

The ATraMS Methodological Framework for Assessing Biomimicry Design Failure in Industrial Design Innovation

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ABSTRACT

Biomimicry is increasingly recognized as a sustainability-driven approach in industrial design; however, its translation into viable industrial applications remains inconsistent. Many biomimicry concepts fail during development due to limitations in interpreting biological principles and aligning them with technical and production constraints. Despite this, existing research predominantly focuses on successful applications, with limited attention to systematic failure evaluation. This study proposes the ATraMS conceptual framework as a structured methodological tool for assessing failure risks in biomimicry design. Developed through literature review and thematic analysis, the framework integrates four critical dimensions: appreciation, transformation, manufacturability, and scalability. A qualitative evaluation model is applied to seven conceptual design case studies to examine feasibility across these dimensions. The findings identify transformation as the most influential factor affecting design failure, with weak translation of biological principles significantly reducing feasibility regardless of manufacturability or scalability. In contrast, designs demonstrating balanced performance across all dimensions exhibit lower failure risk. While the study is limited by its conceptual and qualitative nature, the ATraMS framework contributes a systematic approach for early-stage evaluation, supporting more rigorous decision-making and improving the reliability of biomimicry industrial design outcomes.

Keywords: Biomimicry, Industrial Design, Failure Evaluation, Design Methodology, Sustainability

INTRODUCTION

Biomimicry has gained significant attention as an innovative and sustainability-driven approach in industrial design, deriving solutions from the observation and emulation of natural systems. The literature widely describes biomimicry as a design approach that transfers biological strategies into technological and product development contexts, especially to improve efficiency, adaptability, and environmental performance (Kennedy, 2017). Because nature has evolved optimized forms, structures, and processes over millions of years, researchers argue that it offers valuable models for solving human design problems with lower material use, better performance, and greater ecological sensitivity (Eid & Al-Abdallah, 2024).

In recent years, biomimicry has been increasingly integrated into industrial design education and professional practice, particularly in the context of sustainable innovation. Studies in design education and design thinking show that biomimicry strengthens creative problem-solving, supports interdisciplinary thinking, and helps designers connect biological structure-function relationships with human needs (Jacobs et al., 2022). At the professional level, biomimicry is increasingly positioned within sustainable innovation frameworks because it encourages designers to generate solutions that are not only novel but also aligned with circularity, environmental responsibility, and long-term system resilience (Kanwal & Awan, 2021).

Despite its growing popularity, companies still implement biomimicry concepts inconsistently in industrial contexts. Research suggests that many biomimicry ideas are strong at the conceptual stage but become difficult to realize when designers must translate biological inspiration into technically feasible, manufacturable, and scalable products (Moheb, 2025). Similar implementation barriers are also discussed in adjacent design and manufacturing literature, where feasibility problems often arise from production constraints, weak standardization, and limited industrial readiness (Bănică et al., 2024). This indicates that the core challenge in biomimicry industrial design is not inspiration itself but the reliable transformation of biological principles into workable industrial solutions. A critical limitation in existing research is the strong emphasis on successful biomimicry outcomes, with relatively little attention given to failure or to the reasons why certain biomimicry designs do not advance beyond promising concepts. Existing biomimicry scholarship tends to focus more on methods, educational benefits, and successful case examples than on systematic analysis of rejection, breakdown, or impracticality during product development (Cohen et al., 2016). More broadly, implementation research shows that innovations frequently fail because researchers do not evaluate feasibility, value, adoption, and scale early enough in development. In biomimicry design, the absence of a structured failure-orientated assessment may therefore contribute to inefficient design cycles, higher development costs, and poor implementation outcomes.

To address this gap, this study proposes a failure evaluation framework for biomimicry industrial design, referred to as the ATraMS conceptual framework. The framework is intended to support designers in evaluating biomimicry concepts through key dimensions that strongly influence industrial success, such as economic viability, manufacturability, functional fidelity, and scalability. This direction is consistent with prior research arguing that design and innovation frameworks are more effective when they evaluate feasibility together with performance and value creation rather than relying solely on creative potential (Greenhalgh et al., 2017). By introducing a structured evaluation process, the ATraMS framework aims to strengthen decision-making during the early design stages and reduce the risk of pursuing biomimicry concepts that are inspiring in theory but weak in industrial application.

Furthermore, this study applies the proposed framework to seven case studies of conceptual biomimicry design, derived from different stages of design development, including early exploration, idea generation, and final design outcomes. Case-based application is important because previous biomimicry and design-method studies have indicated that frameworks become more useful when tested across multiple design scenarios rather than discussed only at the theoretical level (Cohen et al., 2016). Through these case studies, the research seeks to identify recurring patterns of weakness or incompatibility in biomimicry design practice, especially across stages where ideas typically shift from abstraction to industrial consideration.

Through this approach, the study contributes both theoretically and practically by offering a methodological tool that bridges the gap between biological inspiration and industrial feasibility, ultimately supporting more effective and sustainable innovation in industrial design. The study also responds to calls in the literature for stronger interdisciplinary methods, improved educational transfer, and more realistic implementation pathways that move biomimicry beyond inspiration toward measurable design performance and sustainable production (Ibrahim et al., 2025). In this sense, the proposed framework may help designers and researchers better understand not only how biomimicry concepts succeed but also why they fail and how such failures can be anticipated earlier in the design process.

LITERATURE REVIEW

Biomimicry in Industrial Design

Biomimicry is defined as an interdisciplinary design approach that draws inspiration from biological systems to address human challenges. In industrial design, biomimicry involves translating natural forms, processes, and systems into functional products and solutions. This approach is commonly categorized into three levels: form-based, process-based, and system-based biomimicry (Fecheyr-Lippens et al., 2017).

Form-based biomimicry focuses on replicating the physical characteristics of organisms, while process-based biomimicry emulates biological mechanisms and functions. System-level biomimicry extends this approach by

incorporating ecological relationships and interactions into design solutions. Collectively, these levels have contributed to advancements in product design, materials engineering, and sustainable systems, with applications in fields such as nanotechnology, architecture, and biomedical engineering (Amin et al., 2019; Nagpal et al., 2018).

Despite its potential, the success of biomimicry in industrial design depends heavily on the designer's ability to accurately interpret and translate biological knowledge into practical applications. This translation process remains challenging due to differences in disciplinary knowledge, difficulties in abstraction, and limitations in applying appropriate analogies between biological and engineering systems (Weidner et al., 2018).

Furthermore, biomimicry in industrial product design has evolved from aesthetic imitation (biomorphism) toward a more function-driven methodology that emphasizes performance and sustainability. Contemporary studies highlight that nature-inspired design can produce multi-functional, lightweight, and energy-efficient solutions (de Sá et al., 2023). By abstracting biological principles, designers are able to address complex engineering challenges, including drag reduction, thermal regulation, and structural optimization, which are critical for the development of next-generation industrial products.

Biomimicry and Sustainable Design Integration

Biomimicry is closely associated with sustainable innovation because it draws from natural systems that function efficiently within environmental limits. Literature reviews show that biological systems are repeatedly described as models for energy efficiency, resource optimization, low-waste cycles, and long-term resilience, which is why biomimicry is often positioned as a strong foundation for sustainability-oriented design and innovation (de Sá et al., 2023).

In industrial design, biomimicry has been applied to reduce environmental impact, improve product performance, and support circular design strategies. Review studies indicate that designers increasingly use biomimicry to guide product conception, material and structural innovation, resource-saving solutions, and sustainability integration across production cycles; this aligns with broader circular design research that emphasizes reduced material use, longer product lifespans, and improved resource efficiency (Rotondo et al., 2025).

However, translating biomimicry principles into industrial applications is not always straightforward. Recent literature reviews note that although biomimicry offers clear conceptual and sustainability advantages, implementation is often limited by fragmented design tools, lack of standardization, difficulties in integration into new product development processes, and wider constraints related to economic feasibility and production systems; this suggests a strong need for more systematic evaluation and decision-support methods in industrial practice (Liu et al., 2025).

Recent scholarly studies emphasize a hierarchical approach to biomimicry application, categorizing sustainable innovation into three distinct levels of abstraction: the organism, behavioral, and ecosystem levels. At the organism level, research focuses on mimicking specific biological forms and morphological adaptations to optimize resource efficiency. For instance, Metwally (2025) highlights how the integration of lattice structures modeled after the internal porosity of bone tissue into 3D-printed construction allows for the maintenance of high structural integrity while significantly reducing overall material consumption. This level of mimicry is increasingly utilized in industrial design to achieve lightweighting and structural optimization that traditional manufacturing methods often overlook. Beyond physical form, the behavioral level explores how organisms interact with their environment to manage energy and environmental stressors. In the context of tropical architecture, Mfon et al. (2024) demonstrate that passive ventilation systems inspired by the complex morphology of termite mounds can effectively regulate internal temperatures. Their findings suggest that these nature-inspired cooling mechanisms can reduce energy loads by 30–50% compared to conventional HVAC systems, presenting a viable pathway for net-zero building performance in warming climates. This shift from mimicking "what nature is" to "how nature acts" allows for more dynamic and responsive sustainable solutions.

Finally, the most holistic approach is found at the ecosystem level, where innovation seeks to replicate the functional principles of entire natural systems. Chayaamor-Heil and Hannachi (2024) argue that this level is essential for the realization of true industrial symbiosis, where industrial parks are designed to mirror the nutrient cycling of a forest. In such models, the waste outputs of one industrial process are utilized as raw materials for another, effectively eliminating the concept of waste in favor of a closed-loop system. By aligning industrial production with ecosystem level dynamics, biomimicry provides a foundational framework for the circular economy, ensuring that human innovation functions within the regenerative boundaries of the biosphere.

ATraMS Conceptual Dimensions in Biomimicry Design

This section forms the core of the literature review, where each dimension directly supports the development of the proposed framework.

Appreciation of Biological Systems

Appreciation refers to the ability of designers to accurately understand and interpret biological systems before translating them into design solutions. Effective biomimicry requires more than visual observation; it demands a deep understanding of the functional principles underlying biological phenomena. This aligns with biomimicry principles that emphasize learning from nature's processes and systems rather than merely replicating its appearance (Coban & Coştu, 2023).

Several studies highlight that misinterpretation of biological systems is a common issue in biomimicry design. Designers frequently emphasize superficial attributes, such as form or appearance, instead of the fundamental mechanisms that facilitate functionality. As a result, designs may achieve aesthetic resemblance but fail to replicate biological performance (Omar & Rahman, 2015; Qureshi, 2022).

Limited interdisciplinary collaboration between designers and biologists further compounds this issue, leading to an incomplete or inaccurate understanding of biological principles. Since biomimicry inherently requires integration across biology, design, and engineering, inadequate appreciation can significantly increase the risk of design failure at later stages (Omar et al., 2022). Therefore, appreciation represents a critical foundation for successful biomimicry translation.

Transformation of Biological Principles into Design

Transformation refers to the process of converting biological knowledge into applicable design solutions. This stage involves abstracting biological principles and adapting them to meet industrial and technical requirements. However, the transformation process is inherently complex, as biological systems operate under conditions that differ significantly from engineered environments. Designers are required to simplify, reinterpret, or modify biological strategies, which may result in the loss of essential functional characteristics. Prior studies demonstrate that the lack of organized translation methodologies leads to discrepancies in biomimicry results. Without a systematic approach, designers often struggle to balance biological inspiration with technical feasibility, increasing the likelihood of impractical or non-functional designs (Appio et al., 2017; Antonini et al., 2022).

Furthermore, the gap between biological knowledge and engineering application highlights a key limitation in biomimicry design. This gap reinforces the need for structured frameworks that support effective transformation and reduce failure risks during the design process (Appio et al., 2017).

Manufacturability Constraints in Biomimicry Design

Manufacturability is a critical factor influencing the feasibility of biomimicry design in industrial applications. Many biological systems involve complex geometries, hierarchical structures, and micro- or nano-scale features that are difficult to replicate using conventional manufacturing processes. Unlike industrial production, which relies on standardized and repeatable processes, natural systems are formed through self-assembly and growth mechanisms. This fundamental difference creates significant challenges in translating biological inspiration into manufacturable products (Lippens et al., 2017; Clayton et al., 2019).

Even when biomimicry concepts demonstrate strong functional potential, they may fail due to fabrication limitations. High precision requirements, specialized materials, and complex production techniques often increase cost and reduce feasibility. For example, biomimicry nanostructures require advanced control at micro- and nano-scales, which remains difficult to scale for industrial production (Amin et al., 2019; Nagpal et al., 2018). This mismatch between biological complexity and industrial capability frequently results in compromised design performance or complete implementation failure. Therefore, manufacturability must be considered early in the design process to ensure that biomimicry concepts are both innovative and practically achievable (Bilici et al., 2021).

Scalability of Biomimicry Solutions

Scalability refers to the ability of a biomimicry design to maintain functionality and performance when applied at larger or industrial scales. While many biomimicry concepts perform well in controlled or experimental settings, they often face significant challenges during real-world implementation. These challenges are commonly associated with fabrication complexity, integration into existing production systems, and cost constraints (Wang et al., 2025; Kantaros et al., 2025). Biomimicry designs that rely on intricate micro- or nano-scale structures are particularly difficult to scale, limiting their commercial viability.

In addition, functional principles that operate effectively at small scales may not translate directly to larger systems, creating further barriers to implementation. As a result, scalability is a key factor determining whether a biomimicry concept can move beyond the conceptual stage. Despite its importance, scalability is often overlooked during early design development, where emphasis is placed on creativity and biological inspiration rather than feasibility. This oversight increases the risk of developing concepts that are difficult or impossible to implement in real-world contexts (Ulhøi, 2015). To address this limitation, scalability considerations must be integrated early in the design process, including evaluation of production systems, lifecycle performance, and long-term feasibility. This approach can improve the likelihood of successfully translating biomimicry concepts into scalable and sustainable industrial solutions (Innovation Inspired by Nature, 2024).

Research Gaps and Synthesis

Although biomimicry has been widely explored as a design approach, existing studies primarily focus on its benefits and successful applications, with limited attention given to failure within the design process. While the literature identifies key challenges related to appreciation, transformation, manufacturability, and scalability, these dimensions are often examined in isolation rather than as an integrated process linking biological understanding to industrial implementation.

As illustrated in Figure 3 (ATraMS framework), a critical gap exists between the transformation stage and the final industrial outcome. Specifically, there is a lack of systematic evaluation to determine whether translated biological principles can be effectively realized in practical and industrial contexts. This gap leads to inconsistencies between conceptual design and real-world application, resulting in high failure risks despite strong initial biological inspiration.

This limitation highlights the need for a structured and integrated evaluation framework that can systematically assess feasibility across all stages of biomimicry design. The ATraMS conceptual framework addresses this gap by linking the key dimensions of appreciation, transformation, manufacturability, and scalability into a unified process. By enabling early-stage evaluation of failure risks, the framework supports more informed decision-making and enhances the reliability of biomimicry industrial design outcomes.

METHODOLOGY

Research Design

This study adopts a qualitative, theory-driven research design to develop and demonstrate the ATraMS conceptual framework for assessing failure risks in biomimicry industrial design. The research follows a structured, multi-phase approach that integrates theoretical development with illustrative application.

The study is organised into three main phases: (1) identification of failure-related factors through a systematic literature review, (2) development of the ATraMS framework based on thematic synthesis, and (3) application of the framework to selected case studies for analytical demonstration. This design enables the integration of existing theoretical knowledge with a structured evaluation model, supporting both conceptual rigor and practical relevance in biomimicry design assessment.

The study is structured in three main phases:

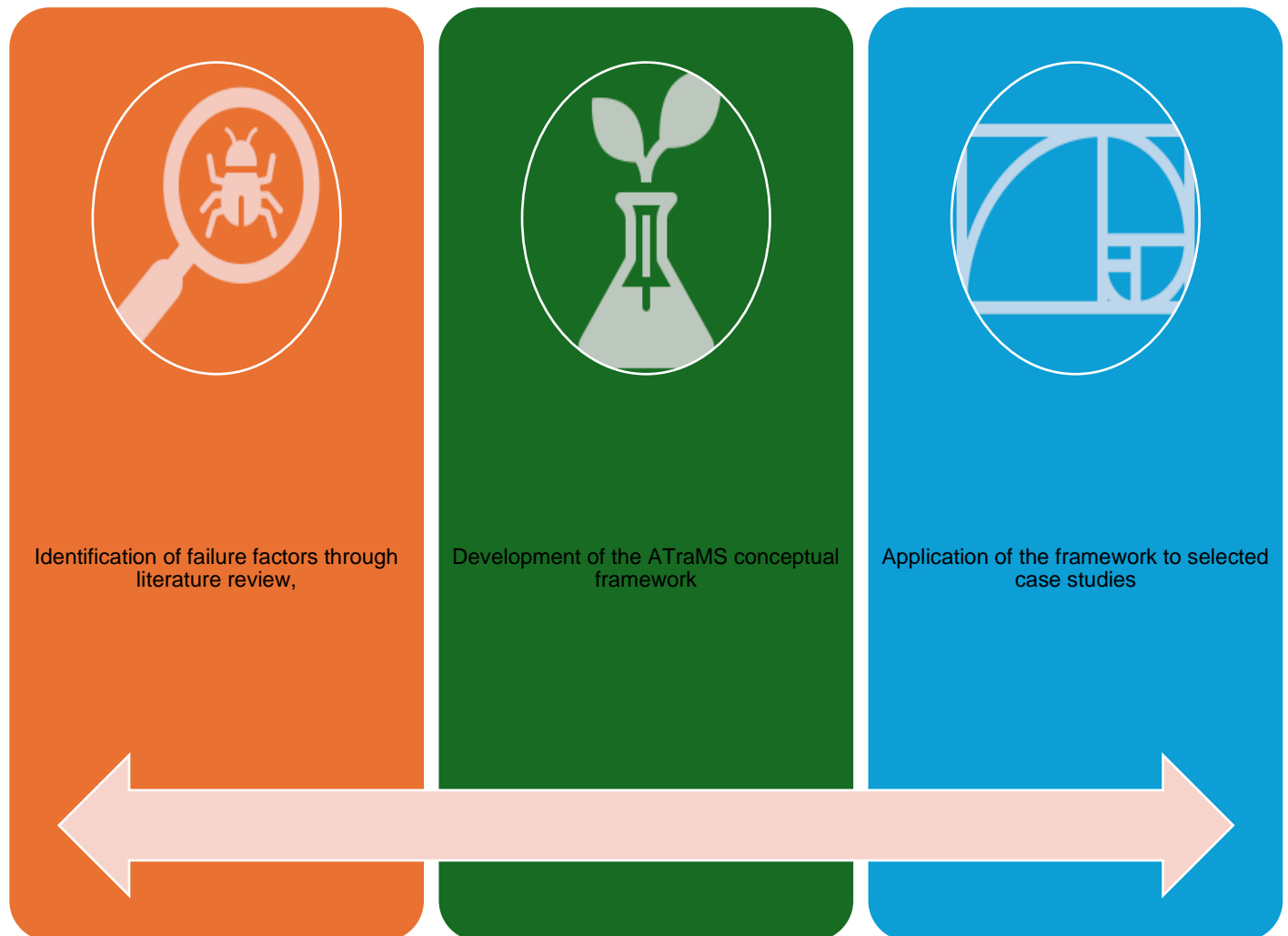


Figure 1: Research Design Process for ATraMS Framework Development

This approach enables both theoretical development and practical illustration of the framework within the context of biomimicry design.

Literature-Based Thematic Analysis

A comprehensive literature review was conducted to identify recurring challenges and limitations associated with biomimicry design in industrial contexts. Academic journal articles, conference papers, and relevant design studies were systematically examined to extract key failure-related themes. A thematic analysis approach was employed to synthesise these findings, allowing for the identification, categorisation, and integration of critical factors influencing biomimicry implementation.

Through this process, four dominant dimensions were identified: appreciation of biological systems, transformation of biological principles, manufacturability, and scalability. These dimensions represent recurring points of failure highlighted across the literature and form the conceptual foundation of the ATraMS framework. The use of thematic analysis ensures a structured and transparent synthesis of knowledge, strengthening the theoretical grounding of the proposed model.

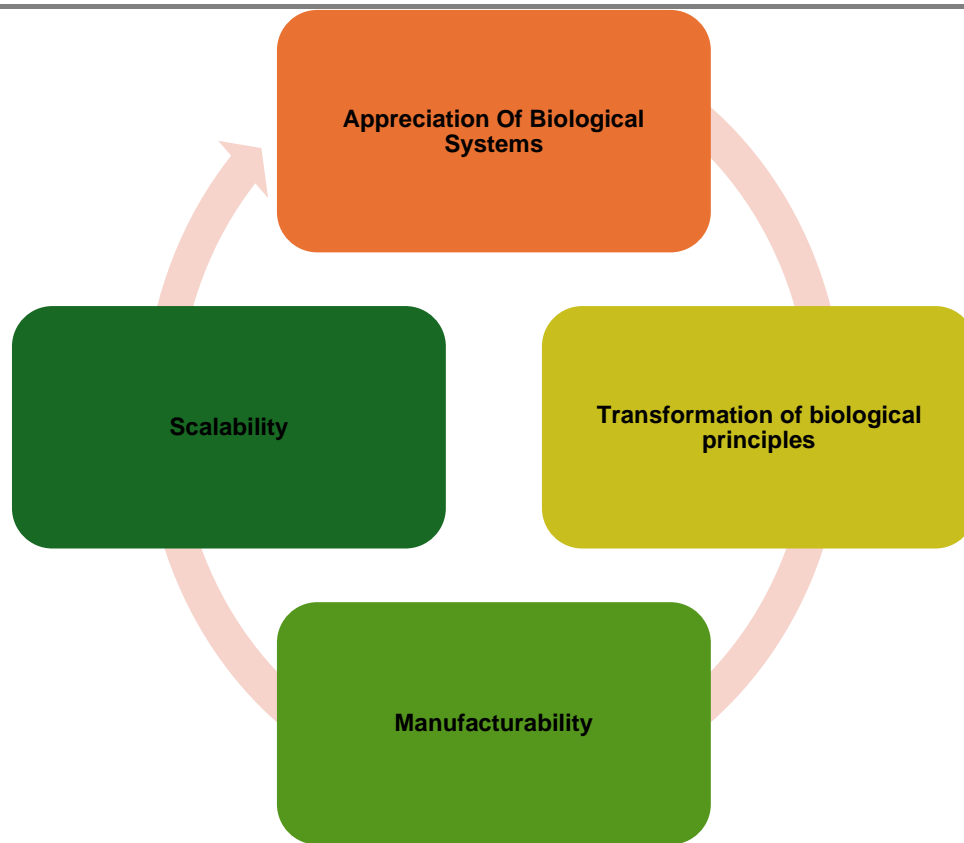


Figure 2: ATrAMS Dimensions Identified through Thematic Analysis

These dimensions form the foundation of the proposed ATrAMS conceptual framework. The thematic approach allows for systematic synthesis of existing knowledge and supports the development of a structured evaluation model.

Development of the ATrAMS Framework

Based on the identified thematic dimensions, the ATrAMS conceptual framework was developed as an integrated evaluation model for assessing failure risks in biomimicry industrial design. The framework combines four interrelated dimensions—appreciation, transformation, manufacturability, and scalability into a unified structure that reflects the progression from biological understanding to industrial implementation.

Each dimension is operationalised through specific evaluation criteria that capture both conceptual and practical considerations in design development. A qualitative scoring system is introduced to assess biomimicry concepts across these dimensions, enabling comparative analysis and systematic identification of potential failure risks. The framework is designed for application in early-stage design evaluation, where critical decisions regarding feasibility and development direction are made.

While the framework provides a structured and systematic approach, it is important to note that its current validation remains conceptual and illustrative. Further empirical application is required to assess its effectiveness in real-world industrial contexts.

Case Study Selection

To demonstrate the applicability of the proposed framework, seven biomimicry design concepts were selected as case studies from the course Industrial Design Applied Industrial Design 1 (IDE615). These cases represent a range of design maturity levels, including early-stage exploration, idea development, and final design outcomes, allowing for comparative analysis across different stages of the design process.

The selected case studies are derived from conceptual design projects and are used as illustrative examples to evaluate the framework. The selection criteria include: (1) relevance to biomimicry principles, (2) variation in

design development stages, and (3) the ability to demonstrate challenges in translating biological inspiration into industrial design solutions. This approach ensures that the cases reflect diverse conditions under which biomimicry concepts may succeed or fail.

To maintain academic integrity, all case studies are presented as anonymized conceptual design cases and are used solely for research purposes. It is important to note that these cases are illustrative and do not constitute empirical validation of industrial implementation.

Framework Application and Evaluation

Each case study was analyzed using the ATraMS framework through a structured evaluation process consisting of the following steps:

- a) Identification of the biomimicry design concept
- b) Description of the biological inspiration and intended function
- c) Evaluation across the four ATraMS dimensions
- d) Assignment of qualitative scores using a five-point scale
- e) Interpretation of failure risk based on the combined evaluation
- f) Evaluation of case studies based on the comparative performance of seven biomimicry design developments across the four ATraMS dimensions.

The scoring system ranges from 1 (very weak) to 5 (very strong), allowing for consistent assessment across all case studies. Lower scores indicate higher risk of failure, while higher scores suggest greater feasibility.

Cross-Case Analysis

Following individual case evaluations, a cross-case analysis was conducted to identify recurring patterns and common challenges across the seven biomimicry design concepts. This analysis enables comparison between cases and highlights which dimensions most frequently contribute to failure risks. The cross-case analysis supports the validation of the framework by demonstrating its ability to reveal consistent trends and insights in biomimicry design practice.

Research Limitations

This study adopts a qualitative, conceptually driven approach to develop and demonstrate the ATraMS framework, which introduces several limitations. The primary limitation is the absence of empirical validation using real-world industrial applications. The framework is evaluated through conceptual case studies derived from design projects, which, while useful for illustrating early-stage design challenges, may not fully capture the complexities of industrial implementation, such as production constraints, cost factors, and market dynamics.

In addition, the qualitative evaluation process involves a degree of interpretative judgment, which may introduce subjectivity in scoring and analysis. Although structured evaluation criteria and a consistent scoring system are applied to enhance reliability, the results remain dependent on the evaluator's interpretation.

Furthermore, the case studies are limited in scope and context, as they are drawn from a specific educational setting. This may affect the generalisability of the findings to broader industrial environments.

Future research should address these limitations by incorporating quantitative or mixed-method approaches, expanding the diversity of case studies, and applying the ATraMS framework to real industrial projects to validate its effectiveness and practical relevance.

Atrams Framework Development

Research Gap

Lack of systematic evaluation between *Transformation* and *Industrial Outcome*



Figure 3: ATraMS Framework for Biomimicry Design

Conceptual Overview of the ATraMS Framework

The ATraMS conceptual framework is proposed as a structured methodological tool for evaluating failure risks in biomimicry industrial design. The framework is developed based on the synthesis of recurring challenges identified in the literature, particularly those related to appreciation, transformation, manufacturability, and scalability. These four dimensions represent critical stages in the translation of biological inspiration into industrial applications.

The ATraMS framework is designed to support designers in assessing the feasibility of biomimicry concepts during the early stages of design development. By systematically evaluating potential limitations across these dimensions, the framework enables more informed decision-making and reduces the likelihood of unsuccessful implementation.

The framework follows a sequential evaluation process, beginning with the identification of a biomimicry concept and progressing through structured assessment and decision-making stages. It integrates both conceptual understanding and practical constraints, bridging the gap between biological inspiration and industrial feasibility.

ATraMS Dimensions and Definitions

The framework consists of four key dimensions, each representing a critical factor influencing the success or failure of biomimicry design.

Appreciation of Biological Systems

Appreciation refers to the ability to accurately understand and interpret the biological system being used as inspiration. This involves identifying the underlying functional principles rather than focusing solely on visual or structural characteristics.

A lack of proper appreciation may result in superficial imitation, where the design replicates the appearance of a biological system without capturing its functional mechanisms. Therefore, effective appreciation requires interdisciplinary knowledge and careful analysis of biological behavior.

Transformation of Biological Principles

Transformation involves converting biological knowledge into applicable design strategies. This process requires abstraction of biological functions and adaptation to meet technical and industrial requirements.

Challenges in transformation often arise due to differences between natural systems and engineered environments. Improper transformation may lead to loss of functionality or oversimplification of biological principles, reducing the effectiveness of the final design.

Manufacturability

Manufacturability refers to the feasibility of producing the biomimicry design using existing or available manufacturing technologies. Many biological structures are complex and hierarchical, making them difficult to replicate using conventional industrial processes. Limitations in manufacturability can result in increased production costs, reduced efficiency, or inability to fabricate the design at all. Therefore, manufacturability must be considered as a key constraint during the design process.

Scalability

Scalability addresses the ability of the biomimicry design to function effectively when expanded from prototype or conceptual stages to real-world industrial applications. While some biomimicry concepts perform well at small scales, they may fail when applied to larger systems or mass production. Scalability considerations include durability, consistency, cost efficiency, and adaptability to industrial production systems. Failure to address scalability can prevent otherwise innovative designs from being implemented successfully.

Evaluation Criteria and Scoring System

To operationalize the ATraMS framework, a qualitative scoring system is introduced to assess biomimicry design concepts across the four dimensions. Each dimension is evaluated using a five-point scale, which is defined as follows:

Table 1: ATraMS Key Evaluation Questions and Indicators

Dimension	Key Evaluation Question	Indicators
Appreciation	Is the biological principle correctly understood?	Depth of biological analysis, functional understanding
Transformation	Is the principle effectively translated into design?	Abstraction quality, design adaptation
Manufacturability	Can the design be produced using available methods?	Fabrication feasibility, material/process compatibility
Scalability	Can the design perform at industrial scale?	Durability, consistency, cost efficiency

The ATraMS key evaluation questions and indicators are used to support clearer analysis of case study factors, including product type, descriptive interpretation, and biomimicry principles.

Table 2: ATraMS Evaluation Criteria by Likert Scale Scoring

Score	Description
1	Very weak (high risk of failure)
2	Weak (significant limitations)
3	Moderate (acceptable but with risks)
4	Strong (minor limitations)
5	Very strong (high feasibility)

The evaluation criteria, based on Likert scale scoring, is employed in a radar graph analysis for each case study to systematically examine the results and provide justification for key issues in the assessment of ATraMS case studies.

Failure Risk Assessment

The evaluation results are used to determine the overall failure risk of a biomimicry design concept. The combined scores across the four dimensions provide an indication of feasibility.

Failure risk is categorized as follows:

1. **Low Risk (Proceed):** Majority of scores are 4–5, indicating strong feasibility
2. **Moderate Risk (Revise):** Scores are mixed, with some dimensions at 3 or below
3. **High Risk (Reject):** Multiple dimensions score 1–2, indicating significant limitations

This classification supports decision-making by guiding designers on whether to proceed with, revise, or abandon a design concept.

Framework Application Process

The ATraMS framework is applied through a structured five-step process:

Concept Identification

Define the biomimicry design concept and its intended function.

Biological Principle Extraction

Identify the biological system and the functional mechanism being emulated.

ATraMS Evaluation

Assess the concept across the four dimensions using the defined criteria.

Scoring and Analysis

Assign qualitative scores and analyze strengths and limitations.

Decision Outcome

Determine the failure risk level and recommend appropriate action (proceed, revise, or reject).

Contribution of the Framework




The ATraMS framework contributes to biomimicry design research by providing a structured and systematic approach to evaluating failure risks. Unlike existing approaches that focus primarily on successful outcomes, this framework emphasizes the importance of early-stage evaluation and critical analysis.

The framework supports more realistic and feasible design development by combining appreciation, transformation, manufacturability, and scalability into one model. It also offers practical value for designers, educators, and researchers by improving decision-making and reducing the likelihood of unsuccessful implementation.

Case Study Analysis

Analysis 1: Understanding of Design principles

Table 3: Analysis on design principles

CASE NO.	TYPE OF PRODUCT	DESCRIPTION	BIOMIMICRY PRINCIPLE
1	<p>CASE STUDY 1 AO-RYU</p> 	<p>AO-RYU is a conceptual water drone inspired by <i>Glaucus atlanticus</i> (blue dragon), designed for aquatic exploration with multiple fin-like extensions for stability and movement.</p>	<p>The design adopts radial symmetry and appendage distribution to enhance buoyancy and hydrodynamic balance.</p>
2	<p>CASE STUDY 2 BEE-WARE</p> 	<p>Bee-Ware is a modular food container inspired by honeycomb geometry, designed for efficient storage and organization.</p>	<p>Applies hexagonal structure for space optimization and material efficiency.</p>
3	<p>CASE STUDY 3 MONTREUX LAMP</p> 	<p>Montreux Lamp is inspired by tulip flowers, featuring petal-like components that open and close to control lighting.</p>	<p>Imitates dynamic petal movement and environmental responsiveness.</p>

<p>4</p>	<p>CASE STUDY 4 HOPE (THE PLANTING KIT PRODUCT)</p>	<p>HOPE is a planting kit inspired by bamboo, designed for plant growth in extreme environments.</p>	<p>Applies bamboo's resilience, strength, and adaptability.</p>
<p>5</p>	<p>CASE STUDY 5 LIGHTING PAPERBACK</p>	<p>Lighting Paperback is a recyclable bag inspired by butterfly wings, focusing on foldable structure and visual aesthetics.</p>	<p>Uses symmetry and visual patterns of butterfly wings.</p>
<p>6</p>	<p>CASE STUDY 6 E-VIS</p>	<p>E-VIS is a turbine device inspired by the aerodynamic body of the peregrine falcon, designed for water or wind energy generation.</p>	<p>Applies streamlined form to optimize fluid flow and energy efficiency.</p>
<p>7</p>	<p>CASE STUDY 7 BLOOM PORTABLE WATER PURIFIER</p>	<p>Bloom is a portable water purifier inspired by the lotus seed pod, designed for clean water access.</p>	<p>The design is inspired by the structural pattern of lotus seed pod</p>

Analysis 2: The Result ATraMS Scores Across Case Studies

Table 4: ATraMS cross analysis

Case	Product	A	Tra	M	S	Risk Level
1	AO-RYU Drone	4	3	2	3	Moderate
2	Bee-Ware Container	5	4	4	5	Low
3	Montreux Lamp	4	3	3	3	Moderate
4	HOPE Planting Kit	4	4	4	5	Low
5	Lighting Paperback	3	2	2	3	High
6	E-VIS Device	4	4	4	4	Low–Moderate
7	Bloom Purifier	3	2	4	4	Moderate–High

The table summarizes the evaluation of seven biomimicry case studies based on the four ATraMS dimensions: appreciation (A), transformation (Tra), manufacturability (M), and scalability (S), alongside their corresponding risk levels. The results reveal distinct performance patterns that differentiate successful, moderate, and high-risk designs. A key trend is that low-risk cases (Case 2 and Case 4) demonstrate consistently high scores across all four dimensions. These designs show strong biological understanding, effective transformation into functional solutions, and high feasibility in both manufacturing and scalability. This balanced performance indicates that successful biomimicry design requires alignment across all ATraMS stages rather than excellence in only one area.

In contrast, high and moderate-high-risk cases (Case 5 and Case 7) are characterized by low transformation scores. Despite Case 7 having relatively high manufacturability and scalability, its weak transformation highlights a lack of logical connection between biological inspiration and product function. This suggests that transformation is the most critical factor influencing design success, outweighing even practical feasibility. The moderate-risk cases (Case 1 and Case 3) show uneven performance, particularly in manufacturability. For example, Case 1 has strong appreciation but low manufacturability due to complexity and cost issues, while Case 3 reflects balanced but average scores, indicating partial success without strong optimization. Case 6 represents a balanced engineering-driven approach, achieving high scores across all dimensions with only slight limitations, resulting in a low–moderate risk level. This suggests that technically grounded biomimicry may provide more reliable outcomes.

Overall, the table demonstrates that effective biomimicry design depends on the integration of biological understanding, functional translation, and practical feasibility, with transformation emerging as the most influential factor in determining success or failure.

Analysis 3: Case Study Evaluation

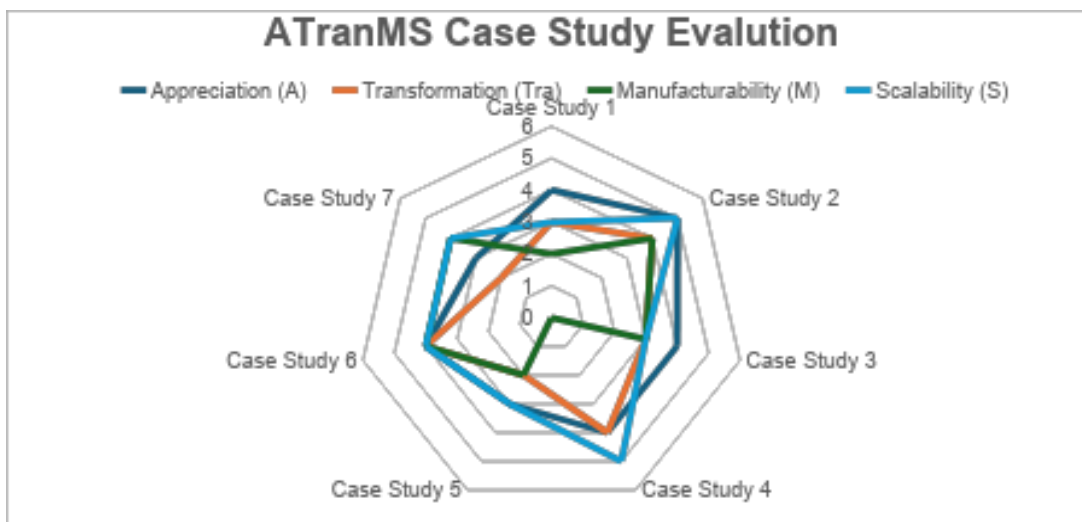


Figure 4: Radar Chart of ATraMS Evaluation Across Seven Case Studies

The radar chart illustrates the comparative performance of seven biomimicry case studies across the four ATrAMS dimensions: appreciation, transformation, manufacturability, and scalability. Overall, the chart shows that most cases achieve relatively high scores in appreciation, indicating that designers generally demonstrate a satisfactory initial understanding of biological systems. However, performance becomes more inconsistent in the later stages, particularly in transformation and manufacturability.

A key pattern observed is the significant variation in transformation (Tra) scores, which directly correlates with failure risk. Case Studies 2, 4, and 6 maintain strong, balanced profiles across all dimensions, reflecting effective translation of biological principles into functional design. In contrast, Case Studies 5 and 7 show clear weaknesses in transformation, resulting in distorted radar shapes and higher failure risks. This confirms that transformation is the most critical stage influencing biomimicry design success.

The chart also shows how manufacturability (M) affects feasibility. Case Studies 1 and 3 show noticeable drops in manufacturability, indicating challenges related to complexity, cost, and production processes. These limitations contribute to their moderate failure risk, despite having relatively strong appreciation scores. In terms of scalability (S), successful cases demonstrate consistent high values, suggesting that designs with clear functional logic and simple structures are more adaptable to real-world applications. Conversely, cases with weak transformation or high complexity show reduced scalability, limiting their practical implementation. Overall, the radar chart reinforces that successful biomimicry design requires a balanced performance across all ATrAMS dimensions, with transformation acting as the central factor linking biological understanding to industrial feasibility.

Summary of Analysis

The three analyses collectively demonstrate that while designers generally exhibit strong initial appreciation of biological systems, the success of biomimicry design depends primarily on effective transformation and practical feasibility. As shown in the ATrAMS scores and radar chart, cases with balanced performance across all dimensions achieve lower failure risk, whereas weak transformation leads to higher failure regardless of manufacturability or scalability. This finding is significant as it justifies the need for a structured evaluation framework like ATrAMS, highlighting that biomimicry should prioritize functional translation over aesthetic imitation to ensure successful industrial application.

CONCLUSION

This study examined the limitations and failure risks associated with biomimicry in industrial design by proposing the ATrAMS conceptual framework as a structured methodological tool. While biomimicry is widely recognised for its potential to support sustainable innovation, the findings indicate that its implementation is frequently constrained by challenges in translating biological principles into feasible industrial solutions.

The application of the ATrAMS framework across seven case studies demonstrates that successful biomimicry design depends on the integration of four key dimensions: appreciation, transformation, manufacturability, and scalability. Among these, transformation emerges as the most critical factor influencing failure, as ineffective translation of biological principles significantly reduces design feasibility regardless of strengths in other dimensions. This finding highlights the need to prioritise functional interpretation over aesthetic imitation in biomimicry design practice.

The study contributes to the field by introducing a failure-oriented evaluation framework that extends beyond existing approaches, which predominantly emphasise successful outcomes and creative inspiration. By incorporating feasibility-driven dimensions, ATrAMS provides a more balanced and practical perspective for early-stage design assessment and decision-making.

However, the study is limited by its reliance on conceptual case studies and qualitative evaluation. Future research should focus on empirical validation through real-world industrial applications and the integration of quantitative or mixed-method approaches to strengthen the framework's reliability and generalisability. Overall,

the ATrAMS framework offers a foundation for more systematic, critical, and feasible development of biomimicry design solutions.

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