

Article

A Generalized Prototyping Framework for Engineering Design and Advanced Manufacturing: From Ideation to Validation

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Abstract

Prototyping plays a central role in engineering design by supporting creativity, modeling, experimentation, and validation under conditions of uncertainty. However, existing prototyping approaches remain fragmented across disciplines, with limited integration between design activities, fidelity selection, and decision-making processes. This lack of coherence makes it difficult to systematically guide prototyping across different stages of the engineering design lifecycle. This paper proposes a generalized, context-sensitive prototyping framework developed through a structured and critical synthesis of engineering design literature. The framework integrates four iterative stages: creativity and concept generation, modeling and analysis, prototyping strategy and execution, and experimental validation. It further incorporates key dimensions influencing prototyping decisions, including fidelity levels, risk considerations, stakeholder involvement, and uncertainty management. The framework is derived through thematic analysis of peer-reviewed literature spanning foundational prototyping models and recent developments in digital engineering, rapid prototyping, and AI-supported design. Representative case examples are used to illustrate the applicability of the framework across different engineering contexts. The contribution of this work is a unified conceptual and process-oriented framework that clarifies relationships among prototyping activities and provides a structured perspective for understanding prototyping under uncertainty. This study also identifies limitations of current approaches and outlines directions for future research in adaptive and data-driven prototyping systems.

Keywords: generalized prototyping framework; prototype fidelity; iterative design; uncertainty reduction; decision-oriented prototyping; experimental validation



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1. Introduction

Recent advances in additive manufacturing, rapid prototyping technologies, computational modeling, and digital engineering tools have significantly transformed engineering design processes. In particular, the widespread accessibility of 3D printing technologies has made prototyping faster, more affordable, and more convenient than ever before, enabling designers and engineers to rapidly convert conceptual ideas into physical or virtual representations for evaluation and testing [1–3]. As a result, prototyping has evolved from a limited development activity into a central component of modern engineering design, supporting creativity, communication, experimentation, validation, and iterative decision-making across diverse engineering applications [4,5].

The increasing accessibility of prototyping technologies has expanded both the scope and frequency of prototype usage throughout the design lifecycle. Prototypes are now

routinely employed during conceptual ideation, analytical modeling, manufacturability assessment, stakeholder communication, functional testing, and experimental validation. Furthermore, the emergence of hybrid physical–virtual environments, digital twins, artificial intelligence-assisted design, and Industry 4.0 manufacturing systems has further increased the complexity and strategic importance of prototyping activities within engineering systems development [6,7].

Beyond its technological convenience, prototyping should not be viewed merely as a fabrication activity, but rather as a critical mechanism for validating industrial projects and supporting engineering decision-making throughout system development [8]. Depending on the product, system, and design objectives, prototyping may serve multiple purposes, including verification of functionality, evaluation of manufacturability, assessment of user interaction, reduction in technical risk, and validation of system performance prior to full-scale implementation [9]. Consequently, the growing importance of prototyping technologies also increases the need for systematic methodologies capable of guiding how, when, and why different prototyping approaches should be applied within engineering design processes.

Numerous prototyping approaches have been proposed in the literature to address different design objectives and development stages [10]. Floyd [11] categorized prototyping into exploratory, experimental, and evolutionary forms based on development purpose. Gomaa and Scott [12] emphasized prototyping for requirements clarification and iterative system refinement. Buchenau and Suri [13] highlighted experiential prototyping as a means of understanding interaction and user experience, whereas Dow et al. [2] demonstrated the value of parallel prototyping for enhancing creativity and reducing design fixation. Kent et al. [14] further reviewed different types of prototyping approaches used across engineering design applications. More recent research has expanded prototyping toward digital integration, rapid experimentation, flexible manufacturing, innovation-driven development, and learning-oriented design processes [15–17]. Chen et al. [18] investigated uncertainty propagation in multi-dimensional flow field responses.

Although these studies provide valuable contributions, existing prototyping approaches are often developed independently around specific tools, technologies, domains, or design objectives. Some approaches primarily emphasize creativity and concept generation, whereas others focus on modeling and simulation, fabrication, usability assessment, manufacturability, experimentation, or system validation. Consequently, limited guidance exists for systematically integrating these dimensions into a generalized prototyping methodology capable of supporting multidisciplinary and uncertainty-driven engineering design processes [19].

Another important limitation is that prototyping is frequently treated as a generic iterative activity rather than as a structured mechanism for supporting engineering decisions and reducing uncertainty. In practice, effective prototyping depends on multiple interconnected factors, including system complexity, technical risks, fidelity requirements, manufacturability constraints, stakeholder involvement, validation objectives, and available analytical capabilities. Therefore, prototyping activities cannot be effectively planned in isolation from the engineering context and the specific uncertainties being addressed. Depending on the product or system, prototyping intentions may include, but are not limited to, verifying functionality, evaluating operational performance, improving user interaction, or validating integration strategies [9]. Furthermore, recent studies have also explored the role of prototyping as a learning and training tool in engineering education and professional practice [20].

As engineering systems become increasingly multidisciplinary, data-driven, and digitally integrated, there is a growing need for generalized prototyping frameworks capable

of systematically linking creativity, modeling and analysis, prototyping strategy selection, experimentation, and validation activities within a unified structure. Fundamental questions remain regarding how and when prototyping should be used and how its effectiveness should be evaluated across varying engineering contexts [21]. In addition, several technical and organizational challenges associated with prototyping processes remain unresolved [22]. Existing approaches often lack a higher-level decision-oriented structure capable of supporting adaptive prototyping processes across diverse engineering domains. Santiago et al. [23] proposed a conceptual live-prototyping framework based on artificial intelligence (AI).

Most recently, studies have advanced the understanding of prototyping practices, uncertainty management, and hybrid physical–virtual development environments. For example, Ege et al. (2024) [24] demonstrated that prototyping decisions are strongly influenced by project objectives, uncertainty levels, and resource constraints, while Giaccardi et al. (2024) [25] highlighted the increasing role of data, algorithms, and uncertainty-aware prototyping in contemporary design processes. Similarly, Shen et al. (2025) [26] emphasized the growing convergence of physical and virtual prototyping approaches within integrated product development environments. Despite these advances, existing approaches remain largely fragmented and do not provide a unified framework that systematically integrates creativity, modeling, fidelity progression, stakeholder involvement, and experimental validation across the engineering design lifecycle.

Motivated by these challenges, this paper proposes a generalized prototyping framework for engineering design that integrates recurring prototyping dimensions into a unified and iterative process structure. The framework organizes prototyping activities into four interconnected stages: creativity and ideation, modeling and analysis, prototyping strategy and execution, and experimental verification and validation. Rather than representing a rigid linear sequence, the framework emphasizes iterative feedback loops and adaptive transitions between stages to support uncertainty reduction, knowledge generation, and informed engineering decision-making throughout the design lifecycle.

The remainder of this paper is organized as follows. Section 2 reviews the principles and purposes of prototyping in engineering design. Section 3 describes the proposed generalized prototyping framework and its conceptual structure, as well as discusses the major framework dimensions and their interactions. Section 4 presents illustrative engineering examples demonstrating the application of the framework. Finally, Section 5 discusses the limitations, implications, and future research opportunities associated with generalized prototyping methodologies in engineering design.

2. Prototyping in Engineering Design

Prototyping is used for a wide range of purposes, including:

- Exploration and discovery.
- Generating and evaluating ideas.
- Risk and uncertainty analyses.
- Communication and alignment.
- Supporting decision-making and learning.

Prototyping can be used at very early stages toward the final product and marketing, such as:

- Problem definition.
- Conceptual design.
- Concept selection.
- Generating preliminary results.
- Detailed design.

- Testing, validation, and verification.
- Production and marketing communications.
- Product/service support and learning from.

Depending on the purpose and design stages, prototyping requires close alignment between approaches, technologies, dimensions, and representations, as shown in Figure 1.

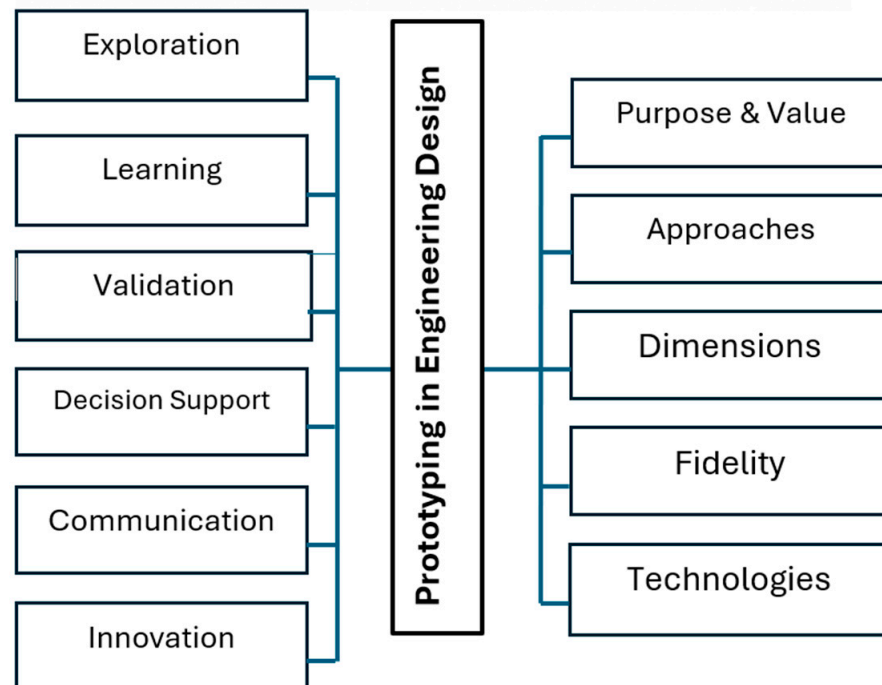


Figure 1. Schematic illustration of prototyping in engineering design.

Prototyping approaches include:

- *Throwaway* (non-functional): built to test specific aspects and discard them.
- *Evolutionary* (incremental): refine iteratively with increasing details.
- *Experimental*: built to test hypotheses and gather data.
- *Pre-production/pilot*: near-final prototypes for real-world validation.
- *Virtual prototyping*: digital models, simulation, and virtual testing.
- *Hybrid prototyping*: combination of physical and virtual methods.

A variety of technologies can be used for building a prototype:

- CAD/CAE.
- Simulation and analysis.
- Additive manufacturing (3D and 4D printing).
- Subtractive manufacturing.
- Rapid tooling and modeling.
- Digital twins and Internet of Things (IoT).
- Artificial intelligence and machine learning (AI/ML).
- Generative design.
- Augmented reality and virtual reality (AR/VR).
- Cloud and data analysis.

To select a prototyping approach, one should consider the following aspects:

- *Context and Objectives*: design goals, constraints, domain characteristics, and decision needs.

- *Uncertainty and Risk*: technical, requirements, integration, manufacturing, and operational uncertainties.
- *Stakeholders and Collaborations*: users, customers, experts, manufacturers, regulators, and cross-functional teams.
- *Time and Iterations*: early vs. late prototyping, iteration, cycles, learning progression.
- *Cost and Resources*: budgets, resources, and trade-offs across the design process.

Based on the stage, approach, and considerations of prototyping, the built prototype may be represented as:

- *Low fidelity*: a simple two-dimensional sketch or a three-dimensional model representing the overall shape/geometry and basic elements.
- *Medium fidelity*: a model composed of the most fundamental components that can be used to demonstrate functionality of the design in a laboratory or in controlled conditions.
- *High fidelity*: a realistic model with full functionality in real operating conditions.

Considering the above explanation, it is evident that although prototyping is a practical approach in design, it can become an expensive and time-consuming process if it is not selected appropriately. The next section proposes a general prototyping framework aimed at making prototyping a systematic approach that can be applied not only to physical product design, but also to software products and systems.

3. Proposed Generalized Prototyping Framework

The proposed framework should not be interpreted as a prescriptive or universally uniform prototyping methodology. Prototyping strategies are inherently context-dependent and derive their value from their ability to resolve specific uncertainties and support design decisions under particular technical, organizational, regulatory, and economic constraints. Consequently, the fidelity, scope, timing, and implementation of prototypes may differ substantially across engineering domains. For example, prototyping strategies in aerospace systems, where certification requirements and safety constraints dominate, differ fundamentally from those in consumer products or software-intensive systems, where rapid iteration and user interaction may be prioritized. The framework proposed in this study therefore aims to identify recurring and transferable prototyping principles observed across the literature while recognizing that their practical instantiation must remain domain-sensitive and decision-driven.

The proposed framework is intended as a process-oriented conceptual framework and decision-support structure rather than a predictive theory, optimization model, or prescriptive design methodology. Its purpose is to organize and integrate prototyping activities commonly reported in engineering design practice, while providing a systematic perspective for understanding how creativity, modeling, prototyping, and validation interact to support uncertainty reduction and engineering decision-making. Accordingly, the framework should be interpreted as an integrative structure for guiding prototyping activities rather than a universally applicable procedure or a substitute for domain-specific engineering methods.

The proposed framework synthesizes recurring themes identified in the literature into four interconnected stages: initial creativity and ideation, modeling and analysis, prototyping strategy and execution, and experimental verification and validation. Rather than representing a strictly linear progression, the framework emphasizes iterative feedback loops between stages, enabling continuous refinement of both problem understanding and solution development under varying levels of uncertainty. In addition to linking prototyping stages, the framework integrates learning-oriented iteration, stakeholder involvement,

modeling integration, and risk-reduction considerations within a unified prototyping perspective. The general prototyping framework is schematically presented in Figure 2.

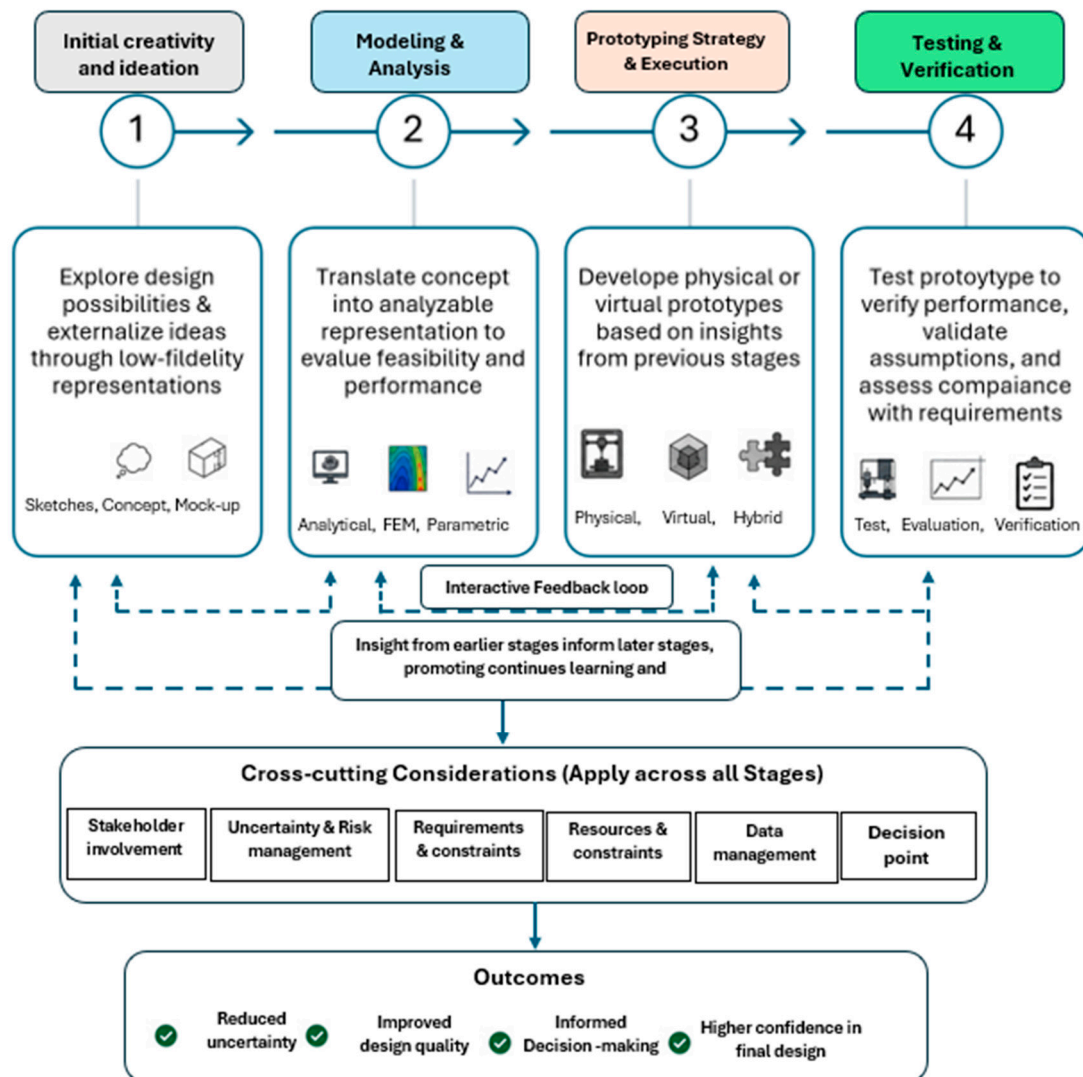


Figure 2. The general prototyping framework.

3.1. Framework Structure

The proposed framework consists of four interconnected stages: explicitly linking initial creativity → modeling, analysis → prototyping, and strategy → experimental verification, which is developed in the following section. Rather than a linear progression, the framework emphasizes feedback loops between stages, allowing insights gained at later stages to inform earlier design decisions.

3.1.1. Initial Creativity and Ideation

The framework begins with creative exploration, where designers generate and externalize ideas using low-fidelity representations such as sketches, diagrams, and conceptual mock-ups. Prototyping at this stage supports exploration of the design space, communication of intent, and early identification of requirements and constraints. The primary objective is learning, not validation.

3.1.2. Modeling and Analysis

Modeling activities translate conceptual ideas into analyzable representations. Analytical calculations, numerical simulations, and parametric models are used to evaluate feasibility, performance trends, and sensitivities. Modeling guides decision-making by identifying promising design alternatives and informing prototype fidelity and testing priorities.

3.1.3. Prototyping Strategy and Execution

Physical or virtual prototypes are developed based on insights arising from the creativity and modeling stages. Prototype fidelity is selected according to the specific questions being addressed, such as functionality, usability, or integration. Iterative prototyping cycles enable refinement of design features and reduction in uncertainty, supported by continuous feedback from stakeholders.

3.1.4. Experimental Testing and Performance Verification

In the final stage, prototypes are subjected to experimental testing to verify functional performance, validate assumptions, and assess compliance with requirements. Testing results inform design refinement and, when necessary, trigger iteration back to modeling or ideation stages. This stage supports confidence in design decisions prior to finalization or deployment.

3.2. Framework Dimensions

3.2.1. Prototype Components Dimension

The components dimension is grounded in systems engineering literature and defines a prototype through three interrelated elements: outputs, capabilities, and cosmetics.

- **Outputs:** This refers to the observable results of a prototype during operation. These include system behavior, performance responses, and user interactions under specific operational constraints (e.g., environmental conditions, software platforms). Examples of outputs are measured speed, load capacity, and temperature. Outputs partially define and reveal prototype capabilities.
- **Capabilities:** This represents the integration of functional and non-functional elements required for the prototype to generate its output and meet stakeholder expectations. Capabilities link an internal system structure with externally observable behavior and, in turn, influence prototype cosmetics. Examples of capabilities are motor control, structural strength, software algorithms, and energy efficiency.
- **Cosmetics:** This encompasses the esthetic and sensory attributes of the prototype, such as the shape, materials, color, texture, and even its sound or smell. While often considered secondary, cosmetics can significantly constrain or influence both outputs and capabilities. Examples of cosmetics are form factors, surface finishes, color schemes, material feel, and sounds.

These three components are not developed independently; rather, they co-evolve through iterative prototyping cycles.

A successful prototype requires alignment among outputs, capabilities, and cosmetics to ensure that observable results, system functionality, and user perception work together to meet the design objectives and stakeholder expectations. Figure 3 illustrates the schematic alignment among the three components of a successful prototyping structure.

Understanding the balance and interaction among these three components helps designers make informed decisions about what to build and how it will be perceived.

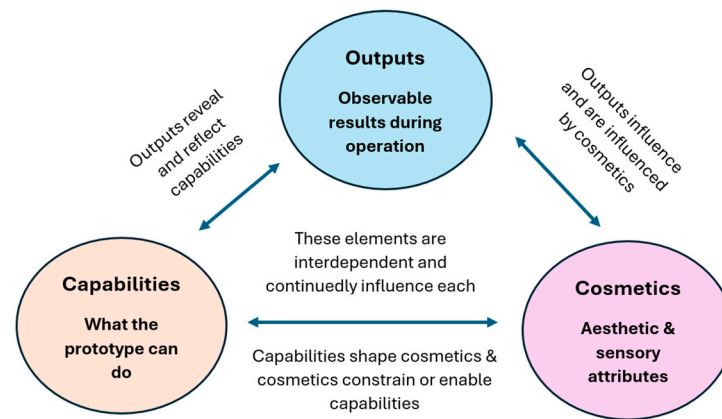


Figure 3. The dimension of prototyping framework.

3.2.2. Iterative Prototyping Cycle

The development of prototype components occurs through a recurring four-step iteration:

- **Build:** This involves creating a value increment in the prototype based on customer needs, stakeholder expectations, and known constraints. Learning generated at this stage includes improved understanding of requirements and design feasibility.
- **Validate:** This assesses whether the value increment satisfies defined needs and constraints. This step produces learning about functional adequacy, deficiencies, and opportunities for enhancement.
- **Refine:** This applies insights from validation to modify the prototype, addressing shortcomings and incorporating improvements. This step generates a new value increment.
- **Define:** This concludes the iteration by either accepting the increment and progressing forward or rejecting it and returning to an earlier stage of the cycle. This decision governs the direction and scope of subsequent iterations.

Each iteration is intentionally short to maximize learning while minimizing cost and commitment. Figure 4 illustrates a single iteration cycle.

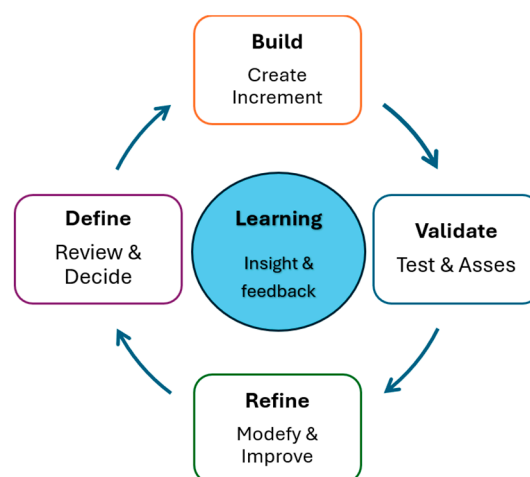


Figure 4. The iteration cycle of prototyping.

The proposed framework does not assume a strictly linear progression through prototyping activities. Instead, advancement, iteration, or regression is determined by the outcomes of each validation cycle. Transitions between fidelity levels and development stages are influenced by several decision factors, including technical uncertainty, design risks, stakeholder objectives, prototype performance, and resource constraints. When validation activities provide sufficient evidence to support design decisions and reduce

critical uncertainties, the prototype may progress to a higher fidelity level or subsequent development stage. Conversely, unresolved risks, inadequate performance, conflicting stakeholder feedback, or insufficient confidence in the available evidence may require additional refinement or a return to earlier stages. In this manner, the framework supports adaptive and learning-driven transitions throughout the prototyping process.

3.3. Integration of Components and Fidelity

Developing a prototype requires building capabilities that produce outputs under defined cosmetic constraints. Each component, output, capability, and cosmetic constraint may evolve through distinct but interrelated iteration cycles that inform one another. Figure 5 illustrates the integration of these cycles and their interactions.

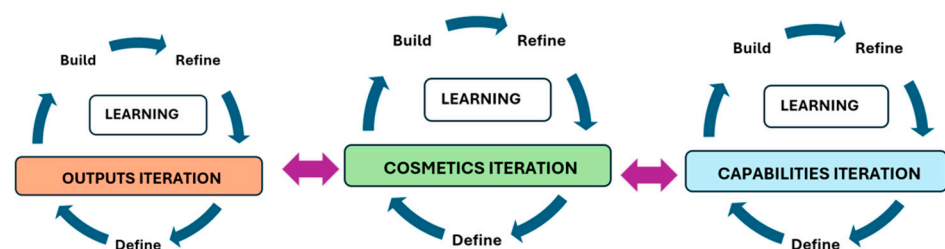


Figure 5. Learning iteration cycle of prototyping.

Each iteration also results in a specific level of prototype fidelity, progressing from abstract representations to fully functional systems.

Decision Factors Influencing Prototype Development

While Figures 4 and 5 describe the iterative and interconnected nature of prototyping activities, progression through the framework is influenced by several decision factors. These include technical uncertainty, risk exposure, fidelity requirements, stakeholder objectives, resource constraints, and validation outcomes. Collectively, these factors determine whether a prototype should advance to a higher fidelity level, undergo additional refinement, or return to earlier stages for further development. Consequently, the proposed framework supports adaptive and evidence-based prototyping decisions rather than a fixed sequential process. Table 1 provides the factors influencing prototype development and decision transition.

Table 1. Decision factors influencing prototype development and transition decisions.

Decision Factor	Influence on Prototype Development
Technical Uncertainty	Determines need for additional exploration and testing
Technical Risk	Influences validation depth and prototype scope
Fidelity Requirements	Guides prototype complexity and realism
Stakeholder Objectives	Defines evaluation criteria and priorities
Resource Constraints	Affects iteration frequency and prototype scope
Validation Outcomes	Supports progression, refinement, or redesign

3.4. Prototype Fidelity Levels

The proposed framework defines five levels of prototype fidelity, enabling structured evaluation, planning, and control of prototyping activities.

- **Verbal Prototypes:** This consists of articulated descriptions of outputs, capabilities, and cosmetics developed collaboratively by the team and customers. They are internal,

abstract, and constraint-focused, serving as a foundation for shared understanding. Learning at this level is primarily conceptual and must be rapidly externalized to avoid loss.

- **Sketch Prototypes:** These provide visual representations of system concepts, typically in two dimensions. They are produced using low-cost, informal tools and prioritize quantity over quality. Sketching supports rapid ideation and produces abstract and visual learning.
- **Rough Prototypes:** These represent the first physical or virtual embodiments of the system. They are intentionally incomplete, inexpensive, and disposable, demonstrating limited outputs without strict adherence to constraints. These prototypes enable abstract, visual, and tactile learning and are often referred to as alpha prototypes in software contexts.
- **Basic Prototypes:** These demonstrate selected outputs within defined constraints and are suitable for evaluation by broader stakeholder groups. While not fully refined, they are more robust and costly than rough prototypes. Emphasis shifts from iteration quantity to quality. These prototypes support extensive user feedback and validation.
- **High-Fidelity Prototypes:** These prototypes closely resemble the final system in appearance and functionality. They integrate outputs, capabilities, and cosmetics within full design constraints and are often costly and time-intensive. High-fidelity prototypes are usually referred to as beta prototypes; they are deployed to large audiences for comprehensive evaluation and generate advanced tactile and experiential learning.

These fidelity levels collectively support deliberate progression from exploration to validation while maintaining flexibility for iteration. Figure 6 presents an integrated view of fidelity progression within the framework.

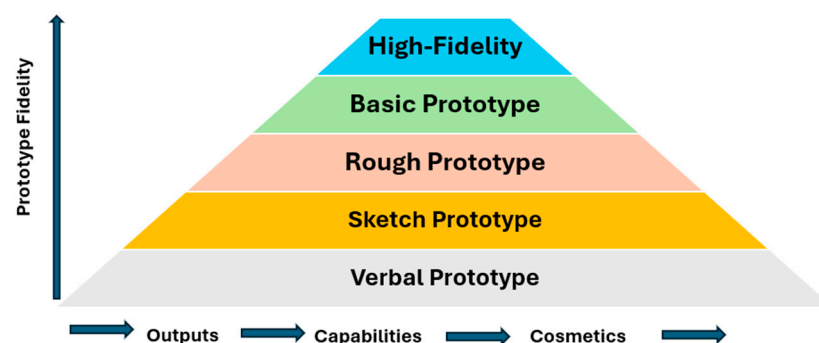


Figure 6. Integrated prototyping fidelity levels.

3.5. Summary of the Framework

The interaction between prototype components, fidelity levels, and iterative learning cycles forms a comprehensive prototyping framework that supports structured prototyping decisions, uncertainty reduction, and iterative development throughout the engineering design process. In this framework, a prototype is defined as a hardware system, a software system, or a combination of both that, under specified constraints, models selected functions and appearances of a target system to fulfill customer needs and stakeholder expectations. Table 2 summarizes the characteristics of each fidelity level in relation to the outputs, capabilities, and cosmetics.

To clarify the advantages of the proposed framework in comparison with existing frameworks, Table 3 presents a comparative analysis of representative prototyping frameworks and the proposed framework.

Table 2. Description of each level of prototyping fidelity with respect to the component of prototypes.

Fidelity Level	Prototype Components		
	Outputs	Capabilities	Cosmetics
Verbal	A design team’s conversation, with or without the customer, focused on articulating main outputs generated by the prototype under certain constraints.	A design team’s conversation about how the prototype elements integrate to generate their outputs under certain constraints.	A team’s conversation, with or without the customer, about the appearance of the prototype under certain constraints.
Sketch	A visual representation of the main outputs of the prototype under certain constraints.	A visual representation of the integration of the elements of the prototype to produce output under certain constraints.	A draft drawing of the appearance of the prototype under certain constraints.
Rough	Few outputs of the prototype are produced physically or virtually but may or may not operate under all the prototype constraints.	A first physical or virtual organization and integration of elements of the prototype to produce few prototype outputs under certain constraints.	A first physical or virtual representation of the esthetics of the prototype. May contain some but not all the quality attributes of the design.
Basic	Some outputs of the prototype are produced physically or virtually within all the prototype constraints.	An advanced physical or virtual organization and integration of elements of the prototype to produce some output under certain constraints.	A more refined visual or virtual representation of the esthetics of the prototype. May contain most but not all the quality attributes of the design.

Table 3. Comparison of the proposed framework with existing prototyping frameworks.

Model/Framework	Main Focus	Key Limitation	Relation to Proposed Framework
Floyd	Types of prototyping	No process integration	Lacks lifecycle + decision structure
Boehm Spiral Model	Risk-driven iteration	Software-focused, weak fidelity detail	Partial overlap in uncertainty handling
Pahl and Beitz	Engineering design process	No explicit prototyping structure	Does not treat prototyping as central mechanism
Ulrich And Eppinger	Product development stages	Limited fidelity/uncertainty linkage	No integrated decision logic
Rapid Prototyping Literature	Speed and fabrication	Technology-centric, fragmented	Lacks modeling + stakeholder integration
Digital Twin/Industry 4.0	Virtual–physical systems	Application-specific, not unified	Emerging but still fragmented
Proposed Framework	Uncertainty-driven integrated prototyping	Conceptual (not yet empirically validated)	Unifies fidelity, modeling, stakeholder, and validation across stages

The novelty of the proposed framework lies not in introducing new prototyping activities, but in explicitly integrating creativity, modeling, prototyping execution, validation,

fidelity progression, and decision-making considerations within a unified uncertainty-sensitive structure.

4. Illustrative Practical Design Examples

Due to advances in additive manufacturing in recent years, prototyping has become a very popular practice in almost all modern industries, including aerospace and defense, automotive and transportation, medical devices and healthcare, consumer products, industrial equipment, energy and environment, civil and infrastructure, and electronics and software-intensive systems. In this section, a few examples are briefly described to demonstrate the applicability of the proposed prototyping framework; selected practical design examples are presented. These examples are drawn from real design projects in which systems were developed from initial concepts, through modeling and prototyping, and ultimately evaluated through experimental testing. The purpose of these examples is not to provide comparative performance analysis, but to illustrate how the framework can be applied in practice to structure prototyping activities and support design decision-making.

4.1. Product Design

4.1.1. Concept-to-Prototype Development of a Wearable Biomedical Device

This project intends to design a wearable device for real-time gait monitoring of patients with partial paralysis experiencing foot drop. This example addresses the development of a wearable biomedical device intended for online gait monitoring in patients with neuromuscular impairments. The project is inherently multidisciplinary, requiring close collaboration among engineers, medical professionals, manufacturers, and end users (patients). The process begins with creativity-driven ideation, during which multiple design concepts are generated through sketches, storyboards, and low-fidelity mock-ups. These early representations facilitate communication of the design intent across disciplines and enable rapid exploration of alternative configurations with minimal resource investment.

Insights gained during the ideation phase guide subsequent modeling and analysis activities. Analytical calculations and numerical simulations are conducted to evaluate technical feasibility, estimate key performance metrics (e.g., sensor accuracy, response time, power consumption), and identify critical design parameters. Modeling results inform decisions related to system architecture, sensing modalities, actuation strategies (if applicable), and component selection.

Based on these findings, a prototyping strategy is defined that explicitly aligns prototype fidelity with learning objectives and risk-reduction goals. A medium-fidelity prototype is developed to evaluate functional behavior, ergonomics, and system integration, including sensor placement, data acquisition, and user interaction. Iterative prototyping cycles are employed, incorporating feedback from preliminary testing, clinical insight, and stakeholder input.

Finally, experimental verification is conducted to assess system performance under representative operating conditions. Experimental results are used to validate modeling assumptions, refine system parameters, and increase confidence in the design prior to finalization. The iterative integration of creativity, modeling, prototyping, and testing supports progressive reduction in uncertainty and informed decision-making throughout the development process.

The overall design journey follows the sequence:

Creativity → Modeling, Analysis → Prototyping, and Strategy → Experimental Verification.

Outputs: (i) Real-time gait monitoring data for patients with foot drop; (ii) quantitative assessment of gait characteristics and anomalies; (iii) actionable feedback to support clinical evaluation and rehabilitation planning.

Capabilities: (i) Sensing systems (e.g., inertial measurement units, pressure sensors, or electromyography sensors); wearable system architecture optimized for comfort, safety, and usability; data acquisition and processing hardware; algorithms and programming code for gait analysis and feature extraction; wireless communication for real-time or near-real-time data transmission; user interface for clinicians and patients; power management suitable for continuous or extended use.

Cosmetics: (i) Ergonomic and unobtrusive form factors suitable for daily wear; esthetic and intuitive device appearance to promote patient acceptance; clear and accessible visualization of gait information in the user interface.

In this project, the levels of prototyping fidelity are as follows:

- **Verbal Fidelity:** Conceptual descriptions of clinical needs, system functionality, and use scenarios.
- **Sketch Fidelity:** Hand-drawn concepts and layout sketches exploring form factors, sensor placement, and user interaction.
- **Rough:** Low-resolution physical mock-ups evaluating ergonomics, attachment mechanisms, and basic functionality.
- **Basic:** Functional system incorporating representative sensors and electronics to assess data acquisition and integration.
- **High Fidelity:** A clinically representative wearable device with validated hardware, software, and user interface, enabling comprehensive experimental verification.

4.1.2. Iterative Prototyping and Performance Verification of a Monitoring System

Integrated engineering system for monitoring the structural stability and maintenance condition of a building. This example focuses on the design of a system composed of multiple interconnected products that collectively enable continuous monitoring of building stability and maintenance needs. The design process begins with the exploration of alternative system concepts, assessing availability, feasibility, and integration of candidate technologies. Early-stage prototyping emphasizes that low-fidelity representations evaluate usability, spatial constraints, sensor placement, data flow, and the overall system layout. These prototypes facilitate rapid feedback from stakeholders and enable early identification of design limitations at minimal cost.

As the design matures, computational modeling is introduced to evaluate performance characteristics and predict system behavior, such as the structural response, sensor sensitivity, data reliability, and fault detection capabilities. Modeling results are used to prioritize design modifications and to determine the appropriate level of prototype fidelity required for further validation. Based on these insights, a higher-fidelity prototype is developed to support an experimental evaluation of critical performance parameters.

Experimental testing is conducted to assess the system's response under representative loading and environmental conditions and to validate modeling assumptions. Discrepancies between predicted and observed behavior prompt targeted refinements of sensing strategies, data processing algorithms, and system integration. These feedback loops between modeling, prototyping, and testing progressively reduce uncertainty and support informed design decisions.

Outputs: (i) Continuous monitoring of building stability and structural integrity; (ii) early detection of anomalies, degradation, or maintenance needs; (iii) actionable diagnostic information to support maintenance and safety decisions.

Capabilities: (i) Sensor systems (e.g., strain, acceleration, displacement, temperature, or vibration sensors); (ii) data acquisition and communication infrastructure; (iii) computational architecture for data processing, storage, and analytics; (iv) algorithms and programming code for signal processing, condition assessment, and anomaly

detection; (v) user interface and visualization tools for monitoring and decision support; (vi) system integration architecture enabling interoperability among hardware and software components.

Cosmetics: (i) Design of the user interface, including dashboards, alerts, and visualization of the system's health; (ii) visual layout and presentation of monitoring information to enhance clarity and usability.

In this project, the levels of prototyping fidelity are as follows:

- **Verbal Fidelity:** Conceptual descriptions of system architecture, monitoring objectives, and data flows to align stakeholders and define requirements.
- **Basic:** Block diagrams, sensor layout sketches, and basic interface mock-ups used to evaluate usability, system integration, and spatial constraints.
- **High Fidelity:** A fully integrated monitoring system incorporating representative sensors, data acquisition hardware, validated algorithms, and operational user interfaces, enabling experimental performance evaluation in realistic conditions.

4.1.3. Iterative Prototyping and Performance Verification of an Unmanned Aerial Vehicle

This project aims to design a prototype for an Unmanned Aerial Vehicle (UAV) for autonomous navigation through obstacle-rich environments. The design process begins with the exploration of alternative system concepts, assessing availability, feasibility, and integration constraints. Early-stage prototyping emphasizes low-fidelity representations to evaluate usability, spatial constraints, system configuration, and functional layout. These prototypes enable rapid feedback from stakeholders and early identification of design limitations at a minimal cost.

As the design matures, computational modeling is introduced to evaluate performance characteristics and predict system behavior, including stability, control response, and energy consumption. Modeling results are used to prioritize design modifications and to determine the appropriate level of prototype fidelity required for subsequent validation. Based on these insights, a higher-fidelity prototype is constructed to support experimental evaluation of critical performance parameters.

Experimental testing is then conducted to assess the system's response and validate modeling assumptions. Discrepancies between predicted and observed behavior prompt targeted refinements, demonstrating the effectiveness of feedback loops between modeling, prototyping, and testing. This iterative process progressively reduces uncertainty and informs data-driven design decisions.

Outputs: The outputs of the project are: (i) autonomous navigation of the UAV through a predefined set of obstacles, (ii) demonstrated stability, obstacle avoidance, and mission execution capabilities.

Capabilities: (i) The hull's structure provides aerodynamic efficiency and structural integrity.

Powertrain: This includes (i) motors and propellers; (ii) a battery system supporting endurance requirements; (iii) a sensor suite (e.g., IMU, GPS, vision, LiDAR) for navigation and perception; (iv) system architecture, integrating hardware and software components; (v) data handling for sensor fusion and control; (vi) programming code for flight control, navigation, and autonomy; (vii) programming interface for parameter tuning and mission planning.

Cosmetics: (i) An exterior hull design, including form factor, finish, and layout; (ii) visual and structural elements that influence aerodynamics and user perception.

In this project, the levels of prototyping fidelity are as follows:

- **Verbal Fidelity:** Conceptual descriptions and discussions of the system's configuration, mission scenarios, and design assumptions to align stakeholders and define requirements.
- **Basic:** Simplified physical or virtual prototypes with limited autonomy, basic control logic, and placeholder components, used to validate layout, integration feasibility, and core functionality.
- **High Fidelity:** A fully integrated UAV system with operational autonomy, validated control algorithms, representative sensors and power systems, and a refined structural and cosmetic design, enabling comprehensive performance testing.

4.2. Software Design: Design Software to Simulate Material Picking

Software systems are characterized as interactive application systems with three aspects: an interactive user interface, algorithmic expert knowledge, and a large database, the quality of which is determined by human users as they perceive their adequacy as tools. A prototype of a software system serves to demonstrate technical feasibility and enhance communication between the development team and potential or intended users regarding the system's usability and suitability.

This project tends to design an interactive software system for virtual reality (VR)-based crane operation and material handling. Software systems can be characterized as interactive application systems composed of three interdependent aspects, namely, an interactive user interface, algorithmic or expert knowledge embedded into system logic, and a large, structured database. The overall system's quality is ultimately determined by users' perceptions of usability, usefulness, and adequacy as a decision-support or training tool. Within this context, a software prototype serves to demonstrate technical feasibility, validate usability, and enhance communication between the development team and intended users regarding system suitability.

Outputs: (i) A virtual reality representation of a crane performing material pickup and handling tasks and (ii) a visualization of crane motion, load dynamics, and operator interactions within a simulated environment.

Capabilities: (i) System architecture defining modular interactions between simulation, control, and visualization components; (ii) data models representing crane geometry, material properties, and operational parameters; (iii) programming code for simulation logic, control algorithms, and interaction handling; (iv) user interface supporting operator inputs and feedback; (v) hardware capabilities, including computing resources and VR peripherals; (vi) virtual reality capabilities, such as rendering, motion tracking, and immersive interaction.

Cosmetics: User interface design, including the layout, controls, and visual feedback; a virtual crane design, encompassing geometry, textures, motion realism, and environmental context; visual consistency and clarity to support user understanding and engagement; design of the user interface; design of a virtual crane.

In this project, the levels of prototyping fidelity are as follows:

- **Verbal Fidelity:** Conceptual description and discussion of system functionality, interaction scenarios, and intended use cases to align stakeholder understanding.
- **Sketch Fidelity:** Hand-drawn or digital sketches illustrating user interface layouts, crane motion sequences, and interaction flows.
- **Rough:** Low-resolution digital mock-ups or simplified simulations with placeholder assets, used to validate interaction concepts and the system's structure.
- **Basic:** Functional software implementation with limited VR interactions, simplified physics, and basic user interface elements to evaluate feasibility and usability.

- **High Fidelity:** Fully integrated VR system with realistic crane behavior, refined user interface, accurate data representation, and immersive interaction that closely approximates the target system.

4.3. Service Design: Design a Prototype for an Outreach and Recruitment Event

The objective is to design a presentation for a university outreach and recruitment event for prospective students and parents.

Outputs: A presentation that communicates the key highlights of the university, including academic programs, campus life, research opportunities, student support services, and career outcomes.

Capabilities: A large meeting room, student ambassadors, a computer, a projector, a screen, a PowerPoint presentation, and institutional data on the university's highlights (enrollment, programs, achievements, facilities, etc.).

Cosmetics: Use the college or university standard PowerPoint presentation template design, transitions, and animations.

In this project, the levels of prototyping fidelity are as follows:

- **Verbal Fidelity:** An informal verbal walkthrough of the presentation content to validate the messaging, structure, and key talking points.
- **Sketch Prototype:** Text-based slide outlines, storyboards, and presentation flow diagrams.
- **Rough Prototype:** Initial PowerPoint slides with placeholder text and simple layouts.
- **Basic Prototype:** Structured presentation with representative graphics, charts, preliminary branding, and limited animations.
- **High Fidelity:** Fully branded presentation using official templates, refined visuals, polished transitions, and rehearsed delivery, closely approximating the final presentation experience.

Experimental verification was conducted through rehearsal sessions and pilot presentations involving faculty members, student ambassadors, and prospective audience representatives. Feedback regarding content clarity, engagement, visual effectiveness, and message delivery was collected and used to refine the presentation prior to deployment. This validation process ensured that communication objectives and stakeholder expectations were adequately addressed.

Table 4 provides the application of the proposed framework for the practical design examples.

Table 4. Application of the proposed framework for representative design examples.

Design Example	Primary Uncertainty	Dominant Framework Activities	Highest Fidelity Achieved	Validation Method	Primary Decision Supported
Wearable Biomedical Device	Sensor integration, usability, and clinical performance	Creativity, modeling, prototyping, validation	High Fidelity	Experimental gait testing and stakeholder feedback	Device configuration and clinical feasibility
Structural Health Monitoring System	Sensor placement, system integration, and data reliability	Modeling, prototyping, validation	High Fidelity	Experimental performance testing under representative conditions	Monitoring architecture and maintenance strategy

Table 4. *Cont.*

Design Example	Primary Uncertainty	Dominant Framework Activities	Highest Fidelity Achieved	Validation Method	Primary Decision Supported
Autonomous UAV System	Navigation performance, stability, and system integration	Modeling, prototyping, validation	High Fidelity	Flight testing and performance evaluation	Control strategy and system optimization
VR Crane Simulation Software	User interaction, simulation realism, and system usability	Creativity, prototyping, stakeholder evaluation	High Fidelity	User testing and software verification	Interface design and simulation architecture
Outreach and Recruitment Presentation	Communication effectiveness and audience engagement	Creativity, prototyping, stakeholder feedback	High Fidelity	Rehearsal, pilot presentation, and feedback	Content organization and presentation strategy

4.4. Observations from Practical Applications

The representative design examples demonstrate the applicability of the proposed framework across diverse engineering and design contexts, including biomedical systems, structural health monitoring, autonomous vehicles, software development, and service-oriented applications. Although the technical characteristics, stakeholders, and validation requirements differ substantially among these examples, the underlying framework structure remains consistent.

Across all applications, prototyping served as a mechanism for reducing uncertainty, generating knowledge, and supporting engineering decision-making through iterative refinement. The examples further demonstrate that prototype fidelity, validation requirements, stakeholder involvement, and iteration frequency vary according to project objectives, technical risk, and system complexity. Consequently, the framework should not be interpreted as a rigid sequence of activities but rather as a context-sensitive structure that guides the integration of creativity, modeling, prototyping, and verification throughout the design process.

Table 4 summarizes how the proposed framework was applied across the representative examples and highlights the relationship between uncertainty reduction, prototype fidelity, validation activities, and decision-making outcomes.

5. Modular Design and Prototyping

Modular design is a powerful strategy that complements and enhances prototyping by dividing a complex system into smaller, independent, interchangeable, and self-contained modules (or subsystems). Each module performs a specific function, has standardized interfaces, and can be developed, tested, modified, or replaced separately.

Key benefits, when integrated with prototyping, include faster iteration and flexibility, reusability and scalability, parallel development, easier upgrades and maintenance, and risk reduction.

Faster iteration and flexibility enable engineers to develop prototypes and test individual modules independently, such as swapping a motor module or sensor block without rebuilding the entire system. This procedure maximizes the number of concepts tested while minimizing time and cost expenditure. Validated modules can be reused across multiple prototypes, product variants, or even future projects, leveraging economies of scale and reducing redundant effort.

Parallel development refers to cross-functional teams that work simultaneously on different modules, such as a mechanical team on structural components and an electronics team on control boards, speeding up overall prototyping timelines. Modular prototypes facilitate technology insertion, feature additions, or repairs by replacing only affected modules, supporting long-term adaptability and MOSA (Modular Open Systems Approach) principles in defense and complex systems. Isolating failures to specific modules simplifies debugging, troubleshooting, and validation. For example, in a mechanical rodeo simulator, the Stewart platform actuation module, bull body module, and control console module can be prototyped and refined separately. Furthermore, modular prototyping significantly reduces risk.

Examples of modular decomposition vary across engineering applications; however, the underlying principle remains the same: complex systems are partitioned into manageable subsystems that can be independently developed, tested, and refined. Table 5 presents representative examples of modular prototyping across different engineering domains and highlights the associated prototyping benefits.

Table 5. Representative examples of modular decomposition in engineering prototyping.

Example System	Representative Modules	Prototyping Benefits
Autonomous UAV	Airframe, propulsion, navigation, communication, payload	Independent testing, reduced integration risk, rapid iteration
Smart wearable device	Sensors, controller, power unit, communication module, housing	Simplified debugging, modular upgrades, parallel development
Mechanical simulator	Actuation system, control unit, structural frame, user interface	Component-level validation and easier maintenance
Mobile robot	Locomotion system, sensing module, control system, power module	Faster subsystem refinement and scalable development

Combining these approaches creates an efficient prototyping approach and should begin by designing the system architecture with modularity in mind from the outset by defining interfaces, standardized connectors, and functional partitioning, and prototype modules rapidly by using 3D printing, off-the-shelf components, or simulation tools.

Module prototypes can be assembled into system-level tests; iterated by modifying or replacing individual modules based on the test results. Then, they can transition seamlessly from prototype to production, where modular design supports scalability, customization, and future upgrades.

Furthermore, prototyping processes drive validation and refinement in engineering design, while modular design amplifies efficiency by enabling focused, parallel, and reusable development. Together, they form a basis of modern product development, particularly for complex mechanical, electromechanical, or mechatronic systems such as simulators, robotics, or automotive subsystems. This approach is especially valuable in resource-constrained or fast-paced environments, allowing engineers to explore more ideas, fail faster (and learn), and deliver robust, adaptable solutions.

6. Conclusions and Discussion

This paper proposed a generalized prototyping framework for engineering design that integrates creativity and ideation, modeling and analysis, prototyping strategies and execu-

tion, and experimental verification within a unified iterative structure. Unlike many existing prototyping approaches that focus on specific tools, technologies, or application domains, the proposed framework provides a context-sensitive and decision-oriented structure that explicitly links uncertainty reduction, fidelity progression, stakeholder involvement, and validation activities throughout the design process. The framework was motivated by the increasing role of prototyping in modern engineering design due to advances in additive manufacturing, digital engineering, and rapid prototyping technologies.

This study highlights several important conclusions:

- Prototyping should be viewed as a decision-oriented activity rather than a standalone development phase. Effective prototyping supports uncertainty reduction, risk management, and informed engineering decision-making within specific design contexts.
- Prototyping dimensions are strongly interconnected. Creativity, modeling, experimentation, fidelity selection, stakeholder involvement, and validation should not be treated independently but as co-evolving activities throughout the design lifecycle.
- Prototyping strategies are inherently context-dependent. The appropriate prototype fidelity, scope, timing, and validation approach depend on system complexity, technical risks, manufacturability requirements, and stakeholder objectives.
- Modern engineering systems require integrated physical and virtual prototyping approaches. Emerging technologies such as digital twins, artificial intelligence, and hybrid simulation–experimental environments are reshaping prototyping practices and increasing the need for generalized prototyping methodologies.

Despite its potential benefits, the proposed framework has several limitations. First, the framework is conceptual in nature and has been developed through the synthesis of engineering design and prototyping literature rather than through extensive empirical validation. Consequently, its effectiveness in improving design outcomes, reducing development time, or enhancing decision quality has not yet been quantitatively established. Second, the framework does not prescribe specific numerical thresholds, optimization criteria, or decision algorithms for selecting fidelity levels or determining stage transitions, as these decisions remain dependent on the project's context and engineering judgment. Finally, while the framework is intended to be broadly applicable across engineering domains, domain-specific constraints, regulatory requirements, and organizational practices may require adaptation of the framework for particular applications. Future research should focus on validating the framework through industrial case studies, comparative project analyses, and longitudinal investigations across diverse engineering contexts.

The proposed framework is intended as a process-oriented and decision-support structure rather than a rigid prescriptive methodology. Its primary contribution lies in providing an integrative perspective that connects creativity, modeling, prototyping, validation, and fidelity progression within a single framework while preserving the flexibility required for domain-specific implementation. By integrating creativity and ideation, modeling and analysis, prototyping strategy and execution, experimental verification, and fidelity progression within a unified iterative structure, the framework provides a systematic perspective for organizing prototyping activities across diverse engineering contexts. Future research should focus on empirical validation through industrial case studies, comparative assessments against existing prototyping approaches, and the development of quantitative decision-support methods for fidelity selection, uncertainty management, and stage-transition planning. Such efforts will help establish the practical effectiveness of the framework and further strengthen its applicability to emerging engineering systems.

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