Science, Engineering & Education, 11, (1), 2026, 15-19

Strategies and Methods for Recreating the Operating Behavior of a Technological Object Through Virtual Prototyping Based on an Optimized Initial Design

Galena Slavova[1], Stanislav Slavov[2*]

[1]*Changzhou Institute of Mechatronic and Information Technology, Cgangzhou, China/Sofia University, Sofia, Bulgaria*
[2]*University of Chemical Technology and Metallurgy, 8 Kliment Ohridski, Sofia 1797, Bulgaria*

Received 07 February 2026, Accepted 09 March 2026
DOI: 10.59957/see.v11.i1.2026.3

ABSTRACT

Virtual prototyping is one of the most significant enablers of accelerated product development, allowing engineers to predict and validate system behavior under realistic operating conditions before physical realization. However, the behavioral gap between optimized initial design models and true working-condition performance remains major limitation due to multi-physics coupling, embedded control interaction, parameter uncertainty, and manufacturing variability. This paper presents an expanded review of strategies and methods for recreating operational behavior through virtual prototyping. Key approaches include multi-domain modeling, reduced-order techniques, co-simulation frameworks, model calibration, uncertainty quantification, and virtual commissioning. A structured workflow is proposed, progressing from optimized CAD/CAE models toward validated behavioral virtual prototypes capable of supporting life-cycle digital twin evolution. Two tables and an architectural figure concept are included to support submission-ready presentation.

Keywords: behavioral simulation, co-simulation, uncertainty quantification, virtual commissioning, multi-physics modeling.

INTRODUCTION

Modern technological systems are increasingly complex, combining mechanical structures, electrical drives, thermal effects, embedded control software, and network automation. Traditional development workflows rely heavily on sequential prototyping, where behavioral validation is achieved primarily through physical testing. This approach is costly and slow, especially when multiple design iterations are needed before reaching acceptable performance.

Virtual prototyping provides an alternative paradigm: operational behavior is recreated computationally before physical realization, enabling early design-space exploration, risk

---

**Correspondence to: Stanislav Slavov, University of Chemical Technology and Metallurgy, 8 Kliment Ohridski, Sofia 1797, Bulgaria, e-mail: stanislavslavov@uctm.edu* reduction, and validation-driven optimization. The concept has been strongly reinforced by Industry 4.0 developments, where virtual models evolve into digital twins capable of continuous life-cycle synchronization [1].

Despite progress in CAD/CAE technologies, engineers continue to face the challenge of reproducing realistic behavior under working conditions. Optimized design models often reflect nominal assumptions and fail to capture:

- nonlinear friction and wear
- transient thermal loads
- control instability
- sensor/actuator imperfections
- manufacturing tolerance variability

As highlighted in recent research, behavioral accuracy requires both higher fidelity, and integrated validation workflows including uncertainty management and closed-loop simulation [2].

Current paper explores strategies, methods, and research directions that enable recreation of operating behavior through virtual prototyping, and proposes a structured framework suitable for JSEE publication.

EXPERIMENTAL

Current paper is based on an extended literature synthesis focusing on peer-reviewed research from manufacturing systems, simulation engineering, and cyber-physical design domains.

The methodology includes:

1. State-of-the-art review of behavioral virtual prototyping approaches, including digital twin-based validation [1, 3].
2. Toolchain-level integration analysis, emphasizing co-simulation frameworks and model interoperability [4].
3. Workflow synthesis, mapping methods across development stages (optimization → simulation → validation → commissioning).
4. Comparative classification, linking methods to their primary contribution: fidelity improvement, computational efficiency, or validation credibility.

Only peer-reviewed journal references from CIRP, IJAMT, RCIM, Simulation Modelling Practice and Theory, and IEEE Access are included.

RESULTS AND DISCUSSION

Multi-Level Workflow for Behavioral Recreation

The proposed workflow consists of six major phases:

Phase 1: Optimized Initial Design Model

The process begins with an optimized design baseline generated through CAD/CAE optimization (Table 1, Table 2 and Fig.1). This stage delivers:

- parametric geometry
- material and boundary assumptions
- target KPIs (mass, stiffness, efficiency)

Optimization-based virtual design has been widely adopted in advanced manufacturing contexts [2].

Phase 2: Behavioral Enrichment Through Multi-Physics Modeling

Real operating behavior requires coupling across physical domains. Multi-physics virtual prototypes combine:

- structural dynamics
- thermal loading
- fluid interactions
- Electro-mechanical drives

Such coupling is central for realistic reproduction of working conditions, particularly in high-performance technological systems [5].

Phase 3: Reduced-Order and Surrogate Modeling

High-fidelity models (FEM/CFD) are computationally expensive and cannot be executed repeatedly in system-level validation

Table 1. Methods supporting behavioral recreation in virtual prototyping.

Method	Contribution	Typical Output
Multi-physics simulation	Captures coupled operational effects	Thermal-mechanical response [5]
Reduced-order models	Enables fast system-level evaluation	Real-time capable models [6]
Co-simulation frameworks	Integrates plant + controller behavior	Closed-loop dynamics [4]
Model calibration	Aligns virtual prototype with reality	Parameter identification [7]
Uncertainty quantification	Robust prediction under variability	Confidence bounds [7]
Virtual commissioning	Early automation validation	Reduced deployment failures [8]

Table 2. Workflow phases and validation evidence.

Phase	Validation Objective	Evidence Type
Optimized design	Nominal KPI achievement	Optimization metrics [2]
Multi-physics enrichment	Physical realism	FEM/CFD correlation [5]
ROM integration	Computational feasibility	Error vs. full model [6]
Co-simulation	Closed-loop correctness	Stability + transient tests [4]
Calibration + UQ	Robust prediction	Statistical confidence [7]
Virtual commissioning	Automation correctness	Cycle-time and logic tests [8]

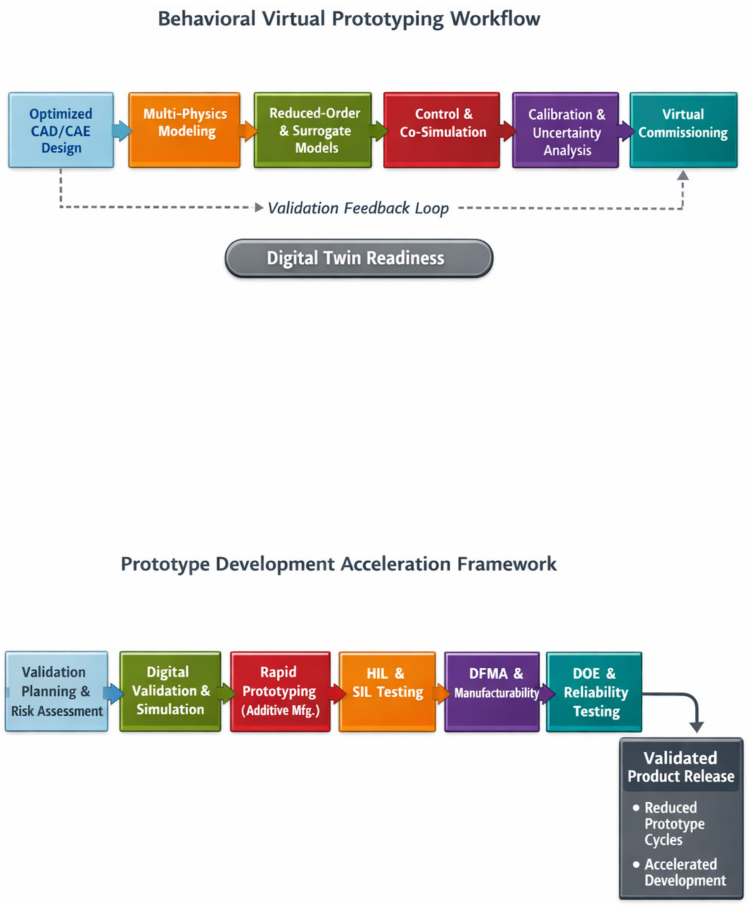

Fig. 1. Illustration of staged workflow for re-creating operating behavior from an optimized initial design through multi-physics enrichment, reduced-order acceleration, closed-loop co-simulation, and validation-driven virtual commissioning.

loops. Reduced-order modeling enables:

- fast evaluation of dynamic response
- integration into control co-simulation
- real-time capable simulation

ROM methods have proven effective in accelerating behavioral prediction while maintaining accuracy [6].

Phase 4: Control Integration and Co-Simulation

Operating behavior is fundamentally closed-loop. Controllers must be integrated into the prototype to reproduce:

- stability margins
- transient response
- fault behavior

Co-simulation techniques allow coupling of plant and control subsystems in heterogeneous environments. Research highlights co-simulation as essential for cyber-physical behavioral validation [4].

Phase 5: Calibration and Uncertainty Quantification

Model calibration aligns simulation parameters with observed test data. This is critical because:

- material properties vary;
- manufacturing tolerances introduce deviations; and
- boundary conditions are uncertain.

Uncertainty quantification (UQ) supports robust behavioral recreation and improves predictive confidence [7].

Phase 6: Virtual Commissioning and Deployment Readiness

Virtual commissioning validates automation behavior (PLC logic, sequencing, timing) before physical installation. Industrial studies show that virtual commissioning significantly reduces commissioning time and integration failures [8].

The reviewed research demonstrates that behavioral recreation through virtual prototyping is not a single-model task but a managed lifecycle process. The strongest industrial outcomes occur when:

- multi-physics realism is combined with ROM acceleration [5, 6]
- calibration and UQ quantify predictive reliability [7]
- co-simulation enables software-inclusive validation [4]
- virtual commissioning reduces deployment risk [8]

Remaining challenges include:

- scalability of uncertainty methods
- semantic consistency across tool chains
- integration into continuous digital twin lifecycles [1, 3]

Future work should focus on automated calibration pipelines and AI-assisted surrogate modeling for real-time cyber-physical prediction.

CONCLUSIONS

Virtual prototyping enables recreation of technological object behavior under realistic working conditions, but achieving predictive fidelity requires structured integration of multi-physics modeling, reduced-order acceleration, co-simulation, calibration, and uncertainty quantification. Virtual commissioning further extends validation into automation deployment readiness. The proposed workflow and supporting tables provide a JSEE - ready framework for developing behavioral virtual prototypes that can evolve toward life-cycle digital twins.

Acknowledgements

This article draws upon research conducted within the scope of Procedure BG16RFOP002-1.016 "Development of Innovation Clusters", under Contract No. BG16RFOP002-1.016-0009-C01 for the project "Development of the Innovation Potential of the Automotive Cluster Bulgaria". The project is co-

financed by the European Regional Development Fund (ERDF) under the Operational Programme "Innovation and Competitiveness" 2014-2020.

REFERENCES

1. F. Tao and M. Zhang, Digital twin shop-floor: A new shop-floor paradigm toward smart manufacturing, IEEE Access, 5, 2017, 20418-20427.
2. J. Lee, B. Bagheri, and H.-A. Kao, A cyber-physical systems architecture for Industry 4.0-based manufacturing systems, Manufacturing Letters, 3 , 2015,18-23. DOI:10.1016/j.mfglet.2014.12.001
3. A. Kritzinger, M. Karner, G. Traar, J. Henjes, W. Sihn, Digital Twin in manufacturing: A categorical literature review and classification, IFAC-PapersOnLine, 51, 11, 2018, 1016-1022. https://doi.org/10.1016/j.ifacol.2018.08.474
4. K. Thramboulidis, Model-Integrated Mechatronics - Toward a New Paradigm in the Development of Manufacturing Systems, IEEE Transactions on Industrial Informatics, 1, 1, 2005, 54-61.
5. M. Bayat, W. Dong, J. Thorborg, A.C. To, J.H. Hattel, A review of multi-scale and multi-physics simulations of metal additive manufacturing processes with focus on modeling strategies, Additive Manufacturing, 47, 2021, 102278.
6. K. Willcox and J. Peraire, Balanced model reduction via the proper orthogonal decomposition, AIAA Journal, 40, 11, 2002, 2323-2330.
7. C. Jiang, Z. Hu, Y. Liu, Z.P. Mourelatos, D. Gorsich, P. Jayakumar, A sequential calibration and validation framework for model uncertainty quantification and reduction, Computer Methods in Applied Mechanics and Engineering, 368, 2020. https://doi.org/10.1016/j.cma.2020.113172
8. P. Hoffmann, R. Schumann, T.M.A. Maksoud, G.C. Premier., Virtual Commissioning Of Manufacturing Systems A Review And New Approaches For Simplification, ECMS 2010 Proceedings, European Council for Modeling and Simulation. doi:10.7148/2010 ISBN: 978-0-9564944-1-2