe. Data accuracy and precision: The degree to which the data accurately represent the true state of the universe. Data Completeness and Coverage: The extent to which the data cover the entire sky or a specific region.

Mission Lifetime: The lifetime of a space mission is vital for measuring success. Important parameters include the duration of the mission, the number of scientific observations made, and the overall effectiveness of the mission.

Instrument Performance: This metric evaluates the ability of the instruments to collect high-quality data, with a focus on their sensitivity and resolution.

Mission Selection: Astrophysics missions are selected not only for their potential to address fundamental scientific questions but also for their feasibility within technological constraints. Notably, NASA missions, such as the Hubble Space Telescope (HST), the James Webb Space Telescope (JWST), and the Chandra X-ray Observatory, have played critical roles in advancing our understanding of the universe.

Role of Model-Based Systems Engineering (MBSE) and SysML in Mission Selection: MBSE and SysML are instrumental in tracing requirements throughout the mission lifecycle. They help establish well-defined success parameters and optimize mission design to achieve these objectives. Furthermore, these methodologies facilitate the evaluation of different mission concepts, identifying the most effective and efficient approaches for achieving scientific goals without the need for extensive practical trials, thereby saving time, energy, and resources [7].

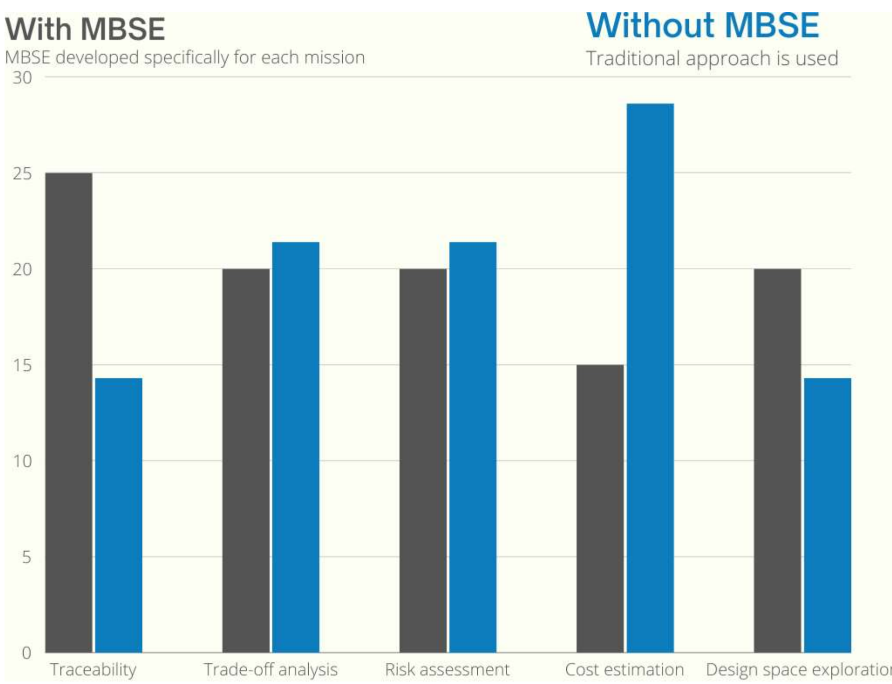

Figure 1. *The traditional mission selection process highlights potential bottlenecks and limitations.*

2.2. Study Design and Comparisons

This study compares model-based systems engineering (MBSE) with traditional spacecraft design methods. MBSE focuses on detailed analysis and verification during the design phases, leading to more robust systems. Traditional methods, such as atomic clocks and analog-to-digital converters (ADCs), assess spacecraft conditions but lack MBSE flexibility and depth.

MBSE offers several advantages. It breaks down systems into manageable parts, making troubleshooting easier. It also allows for thorough exploration of design options, reducing unforeseen issues. MBSE supports trade-off analysis, helping stakeholders balance cost, condition, and risk. Overall, MBSE provides a structured, flexible framework, improving upon conventional methods.

Studies were included if they provided insights into MBSE and SysML or reported their impact on mission success in systems of systems (SoS) or cyber-physical systems (CPS) [7]. Studies that did not cover MBSE or SysML or were not relevant to NASA missions or astrophysics were excluded. This ensured that the gathered data were relevant and valuable for comparing MBSE with traditional methods in spacecraft design.

2.3. Study Design and Comparisons

To comprehensively understand the selection of models, specific examples from existing research must be analyzed. This analysis helps to identify common criteria that can serve as a foundation for future projects. Examining the work of Christian Nigischer et al. (2021) [8] reveals several critical criteria. For early formal evaluation activities such as design space exploration or verification, it is essential to create additional models using modeling languages capable of meeting the extended requirements for simulation and computation. This involves incorporating additional stereotypes with specialized semantics and properties to represent simulation language-specific model artifacts within SysML. When the SysML and simulation models are fully defined, only the parameters need to be transferred between the SysML editors and various simulation and computation environments to enable thorough analysis of the described system. The use of standardized meta-models can significantly ease model transformations for freely available simulation languages, thereby preventing the proliferation of divergent and incompatible meta-model representations.

Continuing with the insights from Todd J. Bayer et al. [4], leveraging existing infrastructure with a modest additional investment can lead to significant advances in the capture and analysis of designs via MBSE. Analyses such as the computation of technical margins are crucial for verifying and validating designs against mission objectives. Other fundamental analyses in science mission design include evaluating science margins, cost estimation, and sizing of the flight system. A key aspect of all space missions is data balance, particularly for remote sensing missions, which are designed to send instruments to a destination to take measurements and return data to scientists on Earth. The use of more sophisticated radiation analysis is also recommended to eliminate some of the conservative assumptions typically made.

Finally, the study by Daniel R. Wibben et al. (2015) [1] highlights the benefits of the MBSE approach over traditional methods. One of the primary advantages is the "onion model," where the system is developed in layers starting from the topmost level. Using MBSE, the requirements development, behavior analysis, architecture development, and verification and validation information are all determined and completed before moving on to the next layer.

This approach is highly effective for breaking down large, complex systems into more manageable components. It also offers the ability to visualize the architecture for all stakeholders and provides the flexibility to make changes quickly, which is particularly important early in the design process. Additionally, requirements verified through analysis, inspection, or demonstration are assigned specific verification events, ensuring that the correct actions are performed.

2.4. Systematic methods for data and bias assessment

We plan to employ a systematic data extraction methodology to ensure an unbiased and comprehensive analysis.

For data extraction, reference management software such as Zotero is used to manage search results efficiently, extract key data (authors, titles, keywords), and organize references.

The risk of bias assessment involves using the selected research, which will then be critiqued with the following questions in mind for the detection of potential sources of bias. How the search was conducted—e.g., whether the authors primarily searched the literature for particular MBSE tools, methods, or mission types such as telescope vs. exploration—will be taken into account for selection bias.

Publication bias involving the analysis will also allow for the possibility that studies with negative or inconclusive results were not produced.

Study design and methodology include evaluating the extent to which the study design and methodology assist in answering the research question, the rigor of data collection and analysis, and the likelihood of researcher bias affecting the research design or presentation of results.

Reporting bias involves the evaluation of the completeness of the reporting of findings in each study, which will be assessed by including all relevant information irrespective of whether the results are positive, negative, or statistically significant.

This organized methodology provides a holistic, unbiased research synthesis of MBSE applications in the future astrophysics missions of NASA.

2.5. Data Synthesis and Mission Success Metric

Model-based systems engineering (MBSE) requires a focus on data synthesis and the measurement of key indicators of mission success for successful operation and assessment of comprehensive systems. This section expounds on the strict methods we use to examine important success indicators, including the satisfaction of requirements, system dependability, design effectiveness, and final mission outcome. The provided table gives an extensive overview of these metrics, showcasing the methods used as well as our data synthesis approaches in our evaluations.

2.6. Methodological Rigor

2.6.1. Credibility

For an astrophysical mission to be credible, there must be deep engagement with the subject matter, including extensive collaboration with NASA engineers, scientists, and stakeholders. Techniques such as persistent observation and triangulation [9] (using multiple data sources such as interviews, project documentation, and system models) are essential to the mission. Peer debriefing, along with experts in MBSE and astrophysics, is necessary for relevant feedback and processing of the validity and credibility of the mission [10].

Mission Success Metric	Description	Data Synthesis Approach
Requirement Satisfaction	Evaluating to which extent mission requirements and objectives are met	Reviewing, documenting, and calculating the percentage of requirements that have been fulfilled.
System Reliability	Evaluating the reliability of the system during the mission	Analyzing failure missions and calculating the success rate of operations.
Design efficiency	Evaluating the use of MBSE and SysML models in the design process and assessing their efficiency	Calculating the percentage of planned designs that are met in the design process.
Mission Outcome	Reviewing the success of the mission	Reviewing and calculating the percentage of achieved objectives.
Cost Effectiveness	Staying within budgeted costs	Cost—benefit analysis, return on investment calculations.
Communication Essentiality	Communication should be easy and undisrupted	Enhanced radiophones, redundant network
Error reduction	Increase convenience by reducing chances of error by prior validation	Moving to a model-centric one to design, verify, and validate systems
System Simplicity	It makes the system less complex to reduce other possible errors	The system is developed in layers beginning from the topmost level.

Table 1. *Data-driven success metrics used in space technology methodologies*

2.6.2. Transferability

Transferability can be achieved by providing extremely detailed and scientific descriptions of the MBSE processes, tools, and methodologies used in various specific NASA projects. Detailed contextualization [Lincoln, Y. S., & Guba, E. G. (1985) of the specific astrophysics missions, the systems involved, and the unique challenges faced allow other researchers and practitioners to assess the applicability of the findings to their projects. This detailed contextualization ensures that the findings are not only relevant but also adaptable to different settings within the field of astrophysics.

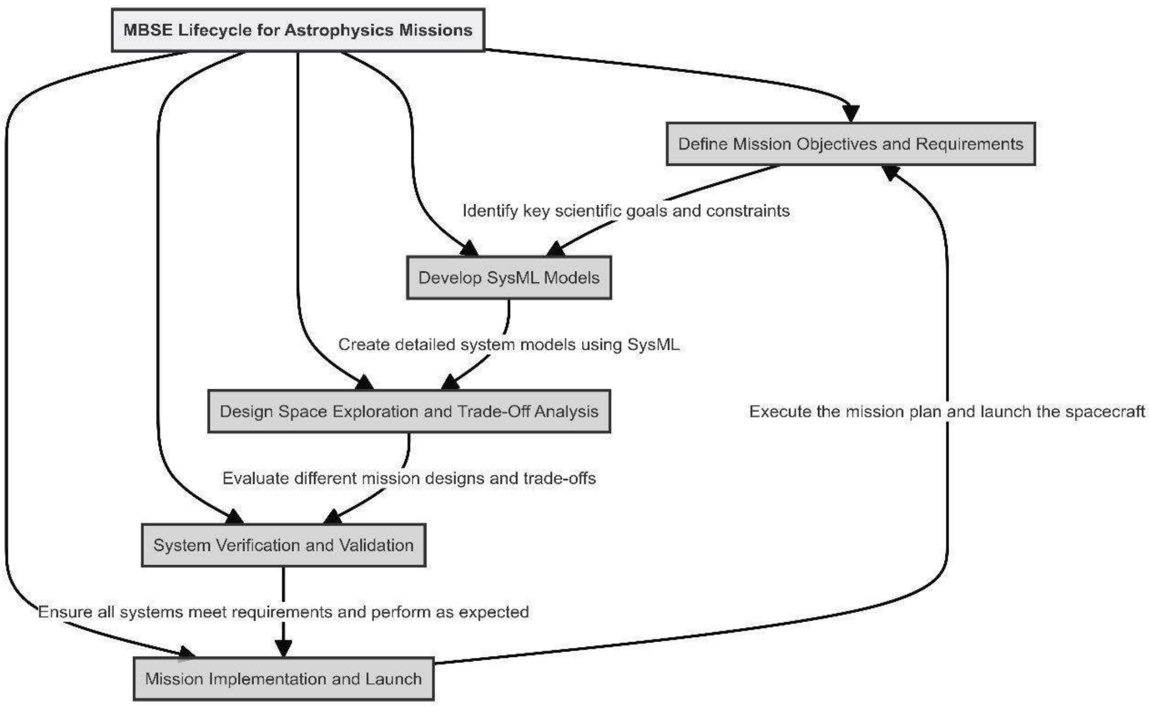

Figure 2. *MBSE is utilized for astrophysics missions with the help of systems-based modeling techniques.*

2.6.3. Dependability

Dependability is the consistency and reliability of the research findings over time. This can be ensured by maintaining systematic documentation of the research process, including detailed notes on the implementation of MBSE practices, challenges encountered, and solutions developed. Methodological consistency across different phases of the study and a dependability audit by an external reviewer can further enhance the reliability of the findings [11].

3. Conclusion

One critical assumption is the necessary expertise in both MBSE and SysML. Furthermore, this level of correctness, for the creation and maintenance of the model, is in many cases impractical and extremely resource intensive. However, MBSE provides the user with improved communication and collaboration among stakeholders and mission designs that are optimized, and it can also evaluate different mission concepts without practical implementation. Future work will focus on developing standardized meta-models to ease model transformations and increase the integration of MBSE and SysML with other simulation and computation environments. Standardized meta-models result in the seamless sharing of information between different modeling tools and environments.

Additionally, the application of MBSE and SysML in astrophysics missions would lead to a more collaborative and interdisciplinary approach to mission planning and execution. Since it provides a common framework for communication and collaboration, the methodology would ensure more integration in mission design and implementation.

To conclude, this research derives a solid foundation upon which to evaluate the potential of MBSE in increasing mission success for future NASA astrophysics projects. By identifying limitations and defining future research paths, this study contributes to the ongoing debate in the field and builds the

foundation for successful MBSE application in the exciting world of astrophysics exploration.
The study demonstrated that Model-Based Systems Engineering (MBSE) and Systems Modeling Language (SysML) can significantly enhance the success of future NASA astrophysics missions. A framework was established to define, measure, and evaluate key performance indicators.

Our approach included data extraction, bias assessment and synthesis to ensure a thorough and objective analysis. The findings highlight the many benefits of using MBSE & SysML across a mission's life cycle. These included aspects such as requirement traceability, concept trade-off analysis, and information exchange among stakeholders.

However, implementing MBSE & SysML for astrophysics missions is not without challenges, such as developing domain-specific SysML libraries, integrating with existing engineering tools, and addressing data ownership and security [12]. MBSE is critical to mission success in previous NASA projects such as the Mars Science Laboratory [13]. Multidisciplinary systems have much promise, but there are technological and cultural barriers that need to be overcome. Some limitations of MBSE include the need for improved modeling language integration and methodologies, which need additional study. Establishing performance metrics and value models, promoting modeling tool interoperability, and developing MBSE best practices and certifications will streamline the process of adoption in other industries over the next decade. Such a model-based methodology will largely assist in handling complexity, enhancing cooperation, and fostering innovation. MBSE is vital for advanced systems in medicine and engineering, with standardized processes and improved usability. With further validation studies and standardized MBSE languages, communication barriers can be overcome by fostering diverse engineering disciplines and simulation software, ensuring transformative impacts. The application of MBSE principles extends beyond traditional engineering domains, as demonstrated in our studies on pathogen detection systems and glucose sensing technologies, highlighting the versatility of this approach in addressing complex challenges across various scientific fields. Multidisciplinary systems have much promise, but there are technological and cultural barriers that need to be overcome [14] [15] [16] [17] [18] [19] [20].

Future work should focus on developing cost–benefit analysis frameworks for MBSE in astrophysics missions, standardizing meta-models for model transformations, and integrating MBSE tools with NASA's existing software. The potential is enormous. While there are challenges, the benefits are too large to ignore.

In conclusion, the authors hope that the findings and recommendations can shape discussions about the use of MBSE and SysML in space exploration. These findings pave the way for more successful, impactful, and cost-effective missions in the years to come.

Author Contributions

SM, SA, AA, TA, SG, OS: conceptualization, writing - original draft, writing - review & editing. SA, SG, AA: visualization.

Conflicts of interest

The authors declare that they have no competing financial interests or conflicts of interest.

References

[1] Wibben, D. R.; Furfaro, R. *Model-Based Systems Engineering Approach for the Development of the Science Processing and Operations Center of the NASA OSIRIS-REx Asteroid Sample Return Mission*. *Acta Astronautica* 2015, *115*, 147–159. https://doi.org/10.1016/j.actaastro.2015.05.016.

[2] Stenzel, J.; Masterson, R.; Simcoe, R. A. *A Model-based Approach for Verification of the Large Lenslet Array Magellan Spectrograph (LLAMAS)*. *IEEE* 1993. https://doi.org/10.1109/aero58975.2024.10521313.

[3] Vipavetz, K.; Shull, T. A.; Infeld, S.; Price, J. *Interface Management for a NASA Flight Project Using Model-Based Systems Engineering (MBSE)*. *INCOSE International Symposium* 2016, *26* (1), 1129–1144. https://doi.org/10.1002/j.2334-5837.2016.00216.x.

[4] Bayer, T. J.; Chung, N. S.; Cole, B.; Cooke, B.; Dekens, F.; Delp, C.; Gontijo, I.; Lewis, K.; Moshir, M.; Rasmussen, R.; Wagner, D. *Model-Based Systems Engineering on the Europa Mission Concept Study*. *IEEE* 2012. https://doi.org/10.1109/aero.2012.6187337.

[5] Karban, R.; Andolfato, L.; Bristow, P.; Chiozzi, G.; Esselborn, M.; Schilling, M.; Schmid, C.; Sommer, H.; Zamparelli, M. *Model-Based Systems Engineering for Astronomical Projects*. *Proceedings of SPIE, the International Society for Optical Engineering/Proceedings of SPIE* 2014. https://doi.org/10.1117/12.2055540.

[6] Infeld, S.; Goggin, D.; Vipavetz, K.; Grondin, T. *A SysML Model Template for NASA Concurrent Engineering Studies*. https://ntrs.nasa.gov/api/citations/20190002554/downloads/20190002554.pdf (accessed 2024-06-19).

[7] Deng, F.; Yan, Y.; Gao, F.; Wu, L. *Modeling and Simulation of*

CPS Based on SysML and Modelica (S). *International Conferences on Software Engineering and Knowledge Engineering* 2019. https://doi.org/10.18293/seke2019-167.

[8] Nigischer, C.; Bougain, S.; Riegler, R.; Stanek, H. P.; Grafinger, M. *Multidomain Simulation Utilizing SysML: State of the Art and Future Perspectives*. *Procedia CIRP* 2021, *100*, 319–324. https://doi.org/10.1016/j.procir.2021.05.073.

[9] Donkoh, S. *Application of Triangulation in Qualitative Research*. *Journal of Applied Biotechnology & Bioengineering* 2023, *10* (1), 6–9. https://doi.org/10.15406/jabb.2023.10.00319.

[10] Admiraal, W.; Akkerman, S. *Quality Control in Qualitative Research: Audit for Determining the Trustworthiness of Educational Research*. *ResearchGate* 2003. https://www.researchgate.net/publication/46657370_Quality_control_in_Qualitative_research_Audit_for_determining_the_trustworthiness_of_educational_research

[11] Wall, S. D. *Model-Based Engineering Design for Space Missions*. *IEEE* 2004. https://doi.org/10.1109/aero.2004.1368208.

[12] Topper, J. S.; Horner, N. C. *Model-Based Systems Engineering in Support of Complex Systems Development*. *ResearchGate* 2013. *Model-Based Systems Engineering in Support of Complex Systems Development*.

[13] Pandya, H. J. et al., "A Microfluidic Platform for Drug Screening in a 3D Cancer Microenvironment," *Biosensors and Bioelectronics*, vol. 94, pp. 632–642, Aug. 2017, doi: https://doi.org/10.1016/j.bios.2017.03.054.

[14] Safavieh, M. et al., "Paper Microchip with a Graphene-Modified Silver Nanocomposite Electrode for Electrical Sensing of Microbial Pathogens," *Nanoscale*, vol. 9, no. 5, pp. 1852–1861, 2017, doi: https://doi.org/10.1039/c6nr06417e.

[15] GhavamiNejad, P.; GhavamiNejad, A.; Zheng, H.; Dhingra, K.; Samarikhalaj, M.; Poudineh, M., "A Conductive Hydrogel Microneedle-Based Assay Integrating PEDOT and Ag-Pt Nanoparticles for Real-Time, Enzyme-Less, and Electrochemical Sensing of Glucose," *Advanced Healthcare Materials*, vol. 12, no. 1, Oct. 2022, doi: https://doi.org/10.1002/adhm.202202362.

[16] Odinotski, S. et al., "A Conductive Hydrogel-Based Microneedle Platform for Real-Time pH Measurement in Live Animals," *Small*, vol. 18, no. 45, Sep. 2022, doi: https://doi.org/10.1002/smll.202200201.

[17] Kulkarni, S.; Dhingra, K.; Verma, S., "Applications of CMUT Technology in Medical Diagnostics: From Photoacoustic to Ultrasonic Imaging", *International Journal of Science and Research (IJSR)*, Volume 13 Issue 6, June 2024, pp. 1264-1269, https://www.ijsr.net/archive/v13i6/SR24619062609.pdf.

[18] Pandya, H. J. et al., "Label-Free Electrical Sensing of Bacteria in Eye Wash Samples: A Step Toward Point-of-Care Detection of Pathogens in Patients with Infectious Keratitis," *Biosensors and Bioelectronics*, vol. 91, pp. 32–39, May 2017, doi: https://doi.org/10.1016/j.bios.2016.12.035.

[19] Gupte, P.; Dhingra, K.; Saloni, "Precision Gene Editing Strategies with CRISPR-Cas9 for Advancing Cancer Immunotherapy and Alzheimer's Disease", *Journal of Knowledge Learning and Science Technology*., vol. 3, no. 4, pp. 11–21, Jul. 2024, doi: https://doi.org/10.60087/jklst.v3.n4.p1.