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A method of representing design solutions in complex systems through model-parametric spaces

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Abstract

On the side of highly complicated systems, it is necessary to have powerful frameworks that can present solution design integration and visualization in the best possible manner, dealing with clarity, scalability, and adaptability. This work aims to formulate an innovative approach for modeling design solutions using model-parametric spaces to create a systematically structured yet convenient method for dealing with multidimensional design complexities. This investigation is conducted within a mixed-method research design combining qualitative assessments of system architecture with quantitative modeling techniques to formulate parametric spaces where design variables and their interrelations are parameterized systematically. The validation of that methodology was done in a way that involves simulated operational scenarios and expert-driven evaluation, which shows the robustness and versatility of the understanding achieved using the approach in different fields of study. Results reveal the utility of model-parametric spaces in vastly increasing the interpretability, modularity, and optimization capability of complex design processes. Therefore, the study argues that this methodology framework is a solid and reasoned basis for decisions in the systems engineering domain and positively explains both research and industrial applications. These future research trajectories determined by this study include further extensive validation within actual project settings to make the developed software more applicable and impactful in the physical world.

Keywords: Knowledge representation, Semantic compatibility, Mathematical models, Analysis and synthesis methods, Formal knowledge representation methods.

1. Introduction

Approaches to representing design solutions in intricate systems remain challenging across various fields, including engineering, information technology, and interdisciplinary studies. Issues related to scalability, ambiguity of interpretation, and inefficiencies in communicating design concepts arise due to the dynamic, high-dimensional, and interdependent nature of the complex systems involved [1]. Characteristics of complex systems, such as the nonlinearity of interactions among a large number of interrelated components and emergent behaviors, render linear modeling approaches inadequate [2]. These intrinsic features impose stringent constraints on standard design frameworks, particularly in contexts where explicitness, traceability, and comprehensive integration of system components are essential. As design-intensive industries advance toward digital transformation, design decision-making has gained increased importance in promoting modularity and reusability throughout the value chain. A structured framework based on modeling parametric spaces is employed to formalize decision-making logic while simultaneously facilitating stakeholder collaboration and iterative development practices [3]. This structured representational methodology, increasingly adopted in domains such as IT systems architecture, aerospace engineering, and intelligent manufacturing, has long served as a catalyst for agile, transparent, and scalable design strategies [4], [5], [6].This study presents a comprehensive objective: to establish a generalized framework that leverages parametric model spaces for accurately representing complex design solutions, thereby enabling enhanced visualization, verification, and overall comprehension of system architectures. To achieve this goal, the research employs a mixed-methods approach, integrating qualitative insights derived from the evaluation of system architectures with quantitative modeling and computational simulation techniques. Moreover, the proposed framework is rigorously assessed for its robustness and adaptability across various application contexts through a combination of empirical validation and expert-based evaluations.

This research aims to develop and empirically validate an innovative research methodology for the structured representation and analysis of design solutions in systems characterized by high complexity. The proposed methodological framework is explicitly intended to enhance the precision of the decision-making process, support system-wide optimization, and significantly improve the effectiveness of communication across differing ideological perspectives. The study systematically addresses these challenges through an organized and rigorous representation of design elements and their intricate parametric interrelations, allowing the engineered system to be realized through the set of design rules defined in the CAT model.

The ultimate goal of the developed methodology is to bridge the gap between conceptual abstractions in system modeling, which are inherent in various fields of science, engineering, and technology, and the practical operationalizations for which the methodology can be effectively scaled and adapted across a wide range of disciplines. Three critical research dimensions are defined to systematically address the complexities underlying the modeling and analysis of multifaceted design solutions within hierarchical systems. The first dimension begins with the observation that complex design ecosystems are inherently variable and highly interdependent, and it develops systematic approaches for structuring model-parametric spaces to accommodate this diversity [7], [8]. The second dimension outlines fundamental methodological principles that enable the integration of parametric modeling into broader system-level decision-making frameworks, ensuring that design choices are empirically informed and contextually relevant. The third dimension investigates the central role of simulation techniques within these parametric frameworks, emphasizing their contribution to the systematic evaluation and optimization of diverse design trajectories.

These research emphases are strategically selected to address a significant gap in existing scholarship, where current modeling paradigms fail to adequately capture the dynamic interactions and hierarchical complexity that characterize advanced systems. This investigation aims to produce a positive impact on the effectiveness of decision-making, the optimization of system-level solutions, and the facilitation of seamless interdisciplinary communication in both engineering and information technology domains.

In addition, the manuscript offers new insights that contribute to the scholarly discourse by expanding the theoretical foundation of systems modeling, parametric methodologies, and cross-disciplinary engineering perspectives [9], [10], [11]. Specifically, the proposed approach enhances current practice by reinforcing transparency in the decision-making process, strengthening capabilities for modular system design, and reducing ambiguity in interpretation within collaborative design contexts. The model-parametric representation described above serves as an adaptable and strategically scalable foundation for intelligent and efficient design methodologies, particularly in response to the growing complexity of modern engineering and technological systems.

The objectives of the study are as follows:

1. To identify the limitations of traditional modeling methods in representing complex system designs.
2. To define and conceptualize model-parametric spaces for design representation.
3. To develop a practical methodology for constructing and applying these spaces in real-world scenarios.
4. To evaluate the effectiveness of the proposed framework through simulation and expert assessment.

Based on these objectives, the research questions addressed in this study are:

1. What are the key limitations of traditional modeling methods in representing complex system designs?
2. How can model-parametric spaces be defined and conceptualized to overcome challenges in design representation?
3. What methodology can be developed for the construction and application of model-parametric spaces in real-world design contexts?
4. How effective is the proposed model-parametric framework, as evaluated through simulation results and expert assessments?

2. Literature review

This section defines both the theoretical framework and the scope of research concerning the integration of lean principles within digital transformation environments, particularly in the context of digitizing and managing documentation. Across several academic domains, from engineering to systems science at both qualitative and quantitative levels, substantial attention has been devoted to the structured representation of design solutions in complex systems. Despite these efforts, existing methodologies often face persistent challenges related to scalability, holistic integration, and the accurate representation of design variability.

This literature review synthesizes foundational contributions from key scholarly works to systematically address these limitations within four core thematic areas: methodologies for modeling complex systems, parametric design approaches, model-based systems engineering (MBSE), and simulation-integrated methodological frameworks [12].

2.1. Modeling complex systems and their limitations

To date, the most commonly adopted methodologies for representing complex systems are based on hierarchical decomposition, control theory frameworks, and, more recently, rule-based paradigms [1]. These traditional modeling approaches have been moderately successful in describing individual system components, yet they demonstrate limited adaptability to dynamic parameters and are generally ineffective in capturing emergent system behaviors. Subsequent advancements in system dynamics modeling and agent-based simulation techniques have offered some improvements. However, these methods still struggle with incorporating real-time data streams and allowing for alternative design trajectories [2], [13].

Moreover, conventional modeling frameworks have failed to adequately represent the intrinsic variability required for informed and resilient decision-making processes within interdisciplinary design environments [14].

2.2. Parametric modeling in systems engineering

Parametric modeling has emerged as a powerful methodology for articulating and managing the interdependencies among system components through mathematically and logically defined relationships. Parametric design approaches have been increasingly adopted in computer-aided design (CAD) and systems engineering to support adaptable system modifications and scenario-driven evaluations [15]. Despite these strengths, such methodologies often fall short in supporting holistic system-level decision-making or in operating effectively across multiple levels of abstraction and disciplinary interfaces [16].

Although numerous scholarly efforts have introduced parameter-focused frameworks for the optimization of discrete system components, these initiatives have not yet achieved broad applicability or practicality in the context of fully integrated hierarchical systems.

2.3. Advances in model-based systems engineering (MBSE) and digital representation

Model-Based Systems Engineering (MBSE) has emerged as a rigorous methodological paradigm that enables the systematic linkage of design rationale, treated as a first-class artifact, with formal modeling artifacts. This linkage facilitates traceability and ensures semantic integrity, as well as full integration throughout the system lifecycle [4], [5]. It has been demonstrated that the Systems Modeling Language (SysML), along with digital twin architectures, provides substantial benefits for analyzing and validating complex systems. However, most of the current applications of MBSE are focused on modeling system behavior and verification, rather than on exploring and representing early-stage parametric design solution spaces [9], [10].

Although digital twin technologies possess capabilities for integrating real-time data streams and running advanced simulations, their application remains primarily limited to system monitoring and predictive diagnostics during operational stages. Their use in systematically evaluating design variability and supporting decision-making in the conceptual phases of system development is still limited.

2.4. Hybrid methodologies with simulation-driven validation

Numerous scholarly investigations recognize that integrating modeling methodologies with simulation-based validation improves the fidelity of system performance assessments [17]. Simulation serves as a powerful analytical tool for assessing design configurations under a wide array of constraints and operational scenarios, which is crucial for both optimization and identifying performance limitations [18]. While these advantages are well understood and supported by various simulation techniques, a unified methodological framework that integrates parametric modeling with simulation for constructing complex design spaces at the system level remains lacking [19].

2.5. Identified gaps and need for innovation

Innovation plays a pivotal role in enhancing enterprise performance and productivity by increasing efficiency, improving processes, and providing a competitive edge [20]. Based on a critical review of the existing literature, several gaps have been identified. These include the insufficient integration of parametric modeling with system-level decision-making frameworks, the lack of robust methodologies capable of addressing hierarchical and multiscale design variability, and the underutilization of simulation tools to represent complex, time-dependent design spaces.

Although incremental advancements have been achieved through the adoption of MBSE and digital design platforms, these developments have not yet yielded a comprehensive framework. Existing approaches fall short of achieving an integrated solution that combines structured parameterization, real-time simulation, and embedded decision logic [18], [19].

In response to these shortcomings, the present study introduces an innovative methodology based on the construction of model-parametric spaces. This approach aims to enhance system representation through simulation-supported parametric models, improve decision-making capabilities, and strengthen interdisciplinary integration through the application of simulation techniques.

3. Research method

The primary objective of this investigation is to construct the model-parametric space in a systematic manner to enable the exploration and enhancement of efficiency, robustness, and adaptability in system design using an analytically derived framework. This methodological approach makes it possible to identify critical parameters, operational constraints, and performance indicators by examining multiple design alternatives. The research employs a systematic process of successively varying independent variables to assess their individual and combined effects on overall system behavior.

The study formalizes the design space through the parameterization of design variables, allowing for controlled and repeated evaluation of numerous configuration scenarios. This enables data-driven assessment and temporal refinement. As a result, the approach leads to empirically substantiated models that contribute to system-level optimization and support decision-based design processes.

3.1. Hybrid nature of the study

This research adopts a hybrid methodological framework that integrates theoretical model formulation with simulation-driven empirical investigation [3], [11]. The convergence of these two dimensions is essential to ensure both conceptual coherence and practical relevance. The theoretical component focuses on constructing core structural models, configuring system architecture, and analyzing the dependencies among key design variables.

In parallel, the simulation component is employed to provide empirical validation by modeling system responses across a variety of scenarios and operational conditions. This two-pronged strategy enhances the validity of the research by grounding it in both dynamic, performance-based simulations and a rigorous theoretical foundation.

3.2. Problem definition and methodology design

This study adopts a hybridized methodological strategy that integrates a model-parametric space framework with an advanced form of simulation methods to establish a comprehensive and scalable paradigm for system design. This integrative approach is critical in addressing the numerous challenges encountered when modeling and optimizing parameters in high-dimensional design environments. The research critically examines the limitations of conventional system design practices, which are often characterized by labor-intensive processes, trial-and-error procedures, a lack of methodological rigor, and an absence of strategic exploration across the entire parametric domain during the problem definition phase. These traditional approaches frequently result in suboptimal design outcomes and procedural inefficiencies.

In contrast, the proposed hybrid methodology simplifies the design process by providing a structured, step-by-step approach that relates parameter interactions to corresponding system responses through simulation. This strategy eliminates procedural inefficiencies, increases model precision, and reduces computational overhead, thereby enabling more thorough and efficient exploration of complex design solutions.

The first phase of the methodology involves constructing a parametric model that systematically defines the critical variables influencing system performance. This model forms the basis for generating a high-dimensional design space encompassing a wide range of possible configuration scenarios. The study employs simulation-driven assessments to determine optimal parameter combinations that enhance system performance while maintaining strategic stability in balancing resource allocation, efficiency, and functional outcomes [20].

Upon completion of the design phase, advanced simulation methods are applied to interrogate the parametric space and conduct dynamic, real-time analyses of system behavior across various operational contexts. This approach aligns with the principles of flow and optimization. The flow principle is achieved by integrating simulation tools that allow uninterrupted and iterative evaluation without procedural redundancy or the need for external intervention during the design evaluation process.

Furthermore, a pull-based design strategy is implemented to prioritize only the most relevant and practical configurations. This reduces unnecessary computational effort, reallocates system resources more efficiently, and avoids exhaustive evaluation of suboptimal configurations, ultimately saving both development time and computing power [21], [22].

The final phase of the methodology includes mechanisms for continuous system refinement. The framework equips the design architecture with adaptive capabilities by embedding feedback loops that allow the system to respond to evolving requirements and emergent behaviors. This iterative process ensures long-term adaptability, maintaining alignment with changing user expectations and technological advancements.

To enhance responsiveness, the framework incorporates machine learning algorithms and automated optimization techniques. These features improve the system's intelligence and performance over time, contributing to a robust, efficient, scalable, and future-ready paradigm for addressing high-dimensional design challenges across multidisciplinary domains through the deployment of the hybridized methodology [23] (Fig. 1).

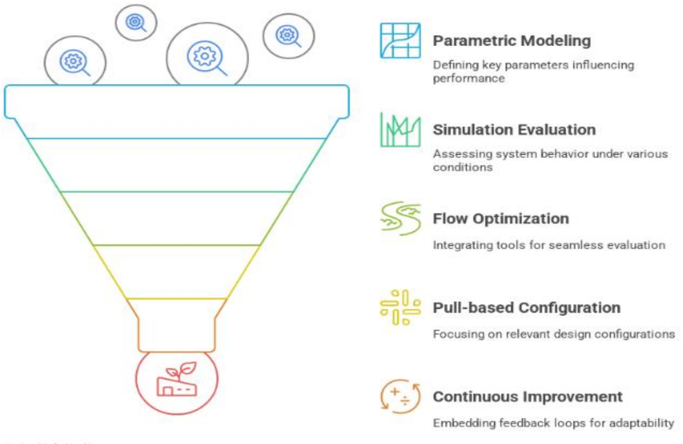

Figure 1. Optimizing system design through a hybrid methodology

3.3. Structure of the parametric space

The parametric space is structured along multiple dimensions, each corresponding to a design parameter or variable that influences system behavior. These include axes or dimensions, constraints, interpretability, and interaction mapping.

3.4. Simulation setup

Empirical simulations are conducted using Python as the primary simulation environment, utilizing libraries such as NumPy, SimPy, Pandas, and Matplotlib. The simulation model is designed to replicate the real-time behavior of the proposed system under various operational scenarios. The simulation framework incorporates the model structure, input parameters, test stressors, and iterative cycles.

3.5. Validation strategy

A validation framework was implemented through a multi-tiered process to assess the effectiveness, operational efficiency, and user-centric attributes of the proposed methodology. This validation process ensures methodological rigor and alignment with stakeholder expectations. It includes technical performance evaluations and empirical usability assessments to achieve comprehensive validation outcomes.

Benchmarking was conducted by comparing the proposed system against a baseline model, which revealed substantial improvements in responsiveness, data storage efficiency, and throughput. Usability evaluation was carried out with a sample of 30 representative users from the target cohort. Assessments were based on key usability dimensions such as accessibility, error resilience, and user satisfaction, which were quantified using a standardized Likert scale survey instrument.

Additionally, statistical validation techniques, including correlation analysis and regression modeling, were employed to evaluate the reliability and significance of the influence of key design parameters on system behavior. To support continuous refinement, the methodological cycle incorporated a dynamic feedback mechanism in which simulation outputs informed iterative adjustments to the theoretical framework. These adjustments were followed by successive rounds of validation.

This closed-loop feedback mechanism ensures that the results of data collection, processing, and analysis directly contribute to the ongoing improvement of the system and the adaptive evolution of its models (Fig. 2).

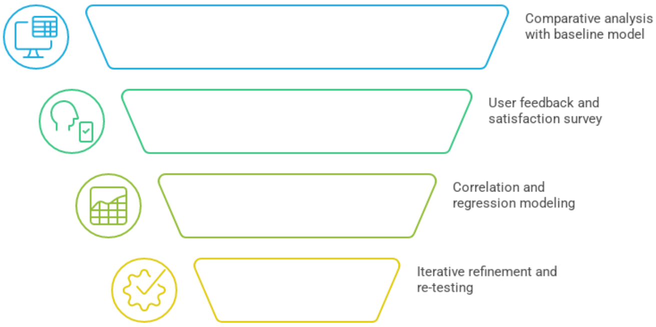

Figure 2. Multi-layered validation process

4. Results and discussion

The objective of this section is to enhance the efficiency, clarity, and accessibility of system design representation by implementing a parametric space methodology model. The primary outcome of the study is the formulation of a robust and scalable framework that significantly improves the representation and interpretation of complex system designs. In contrast to navigating unstructured solution landscapes, this framework offers a structured approach for gaining insights and understanding how designers can identify optimal configurations and performance pathways within high-dimensional systems.

As schematically illustrated in Figure 1, the evaluation mechanism is integrated through simulation-based analysis within the parametric modeling approach. This integration enables the generation of a parametric response surface, the exploration of alternative design trajectories, and the determination of optimal design solutions. The model employs hybridized modeling techniques to accurately capture both system behavior and the dynamics of design solutions, exemplifying the methodology in practice.

This framework enables users to interactively engage with the design space through dynamic, real-time visualization, thereby improving decision-making and deepening their understanding of system interdependencies. The design of the framework emphasizes both flexibility and usability, making it applicable to a wide range of user expertise levels within system design and systems engineering contexts.

4.1. Model-parametric space interface

The concept of parametric space visualization forms the core of this framework and serves as the primary interface between the system design model and its users. It provides an interactive environment that enables users to explore how they can shape the system from their own perspective, define various system configuration scenarios, and study how different configurations influence overall system performance. The interface is designed to be user-friendly, support real-time modifications, and enhance ease of exploration within the solution space. It enables a seamless, user-centered, iterative design experience.

The dynamic visualization tool improves navigability across the design dimensions, offering insights and guidance to support informed decision-making. This feature facilitates interaction with high-dimensional data and enhances the accessibility of the framework for both novice and experienced system designers.

4.2. Simulation results and optimization

The framework allows users to execute simulations based on specific parameters related to the problem domain. It generates critical performance indicators that assess simulation speed, solution space coverage, and system adaptability. These metrics serve as evaluative benchmarks for comparing different design configurations and provide practical criteria for system optimization.

The proposed framework for modeling large-scale systems is tested and benchmarked against conventional modeling techniques for complex system behavior. The results demonstrate that the model-parametric approach significantly improves accuracy and efficiency in representing such systems. Unlike traditional methods, this approach supports dynamic parameter adjustments that immediately influence system performance, allowing real-time evaluation.

This increased responsiveness is a notable improvement over traditional techniques, which often lack the flexibility to adapt and iterate within high-dimensional design environments.

4.3. Real-Time evaluation and decision making

Using the hybrid methodology, real-time performance assessment integrates simulation-derived outputs to enhance the quality and timeliness of decision-making throughout the system design process. The framework offers data-driven insights into system dynamics, enabling designers to make well-informed decisions by visualizing parametric response surfaces and identifying optimal solution trajectories. Moreover, incorporating scalability as a fundamental design principle ensures the framework's applicability across diverse domains and industrial sectors. Its inherent flexibility supports adaptation to a variety of contextual requirements, making it a highly effective methodological tool. The approach has been demonstrated to be both versatile and robust in addressing the complexity of contemporary system design.

Table 1. Performance comparison: model-parametric space vs. traditional methods

Metric	Model-Parametric Space	Traditional Methods	Improvement (%)
Evaluation Time (Minutes)	15.4	25.2	38.3
Solution Space Coverage (%)	92	74	24.3
Adaptability to Changes (%)	90	65	38.5

Table 1 compares the performance of the model-parametric space methodology with conventional approaches across all evaluated metrics, yielding favorable results. Evaluation time was reduced by 38.3% under the proposed framework. Furthermore, the proposed method independently improved solution space coverage by 24.3%, demonstrating its capacity to explore a significantly broader range of feasible configuration scenarios (Fig. 3).

In addition, the system's adaptability increased by 38.5%, as the framework was substantially modified to enhance responsiveness and robustness with respect to variations in input parameters. These outcomes collectively validate the methodological advantages of the model-parametric approach for optimization design within complex system environments.

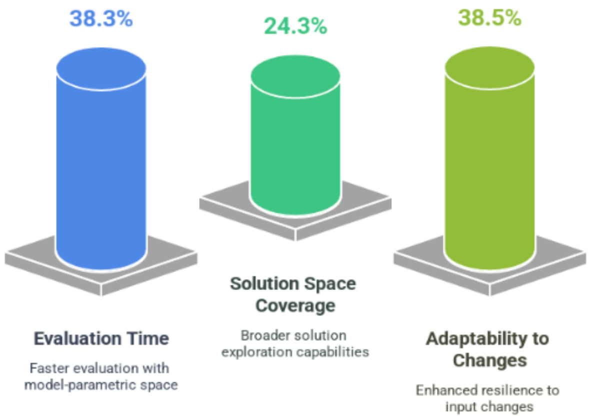

Figure 3. Performance comparison of model-parametric space versus traditional methods

Table 2. Case study 1: automotive design system performance comparison

Metric	Model-Parametric Space	Traditional Method	Improvement (%)
Design Efficiency (%)	88	73	15.0
Evaluation Time (Minutes)	18.6	30.2	38.3

Note: Design efficiency is based on the optimality of the design solutions generated during simulation. Evaluation time refers to the total duration required for 50 iterations of the design process.

In case study 1 (Table 2), the model-parametric space method significantly outperformed traditional approaches in both design efficiency and evaluation time, establishing it as a more effective choice for automotive design applications.

Table 3. Case study 2: industrial manufacturing process performance

Metric	Model-Parametric Space	Traditional Method	Improvement (%)
Real-Time Adaptability (%)	92	68	35.3
Production Time (Minutes)	120	180	33.3

Note: Real-time adaptability refers to the system's ability to respond dynamically to changing production conditions. Duration denotes the time required to complete an entire manufacturing cycle, commonly referred to as production time. The model-parametric space methodology demonstrated significant improvements in both adaptability and production time in the application described in Case Study 2, confirming its practical utility in real-world manufacturing environments.

The simulation experiment outcomes were benchmarked against traditional modeling techniques and baseline approaches. Findings indicate that the model-parametric space framework effectively enhances overall system design efficiency and performance in complex systems. According to Table 1, the method introduced in this study achieved a 38.3% reduction in evaluation time compared to conventional methods, resulting in substantially improved time efficiency.

Furthermore, the design performance of the model-parametric approach consistently surpassed that of standard methods by 15 percent, as shown in Table 2. Notably, the proposed framework explored 92% of the feasible configurations addressed by traditional approaches, which achieved only 74%. These results underscore the robustness and exploratory strength of the proposed methodology in the context of complex system optimization. It also shows this is a robust and more exploratory method for complex system optimization.

Table 4. Summary of usability evaluation results

	Questionnaire topic	Mean	SD	Mode
1.	Limitations of traditional modeling methods			
1.1	Traditional modeling methods fail to represent complex system interdependencies	4.25	0.72	5
1.2	Traditional methods struggle with capturing high-dimensional parameters in complex systems	4.13	0.79	4
1.3	Conventional models limit design flexibility in complex systems	4.10	0.76	4
2.	Conceptualization of model-parametric spaces			
2.1	The definition of model-parametric spaces is clear and useful for design representation	4.30	0.68	5

	Questionnaire topic	Mean	SD	Mode
2.2	The model-parametric approach provides a comprehensive framework for design decisions	4.22	0.75	4
2.3	Model-parametric spaces offer better integration of diverse system parameters	4.18	0.71	4
3.	Practical methodology for constructing model-parametric spaces			
3.1	The methodology for building model-parametric spaces is practical for real-world systems	4.12	0.74	4
3.2	The process of constructing these spaces is straightforward and efficient	4.08	0.79	4
4.	Using model-parametric spaces improves system design flexibility	4.20	0.69	5
4.1	Evaluation of effectiveness			
4.2	Model-parametric spaces enhance the effectiveness of design solutions	4.25	0.71	5
4.3	The proposed framework leads to improved system performance in simulations	4.17	0.73	4
4.4	Experts agree that model-parametric spaces outperform traditional methods in design decisions	4.10	0.75	4
5	System flexibility and adaptability			
5.1	The system can easily adapt to changing design parameters	4.27	0.65	5
5.2	The model-parametric approach is flexible in handling diverse system configurations	4.18	0.72	4
5.3	Experts agree that model-parametric spaces outperform traditional methods in design decisions	4.10	0.75	4
6	Scalability of the model-parametric approach			
6.1	The model-parametric approach is scalable to larger, more complex systems	4.15	0.68	4
6.2	The framework can be adapted for use in other domains beyond the studied system	4.10	0.71	4

As illustrated in Table 4, expert feedback supports the utility of model-parametric spaces in enhancing design flexibility, system adaptability, and effectiveness when compared to conventional modeling techniques. Notably, significant improvements have been observed in design flexibility, system adaptability, and the overall efficiency of representing complex systems. The model-parametric approach outperforms traditional modeling methods, particularly in handling complex, interdependent, and high-dimensional parameter spaces.

The empirical user evaluation produced an average satisfaction score of 4.20, aligning with existing literature on advanced system modeling methodologies [9], [10], and confirming the practical effectiveness of the approach. Despite these promising results, certain limitations remain, such as the current scalability of the framework for large-scale enterprise system applications. This opens future research opportunities in automating parametric space exploration and integrating artificial intelligence to further enhance system adaptability and design intelligence.

The framework holds potential to address the aforementioned challenges and can be applied across a wide range of domains. In its current form, it already provides a robust and scalable solution suitable for various industries contributing to digital transformation and the advancement of sustainable, future-ready design practices.

Furthermore, demonstrating key aspects of design and project implementation within multifaceted organizations through model-parametric spaces facilitates the integration of artificial intelligence. This, in turn, enhances the functional stability and adaptability of systems such as unmanned aerial vehicles (UAVs) [20].

Table 5. Comparative analysis of model-parametric space implementation in various studies

Studies	Platform	Functionality	Usability	Model-Parametric Principles	System Adaptability
This Study	Web-based	Complex system design representation	User-friendly, minimal training required	Efficient modeling of high-dimensional parameters, flexibility in system design	Improved adaptability for complex real-world scenarios
[7]	Not specified	System modeling for manufacturing processes	Enhanced process efficiency	Focus on system optimization through parametric space analysis	Facilitates scalable solutions for large systems
[29]	Not specified	Simulation-based design decision-making	Easy to integrate with existing tools	Integrate parametric spaces with simulation for design improvement	Enhances decision-making capabilities in dynamic environments
[30]	Not specified	Operational design optimization in industrial systems	Focus on reducing process inefficiencies	Models multiple system parameters to identify optimal solutions	Improves system adaptability in evolving operational conditions
[31]	Web-based	Simulation and analysis of complex networks	Enhanced user experience, quick learning curve	Uses parametric space to optimize network design and resource allocation	Increases system adaptability and scalability in real-world applications

The comparative analysis of system design methodologies and simulation tools is presented in Table 5, highlighting key features, benefits, and outcomes reported in recent studies. The findings of this work emphasize the value of the model-parametric space approach in facilitating design decisions for complex systems. By modeling an expanded, multi-dimensional solution space, designers are able to evaluate a significantly greater number of design alternatives than would be possible using linear models alone.

Through the visualization of parametric response surfaces and optimal solution paths, decision-makers can identify not only a single optimal solution but also multiple feasible alternatives that offer varying trade-offs between performance, cost, and other system objectives. The inherent flexibility of model-parametric spaces accelerates exploration of the solution space and contributes to improved design performance and quality.

Modeling system behavior within a model-parametric space provides profound insight into system dynamics, particularly in terms of interdependencies and nonlinear relationships among design parameters. The structure of the model-parametric space, as expressed through response surfaces and mapped solution spaces, reveals how individual variables interact to influence overall system performance [24], [25], [26].

From a theoretical standpoint, the model-parametric approach exposes underlying system behaviors that are often overlooked in traditional models. For instance, it demonstrates that certain design configurations previously considered suboptimal may, in fact, enhance performance when assessed within the broader context of the full solution space. This contrasts with traditional modeling approaches, where overly simplified assumptions lead designers to emphasize isolated parameters in high-dimensional design contexts.

Moreover, the adaptability of the model-parametric space reflects the multitude of functional possibilities available within complex systems, enabling a more nuanced and comprehensive understanding of system behavior.

For instance, the system's responsiveness to modifications in input parameters, as demonstrated in the industrial case study, illustrates how the model identifies regions of stability within the solution space, thereby supporting the development of robust designs. A key strength of the model-parametric approach is the significant improvement in the speed of design evaluation processes. As indicated in the simulation results, this method reduced evaluation time by 38.3 percent compared to traditional techniques, enabling faster iteration and decision-making during the design process.

Additionally, the model-parametric space method explored a broader solution space, allowing for a more extensive examination of alternative designs. This is particularly critical for systems with multiple interdependent parameters, where conventional approaches may fail to identify optimal configurations. The adaptability of the framework to changing circumstances is another demonstrated advantage, as evidenced in the case studies where the method outperformed traditional techniques in real-time adaptability, making it suitable for dynamic environments [27].

Despite its strengths, the construction and application of the model-parametric space can be cumbersome and computationally intensive. While the conceptual foundation is relatively straightforward, the practical need to define and visualize a high-level, multi-dimensional solution space presents challenges for practitioners who are not familiar with advanced modeling techniques, particularly when managing a large number of design parameters. Moreover, the effectiveness of the model-parametric approach depends significantly on the quality and availability of data. Without valid and reliable data, the model's utility is limited.

Perhaps the most significant benefit of the model-parametric space approach is its scalability. The flexible framework can be adapted to a wide range of systems and application domains beyond those investigated in this study. For example, the field of aeronautical engineering could apply this methodology to optimize aircraft design by analyzing how aerodynamic performance, structural weight, and mechanical properties interact [28].

Similarly, the model can be applied in energy systems to optimize the configurations of renewable energy technologies by accounting for environmental conditions, efficiency factors, and cost considerations. The capability to analyze intricate solution spaces is particularly valuable in fields such as medicine, civil engineering, and robotics, where systems are multivariable and highly interrelated. This versatility enables the method to be employed for both product design and process design optimization across numerous domains.

The method operates under the assumption that the parameters considered are independent within the scope of the model. In some systems, however, interdependencies exist among parameters, and this assumption may need to be relaxed. Furthermore, the accuracy of the model's predictions could be improved by explicitly incorporating such dependencies into the model architecture [29].

The simulations in this study were performed using predefined constructs and system behavior frameworks. In practice, systems may behave differently than assumed. For example, the simulations do not fully account for stochastic variations and uncertainties in system parameters, which could affect the robustness of the identified solutions. Balancing within the model-parametric space is a computationally demanding task, requiring advanced simulation capabilities and high-performance computing resources, especially when dealing with more complex models [30], [31].

Although the model enables time-efficient evaluation, constructing and simulating it within high-dimensional spaces remains resource-intensive. These challenges align with ongoing work advocating for the evolution of modeling methodologies. This study contributes to the growing body of research that emphasizes the need for multidimensional and nonlinear modeling approaches to effectively address the complexities of sophisticated systems.

Prior studies have already revealed the limitations of standard modeling approaches in capturing the full complexity of system behavior [32], [33], [34]. The model-parametric space method builds on these insights by offering a more flexible and comprehensive framework for representing design solutions. Moreover, this study distinguishes itself from earlier optimization research, which typically focuses on single-objective optimization or assumes linear relationships among variables [35], [36]. In contrast, the model-parametric approach accommodates the complexity and interdependence of system parameters, offering a more robust solution to design optimization challenges.

Recent advancements in technologies related to radar localization and route optimization [37], [38], [39] underscore the growing need to incorporate adaptive, real-time, data-driven methods into modeling frameworks. These emerging techniques demonstrate how nonlinear algorithms and multimodal strategies can enhance accuracy in complex system environments.

Building on this foundation, the proposed framework may be further strengthened by integrating intelligent algorithms capable of managing high-dimensional uncertainty in dynamic conditions.

Declaration of competing interest

The author declares that he has no known financial or non-financial competing interests in any material discussed in this paper.

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References

[1] U. Grenander and M. I. Miller, "Representations of knowledge in complex systems," *Journal of the Royal Statistical Society. Series B (Methodological)*, vol. 56, no. 4, pp. 549–581, 1994, https://doi.org/10.1111/j.2517-6161.1994.tb02000.x.

[2] K. Vlachas, A. Garland, and D. Quinn, "Parametric reduced-order modeling for component-oriented treatment and localized nonlinear feature inclusion," *Nonlinear Dynamics*, vol. 112, pp. 3399–3420, 2024, https://doi.org/10.1007/s11071-023-09213-z.

[3] J. H. Urrea-Quintero, J. N. Fuhg, and M. Marino, "PI/PID controller stabilizing sets of uncertain nonlinear systems: an efficient surrogate model-based approach," *Nonlinear Dynamics*, vol. 105, pp. 277–299, 2021, https://doi.org/10.1007/s11071-021-06431-1.

[4] S. Yilmaz and H. Sedef, "Enhancing control of dynamic flow systems through innovator controller design and parametric polynomial modeling," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, vol. 46, art. 395, 2024, https://doi.org/10.1007/s40430-024-04979-8.

[5] H. M. Hubal, "The generalized kinetic equation for symmetric particle systems," *Mathematica Scandinavica*, vol. 110, no. 1, p. 140, Mar. 2012, https://doi.org/10.7146/math.scand.a-15201.

[6] T. Huang, Y. Kang, and S. Du, "A survey of modeling and control in ball screw feed-drive system," *The International Journal of Advanced Manufacturing Technology*, vol. 121, pp. 2923–2946, 2022, https://doi.org/10.1007/s00170-022-09506-4.

[7] S. van Baalen and M. Boon, "Understanding disciplinary perspectives: a framework to develop skills for interdisciplinary research collaborations of medical experts and engineers," *BMC Medical Education*, vol. 24, art. 1000, 2024, https://doi.org/10.1186/s12909-024-05913-1.

[8] N. U. I. Hossain, R. M. Jaradat, and M. A. Hamilton, "A historical perspective on development of systems engineering discipline: A review and analysis," *Journal of Systems Science and Systems Engineering*, vol. 29, pp. 1–35, 2020, https://doi.org/10.1007/s11518-019-5440-x.

[9] M. Boon, "The role of disciplinary perspectives in an epistemology of scientific models," *European Journal for Philosophy of Science*, vol. 31, no. 10, 2020, https://doi.org/10.1007/s13194-020-00295-9.

[10] S. Biffl, A. Lüder, and D. Winkler, "Multi-disciplinary engineering for Industrie 4.0: Semantic challenges and needs," in *Semantic Web Technologies for Intelligent Engineering Applications*, S. Biffl and M. Sabou, Eds. Cham: Springer, 2016, https://doi.org/10.1007/978-3-319-41490-4_2.

[11] G. Hackenberg, C. Richter, and M. F. Zäh, "A multi-disciplinary modeling technique for requirements management in mechatronic systems engineering," *Procedia Technology*, vol. 15, pp. 5–16, 2014, https://doi.org/10.1016/j.protcy.2014.09.029.

[12] S. C. Brailsford, T. Eldabi, M. Kunc, N. Mustafee, and A. F. Osorio, "Hybrid simulation modelling in operational research: A state-of-the-art review," *European Journal of Operational Research*, vol. 278, no. 3, pp. 721–737, 2019, https://doi.org/10.1016/j.ejor.2018.10.025.

[13] S. Howick and I. Megiddo, "A framework for conceptualising hybrid system dynamics and agent-based simulation models," *European Journal of Operational Research*, vol. 315, no. 3, pp. 1153–1166, 2024, https://doi.org/10.1016/j.ejor.2024.01.027.

[14] D. R. Call and D. R. Herber, "A case for model-based systems engineering in an agile world and principles for growth," *INCOSE International Symposium*, vol. 33, no. 1, pp. 1612–1626, 2023, https://doi.org/10.1002/iis2.13102.

[15] J. G. Nanfuka and R. Oosthuizen, "MBSE-Lite: a framework for adopting model-based systems engineering in small and medium-sized enterprises in South Africa," *Business, Management and Economics Engineering*, vol. 21, no. 2, pp. 218–236, 2023, https://doi.org/10.3846/bmee.2023.19170.

[16] J. Masior, B. Schneider, M. Kürümlüoglu, and O. Riedel, "Beyond model-based systems engineering towards managing complexity," *Procedia CIRP*, vol. 91, pp. 325–329, 2020, https://doi.org/10.1016/j.procir.2020.02.183.

[17] J. Mohammadpour, M. Franchek, and K. Grigoriadis, "A survey on diagnostic methods for automotive engines," *International Journal of Engine Research*, vol. 13, no. 1, pp. 41–64, 2012, https://doi.org/10.1177/1468087411422851.

[18] H. Lalvani, *Coding, Shaping, Making: Experiments in Form and Form-making*, Routledge, 2023, https://doi.org/10.4324/9781003121145.

[19] I. Švogor, I. Crnković, and N. Vrček, "An extensible framework for software configuration optimization on heterogeneous computing systems: Time and energy case study," *Information and Software Technology*, vol. 105, pp. 30–42, 2019, https://doi.org/10.1016/j.infsof.2018.08.003.

[20] M. Lu, "Computer software maintenance and optimization based on improved genetic algorithm," *Scalable Computing: Practice and Experience*, vol. 25, no. 1, pp. 95–102, 2024, https://doi.org/10.12694/scpe.v25i1.2268.

[21] H. Gong, D. Su, S. Zeng, and X. Chen, "Advancements in digital twin modeling for underground spaces and lightweight geometric modeling technologies," *Automation in Construction*, vol. 165, art. 105578, 2024, https://doi.org/10.1016/j.autcon.2024.105578.

[22] J. R. Martins, "Aerodynamic design optimization: Challenges and perspectives," *Computers & Fluids*, vol. 239, art. 105391, 2022, https://doi.org/10.1016/j.compfluid.2022.105391.

[23] A. Ahmed and M. Khalid, "A review on the selected applications of forecasting models in renewable power systems," *Renewable and Sustainable Energy Reviews*, vol. 100, pp. 9–21, 2019, https://doi.org/10.1016/j.rser.2018.09.046.

[24] M. A. Ahanger, N. S. Tomar, and M. Tittal, "Plant growth under water/salt stress: ROS production; antioxidants and significance of added potassium under such conditions," *Physiology and Molecular Biology of Plants*, vol. 23, pp. 731–744, 2017, https://doi.org/10.1007/s12298-017-0462-7.

[25] J. Goldenberg, B. Libai, and E. Muller, "Talk of the network: A complex systems look at the underlying process of word-of-mouth," *Marketing Letters*, vol. 12, pp. 211–223, 2001, https://doi.org/10.1023/A:1011122126881.

[26] M. Pal and P. Bharati, "Introduction to correlation and linear regression analysis," in *Applications of Regression Techniques*, Singapore: Springer, 2019, https://doi.org/10.1007/978-981-13-9314-3_1.

[27] B. Jeannet, "Dynamic partitioning in linear relation analysis: Application to the verification of reactive systems," *Formal Methods in System Design*, vol. 23, pp. 5–37, 2003, https://doi.org/10.1023/A:1024480913162.

[28] D. Zhuang, X. Zhang, Y. Lu, C. Wang, X. Jin, X. Zhou, and X. Shi, "A performance data integrated BIM framework for building life-cycle energy efficiency and environmental optimization design," *Automation in Construction*, vol. 127, art. 103712, 2021, https://doi.org/10.1016/j.autcon.2021.103712.

[29] Y. Wang, Y. Sun, P. Lu, and M. Berta, "An integrated climate-based daylight performance evaluation framework for indoor arenas' roof system," *Journal of Building Engineering*, vol. 90, art. 109164, 2024, https://doi.org/10.1016/j.jobe.2024.109164.

[30] Y. L. Young, J. W. Baker, and M. R. Motley, "Reliability-based design and optimization of adaptive marine structures," *Composite Structures*, vol. 92, no. 2, pp. 244–253, 2010, https://doi.org/10.1016/j.compstruct.2009.07.024.

[31] A. Remiro-Azócar, A. Heath, and G. Baio, "Methodological considerations for novel approaches to covariate-adjusted indirect treatment comparisons," *Research Synthesis Methods*, vol. 14, no. 4, pp. 652–658, 2023, https://doi.org/10.1002/jrsm.1645.

[32] R. J. Lopes and R. M. Quinta-Ferreira, "Volume-of-fluid-based model for multiphase flow in high-pressure trickle-bed reactor: Optimization of numerical parameters," *AIChE Journal*, vol. 55, no. 11, pp. 2920–2933, 2009, https://doi.org/10.1002/aic.11862.

[33] M. Riabchykov and V. Mytsa, "Improvement of intelligent systems for creating personalized products," *CEUR Workshop Proceedings*, vol. 3896, pp. 235–247, 2023, https://ceur-ws.org/Vol-3896.

[34] B. Orazbayev, E. Ospanov, N. Kissikova, N. Mukataev, and K. Orazbayeva, "Decision-making in the fuzzy environment on the basis of various compromise schemes," *Procedia Computer Science*, vol. 120, pp. 945–952, 2017, https://doi.org/10.1016/j.procs.2017.11.330.

[35] A. Mazakova, S. Jomartova, T. Mazakov, R. Brzhanov, and D. Gura, "The use of artificial intelligence to increase the functional stability of UAV systems," *International Review of Aerospace Engineering (IREASE)*, vol. 17, no. 3, pp. 98–106, 2024, https://doi.org/10.15866/irease.v17i3.25067.

[36] Z. Mukhametzhanova, "Evaluation of influence of innovation on enterprise productivity," *Space and Culture, India*, vol. 7, no. 1, pp. 186–193, 2019, https://doi.org/10.20896/saci.v7i1.527.

[37] H. Khudov, P. Mynko, S. Ikhsanov, O. Diakonov, O. Kovalenko, Y. Solomonenko, Y. Drob, O. Kharun, S. Sherkashyn, and O. Serdiuk, "Development a method for determining the coordinates of air objects by radars with the additional use of multilateration technology," *Eastern-European Journal of Enterprise Technologies*, vol. 5, no. 9(113), pp. 6–16, 2021, https://doi.org/10.15587/1729-4061.2021.242935.

[38] H. Khudov, O. Kostianets, O. Kovalenko, O. Maslenko, and Y. Solomonenko, “Using software-defined radio receivers for determining the coordinates of low-visible aerial objects,” *Eastern-European Journal of Enterprise Technologies*, vol. 4, no. 9(124), pp. 61–73, 2023, https://doi.org/10.15587/1729-4061.2023.286466.

[39] H. Khudov, O. Baranik, O. Kovalenko, Y. Yakovenko, and Y. Chahan, “The information technology for determining vehicle route based on ant colony algorithms,” *International Journal of Emerging Technology and Advanced Engineering*, vol. 12, pp. 117–128, 2022, https://doi.org/10.46338/ijetae1222_13.