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TRL-based mapping of biomimetic projects: identification of development patterns and their influencing factors

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ABSTRACT: This study proposes a framework to map biomimetic innovation progress along TRLs and identify recurring development patterns. Pilot results reveal stagnation between TRL 2–4, linked to generic upscaling struggles and biomimetic-specific barriers. Emerging hypotheses suggest early onset of upscaling challenges post-POC and influence of biological model knowledge on progress. Study insights open paths for methodological work to bridge POC obtention and validation difficulties, and for further use of the framework on bigger datasets, to build a baseline for biomimetic innovation development.

KEYWORDS: bioinspired design, new product development, TRL crossing, development patterns

1. Introduction

Biomimetics, or Bio-Inspired Design (***BID***) is the practice of using biological strategies to solve practical problems (ISO 2015). By emulating biological systems, structures, and processes, designers aim to create innovative, efficient, and sustainable technologies. Despite its recognised potential for innovation (Bar-Cohen, 2006; Keshwani et al., 2017), and a couple success-stories, biomimetics has struggled to produce market-ready products (Jacobs et al., 2014).

Literature acknowledges the difficulty of upscaling, notably through the work related to the "valley of death" in innovation (Markham et al., 2010; Ellwood et al., 2022; Helman, 2023) and identifies struggle in doing so in biomimetic innovation development (Chirazi et al., 2019; Perricone et al., 2021; Banken & Oeffner, 2023). However, to the authors' knowledge, no study has yet explicitly identified a generic strain for biomimetic projects to validate specific Technology Readiness Levels (***TRL***), nor the influencing factors behind this difficulty. This raises a critical question: ***how can we detect and characterise faltering in biomimetics innovation development?***

This article addresses the question by exploring how to highlight the difficulty of progressing along the TRL scale, particularly of transitioning from lab-scale to industrial-scale readiness, in biomimetic projects. It proposes a framework to pinpoint development tendencies and obstacles specific to biomimetic innovation and presents preliminary findings to support this approach.

2. State of the art

2.1. Identified obstacles throughout and around BID

Biomimetics faces multiple obstacles, both within the design process and its broader context. A major challenge is understanding complex biological mechanisms, as misinterpretation can lead to incorrect principles and flawed designs (Wolff et al., 2017; Wang et al., 2023). Collaboration with biologists helps

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bridge this gap but introduces challenges of interdisciplinarity, as diverse expertise often lack a shared language (Graeff et al., 2021).
Translating biological strategies into engineering solutions is equally demanding, due to the disruptive nature of BID and the conceptual distance between biology and engineering (Helms et al., 2009; Vattam & Goel, 2013). Although numerous methodological tools have been developed to support BID steps (Zhang et al., 2025), industrial adoption remains limited, hindered by low awareness and scarce training opportunities (Chirazi et al., 2019; Nagel et al., 2019; Graeff, 2020).
Time is another barrier: biomimetic projects often span for 5 to 12 years (Vilha 2018), contrasting with current demands for rapid innovation cycles (Paun, 2018). High perceived risk combined with few market successes beyond iconic examples like Velcro, winglets, and Speedo's sharkskin swimsuit further heighten uncertainty for investors (Jacobs et al., 2014).

2.2. The upscaling problem

Developed by NASA in the 1970's, Technology Readiness Levels (TRLs) provide a standardised way to assess technology maturity across its lifecycle. The TRL scale has nine levels, marking a technology's journey from concept to full deployment. Each level acts as a milestone for moving products through development phases and serves as benchmarks for communication at the launch of new technologies (Garg et al., 2017). The product development process is linked to the TRL scale as follows (Bonvillian, 2017): Basic research (TRL1-2), Research to prove feasibility (TRL 2-4), Technology development (TRL 3-6), Technology demonstration (TRL 5-7), System/subsystem development (TRL 6-9), System test, launch and operations (TRL 8-market).
The term "upscaling" refers to improving technology maturity from laboratory to industrial scale, essentially validating TRLs 4 to 7 and crossing the valley of death (Riondet et al., 2022). While no studies systematically document a lag after TRL 4 in biomimetic projects, evidence suggests significant attrition: "69% of valuable ideas failed to become viable products" (Jacobs et al., 2014; Chirazi et al., 2019).
Scalability is a major factor, many biological principles work only at their native scale and lose functionality when adapted to engineering dimensions, especially nano- and microstructures (Perez et al., 2011; Perricone et al., 2021). This scaling uncertainty, combined with complex mechanisms, often leads to high manufacturing constraints, requiring precision tools or specialised materials (Pugliese & Graziosi, 2023).
Technological advances such as additive manufacturing have eased some challenges, though issues remain in reproducibility and large-scale production (Herdiana et al., 2022; Ciulla, 2023). Consequently, many bio-inspired concepts remain confined to prototypes or niche applications (Hélix-Nielsen, 2012; Perricone et al., 2021; Wang et al., 2023).
Overall, upscaling is time-consuming and empirical, requiring extensive analysis of biological principles prior to technical application (Chirazi et al., 2019; Graeff, 2020). Additional barriers include unclear project vision, the multiplicity of variables in abstracting biological mechanisms (Vincent, 2017), and the high time and financial costs inherent in disruptive R&D processes (Lebdioui, 2022).

3. Proposed framework

The approach taken in this study to map out biomimetic project advancement along the TRL scale, and the influencing factors around it takes root both in theory, through literature review, and practice, through feedback from experienced individuals.
Highlighting specific troubles in development, means mapping out development in the first place, which consists here, in building "TRL curves" for existing biomimetic projects. A "TRL curve" is a representation through time, of the advancement of a biomimetic innovation during its development, along the TRL scale. Building TRL curves entails knowing the "story" of an innovation, meaning all the milestones it has reached or not reached, and in which time frame.
To gather the necessary data, the authors picked interviews as a vector of information, since both qualitative and quantitative data can be extracted from them. Indeed, the expected outcomes of the final version of this study is to have quantitative data informing on TRL advancement in biomimetic innovations, and qualitative data to identify the influencing factors around it.
Interviews were conducted as semi-directive, so needed information would automatically be provided, without closing the door on discussion around addressed topics to try and dig out conscious and unconscious challenges, and struggles met by the interviewees during biomimetic innovation

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development. The following topics were dealt with for each project: Context of launch, Organisation and governance, Development process and TRL validation, Resources and financing, R&D and technical innovation, Industrialisation and commercialisation, Overall feedback.
Information gathered via interviews was completed by a survey. The point of having two sources of data was to get the same individuals to give different kind of feedback. Interviews aimed to collect project-specific data for building TRL advancement curves and understanding each innovation's development story, while the survey sought participants' views on factors influencing biomimetic project progress. The purpose of the survey was to induce taking a step back in respondents, and get their opinion on biomimetic projects in general, the experience they gained through maybe participating in multiple, the differences they see towards non-biomimetic project development.
Survey questions used a 1–5 Likert scale, asking respondents to rate propositions or indicate agreement with statements. Here is an example of a survey question: "Assess the extent to which each of the following factors contributes to the difficulty of increasing the TRL level (1 = Low; 5 = High)". All propositions were drawn from design science literature to ensure validity and comparability.
For this first test-run of the framework, eight interviews were conducted with individuals experienced in BID, complemented by a survey sent to all participants. They were held via Teams or during the XIXth edition of the French conference on Biomimicry, Biomim'expo. Participants, contacted through email or LinkedIn, had direct experience in biomimetic innovation as team members or project managers.
The panel of interviewees and studied projects is summed up in the following table:

Table 1. Panel composition

Structure	Number in panel	Number of projects	Project in Figure 1
Academic entity	1	2	A ; E
Start-up	3	4	B ; D ; F ; H
Company	2	5	C ; G ; I ; J ; K

In total, 11 projects were mapped out, as some interviewees belonged to entities hosting multiple biomimetic projects. Projects sit at diverse stages of development : 3 are in the very early stages (Projects I, J, K), 3 are in the pre-industrialisation phase (Projects A, E and G), 2 are undergoing tests in makeshift conditions (Projects F and H), 2 are in the later stages of development (Projects B and D), and 1 is going through standard compliance (Project C).
Field of applications are varied in the panel: electronic systems, civil engineering, data storage, electricity transport, biodiversity restoration, air treatment, and cameras.

4. Results

For the pilot phase of the proposed framework, a first batch of results was obtained through 8 interviews, and 5 survey answers that led to the mapping of 11 projects. Since the panel utilised in this work is of limited size, findings from result analysis cannot be considered as facts but can orient hypothesis and assumptions around biomimetic development patterns and their influencing factors.
For all but 3, projects started at TRL 1 and advanced to TRL 2 in the first six months to a year of development. Project E (purple curve) represents an exception, reaching TRL 3 in that time.
Two projects which had a higher initial TRL, showed similar advancement, with a growth of one TRL along the first year of development. However, the light green curve (F) displays a very rapid headway, with validation of TRL 5 from TRL 2 within its first year.
Seven out of the 11 mapped projects entered a stationary phase after TRL 2. A plateau is also visible at TRL 3 or 4 for projects that went faster up to those points. This indicates struggles in the validation of said TRLs. The projects appear stuck at the same TRL for one to two years, before advancing again and breaching the ceiling they were under. Overall, this phenomenon occurs between the first six months of the project, and the second to third year of development.
Once out of their stationary phase, projects appear to make good headway, with a mean of 1,5 TRL validated during the following year.

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4.1. TRL curves

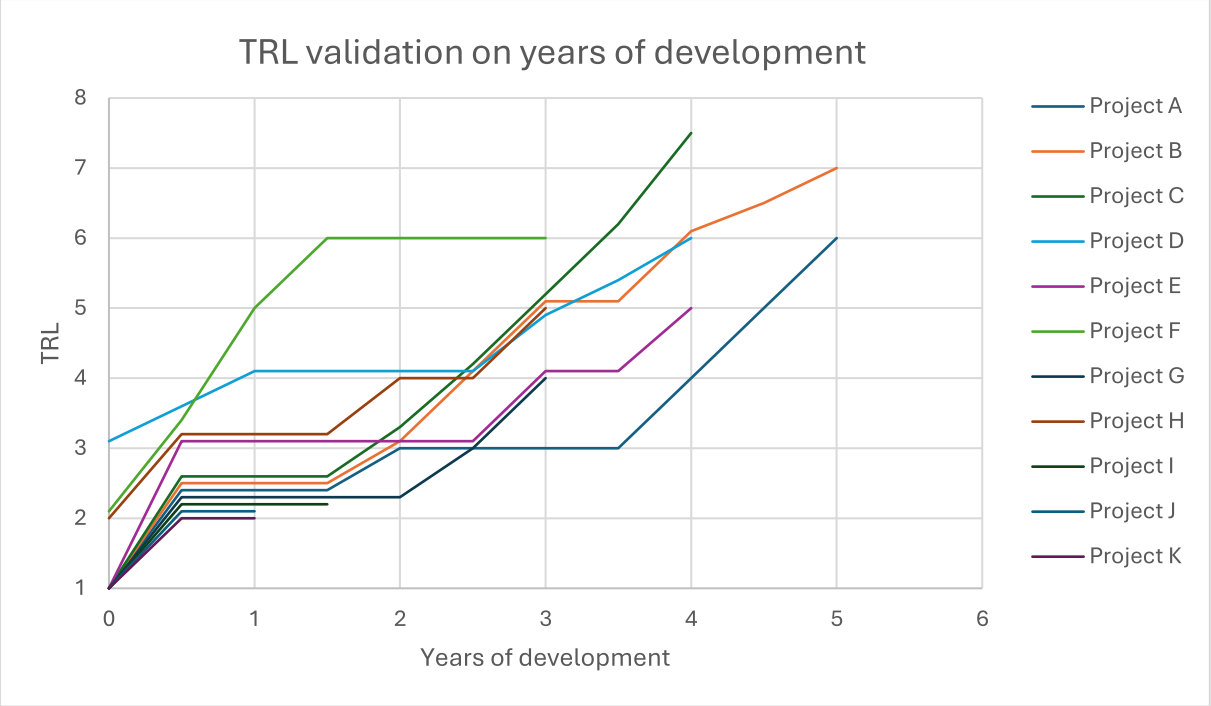


Figure 1. TRL validation on years of development (curves are willingly positioned a slight offset on the graph to improve readability; studied projects started between 2016 and 2015; data displayed on the graph is restricted from project initiation to year 5 of development)

Three projects, A, E and H, follow staircase-like development curves, with two stationary phases at TRL 2 and 3 for project A and at TRL 3 and 4 for project E and H.

Although the panel utilised in this work is of limited size, the purpose of the work is to build a strong framework to assess struggles around specific TRLs. Solid foundation stem from the use of reliable data processing tools. In this mindset, each curve was fitted with a sigmoid model (Equation 1):

$$f(x) = \frac{\mathrm{L}}{1 + e^{-\mathrm{k}(\mathrm{x}-\mathrm{x0})}} \tag{1}$$

This model was selected as it provided the optimal goodness-of-fit for the trends observed in Figure 1, yielding the highest coefficient of determination (R^2) and the lowest Root Mean Square Error (RMSE). This fitting enabled the extraction of essential parameters: asymptote (L), slope (k), and inflexion point (x_0).

For each curve, L was considered as the highest reached TRL and so varies from project to project. High k values point to rapid progression along the TRL scale, and high x_0 values would signify a slow start from a project. Indeed, for the latter, as the inflexion point is the time when half the highest reached TRL value (L) has been obtained, the higher this value is, the longer it took to reach half the TRL the project currently sits at.

The slope, k, and inflexion point, x_0, allowed for clustering amongst projects, which was done through HAC (Hierarchical Agglomerative Clustering). Processing of the 11 projects studied here led to 3 clusters: [A,B,C], [D,E,F,G,H], [I,J,K]. The third one, [I,J,K], can be discarded as it contains very young projects, only existing for a year to a year and a half, and currently standing at TRL 2. Nevertheless, the first two clusters were separated along k and x_0 values, leading to a group with both a slow start and slow progression [A,B,C], but which accelerated later on, and a second group[D,E,F,G,H], which seem to have known a faster start, and now follow a rather slow consistent progression along the TRL scale.

With the aim of getting more data, and differentiating parameters, speed of TRL validation per year was calculated per project per TRL segment (TRL 1 to 2, 2 to 3, 3 to 4, and so on). What came out of this analysis is that TRL 2 to 3 and 3 to 4 segments seem to go slower than other segments, with a mean of 1,08 (SD = 0,29) and 1,22 (SD = 0,28) TRL validated per year. Projects A, B, and C were going as low as a speed of 0,66 TRL validated/year on the TRL 2 to 3 segment. In comparison, the mean speed of all

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segments is 1,47 TRL validated/year, thus putting said segments below it. The fastest segment is TRL 1 to 2, with a speed of 2 TRL validated/year, and so, for all studied projects.
Discarding very young projects [I,J,K], the mean speed of TRL validation/year for the rest of the projects if of 1,36 TRL/year.
Another interesting data is the time spent for the TRL 2 to 3 and 3 to 4 segments compared to the time duration of the entire project. The 7 projects in our panel that have gone beyond TRL 4 spent on average more than half their duration time between TRL 2 and TRL 4 (59%). For example, out of the 4 years of development of project C, 2 of them were spent between TRL 2 and TRL 4, so 50% of the time spent on the project to validate two TRLs, whilst 4 levels were crossed in the remaining years.

4.2. Survey results

The survey was distributed among the 8 interviews participants; 5 answers were collected from the survey. Respondents are from different structures: one from an academic entity, three from start-ups and one from a large company. All have years of experience in the biomimetics field, and multiple experiences in biomimetic innovation development. Two of the individuals have professional experience in non-biomimetic innovation development as well. Survey questions used a 1–5 Likert scale, asking respondents to rate propositions or indicate agreement with statements. All propositions were drawn from design science literature to ensure validity and comparability. Answers were then processed to generate PCAs.
The first PCA examined the contribution of literature-identified factors to the difficulty of ascending the TRL scale. The model captured 77.3% of the total inertia (Dim 1 + Dim 2), indicating a representative overview of the dataset. Variable representation quality was assessed via $\cos^2$ calculations.
Results indicate a robust localisation for factors such as "Standard compliance," "Market uncertainty," and "Complex ROI prediction," and a satisfactory localisation for "Lack of key expertise" and "Difficult manufacturability." The analysis splits factors into two categories: Barriers to TRL crossing and Low-impact factors.
The first category contains the factors "Difficult manufacturability", which exhibits the strongest correlation with TRL stagnation, as well as "Standard compliance," "Market uncertainty," and "Complex ROI prediction", which are identified as major impediments. The second category (Low-Impact Factors) is mainly composed of the "Lack of key expertise" factor, which correlates with the axis representing weak contributions, suggesting it is not a primary bottleneck in this context.
Certain variables, notably "Lack of clear POC process" and "Lack of specialized financing", occupied central, unreliable positions in the projection space (low $\cos^2$). This poor positioning, and the variance observed in factors like "Departmental silos", likely reflects structural heterogeneity among respondents. The panel comprised diverse profiles (academics, start-uppers, large company members), leading to context-dependent evaluations. For instance, academic entities are less constrained by standardisation as industrial actors, creating a division of opinion that dilutes the statistical signal for these specific variables.
A second PCA evaluated how specific biomimetic elements influence development speed. This model demonstrated excellent reliability, explaining 94.4% of the variability, with almost all variables showing high representation quality ($\cos^2 > 0.8$).
Development constraints were separated in two groups through PCA analysis:

- Major decelerators: The "scale difference between biological and technological worlds" and the inherent "complexity of biological systems" are strongly correlated with development delays.
- Minor influences: Organisational factors such as "unfamiliarity of teams with biology" and "scepticism about the approach" were associated with only a moderate-to-weak influence on slowing down the process.

Unlike the first analysis, this dataset showed high consensus among respondents, apart from the element "accessibility of biological knowledge." This variable was excluded from interpretation due to its poor representation and extreme divergence in respondent scoring.
Figure 2 below shows a simplified display of the factors identified as influential or not on difficult TRL ascension through pilot PCA results.

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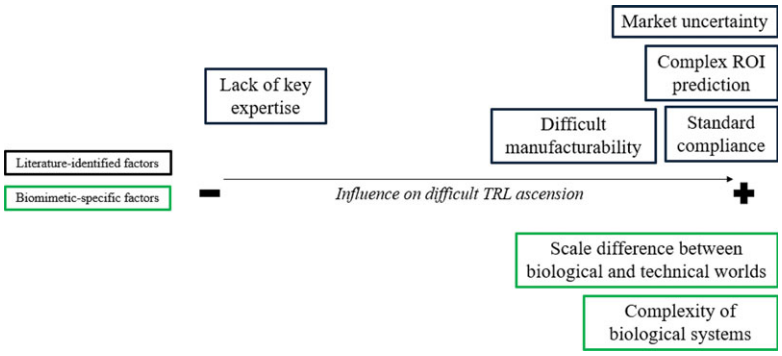


Figure 2. Influence of factors on difficult TRL ascension

5. Discussion

The point of this article was to propose a framework of highlighting struggles at specific point and time during innovation development. The chosen method was to gather existing biomimetic project development stories so both advancement along the TRL scale and general experience of development (highs and lows, encountered barriers, project organisation . . .) could be determined.

The data was then processed to obtain differentiating parameters, so clusters of projects, and tendencies of development could be spotted. The idea was not only to identify development patterns but also to try and explain what they could stem from, and what they could be influenced by. To do so, interviewees were asked through a survey if literature-known factors that hinder development were also, to their knowledge and experience, applicable in biomimetics. To push the analysis a bit further, they were also asked if biomimetic-specific elements contributed to development slow down, and if so, were they additional to the previously mentioned non-biomimetic factors?

Regarding development patterns for biomimetic innovations, two main tendencies are underlined by the first results.

The first one is that development starts off strong. The initial step of formulating concepts seems to be straightforward, as most projects validated a TRL 2 within the first six months to a year, making the segment from TRL 1 to 2 the fastest of the levels to be validated. A concept is considered here as an idea, detailed and drawn on a standardised "idea card", stating a name for the concept, the biological model it is inspired by, the abstracted principles wished to be transferred, benefits and limitations of the concept, and a scheme representing roughly what is in mind.

When it comes to innovation development, biomimetics can adopt one of two approaches, referred to as problem-driven, and solution-based (Hashemi Farzaneh et al., 2016). The former refers to the development of a biomimetic innovation to fix a known practical problem; the latter consists in spotting an interesting biological mechanism and finding an area where such a system could be useful.

The studied projects in the pilot phase of the framework are split unevenly among these approaches, with 7 problem-driven and 4 solution-based innovations. In the batch of data available here, no difference seems to occur between a problem driven and solution-based innovation regarding concept generation as all validated TRL 2 quite quickly. This assumption however needs to be further verified in future works, because elaborating a solution to a known problem and finding an application for a known solution are very distinct and different pathways.

The second tendency is that biomimetic development appears to go through mid-stage stagnation. In other words, it seems that validating POCs and going past these "idea cards" is a complex task. Indeed, the frequent occurrence of stationary phases, observed in seven out of eleven projects, highlights a critical bottleneck in advancing beyond TRL 2. During these stationary phases, the speed of TRL validation stands at its lowest, which underlines the difficulty of validating a POC and thus TRLs 3 and 4. Going as a unit with a slow development speed, TRLs 2 to 4, is also where the development process spends most of its time, strengthening the assumption that the effort required to validate intermediate stages is disproportionate compared to other stages.

What makes validating a POC complicated? A proof of concept is a demonstration, at a basic level and lab scale of the technological feasibility of an idea, meaning that through a POC the workings of the function of interest are validated. Validating a proof of concept entails many actions from the project host. They must design and perform laboratory experiments to test the concept, which means determining the criteria of concept validation, accessing the required testing infrastructure, obtaining funds to support

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the tests . . . Depending on who the project host is, and the arguments in favour of the project, addressing these needs can be complicated. Additionally, tests to validate POCs sometimes follow a trial-and-error process, which feeds iteration cycles and only grows the time and resources consumption.
On top of these potentially complicated actions, feedback from the experienced individuals gained through the interviews informed us on a lost and perplexed feeling amongst projects hosts on what do to with the idea cards. One individual mentioned that they struggled to project the formulated concepts further in the development process. They didn't know how it could be manufactured, how it could fit in the existing chain of value. They recognised the concept as worthwhile but hassled to wrap their heads around the feasibility, preventing the elaboration of criteria to assess it, or to understand how it could be done. Another individual explained that the tough part for them was not having enough physical and mathematical data to build very basic and small numerical models or prototypes of the biomimetic concept they were currently elaborating. The individual felt like that was a major issue, which was strongly responsible for the project being on standby the following year (curve C on Figure 1). This type of understanding is precisely what is needed to build the proof-of-concept tests and validate feasibility. Takeback from what has been said is that there appears to be a lack of understanding and information around the biological mechanisms to be able to build a basic replica of the function of interest, which opens the door to future methodological work.
As seen in the state-of-the-art part of this work, upscaling and the difficulties associated to it, are no stranger to literature. What this second observation points to is that biomimetics encounters the same struggles. However, upscaling is usually considered after POC validation, and what is underlined here are difficulties in obtaining the POC. Maybe, the fact that a concept takes its technical roots in a biological system complexifies the process of obtaining a POC (as a transfer must occur from biology to the chosen application) which resonates with early-on struggles in development. A hypothesis could be made and should be further investigated, that a biomimetic-specific pattern of development is an early start in upscaling difficulties.
The clustering analysis leads the assumption that there are two possible trajectories for biomimetic innovation development: Cluster 1 [A,B,C]: Slow start, later acceleration: Cluster 2 [D,E,F,G,H]: Fast start, steady but slower growth
This divergence may reflect differences in project scope and resource allocation. Projects with a slow start might involve highly novel biomimetic principles requiring extensive exploratory research, whereas faster starts could be leveraging well-documented biological strategies or benefiting from prior groundwork. A hypothesis around biomimetic innovation development could then be that projects grounded in well-characterised biological models progress more predictably, while those exploring less understood phenomena experience delayed, but potentially disruptive breakthroughs once foundational knowledge is secured.
One main pattern seems to take place during biomimetic development: ***stagnation around concept validation***. It has been mentioned that it could be due to the complicated requirements of doing so, as well as due to the testing process. However, slow down in upscaling is a known phenomenon in innovation. Factors such as "Difficult manufacturability", "Standard compliance", "Market uncertainty", and "Complex ROI prediction" have been identified as responsible for difficult TRL crossing in non-biomimetic innovation, and according to the pilot phase results, take on the same tendency for biomimetic innovation development.
Other slowing down factors have been brought to light by the tested framework, such as the "scale difference between biological and technological worlds" and the "complexity of biological systems". The proneness of these specifically biomimetic elements to influence development leads to think that other elements, not yet identified, also partake in boosting or hindering the development process. An extension of the framework employed in this work could dig out such findings.

6. Conclusion and prospects

This article aimed to place the first stones in mitigating the lack of studies dealing with biomimetic development patterns and tendencies, specifically around TRL crossing. To open the door to such studies, the work articulated itself around the question of how to detect and characterise moments of faltering in a biomimetic innovation's development journey. A framework was proposed to map biomimetic innovation advancement along the TRL scale, and to point out factors influencing development and leading to recurring patterns.

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This framework was tested through a pilot phase, and preliminary findings were presented to support this approach. While sample size rules out definitive statistical generalisation, the analysis conducted through sample results serves as a proof-of-concept. It demonstrates the framework's capacity to identify and categorise systemic struggles and validates its use on larger datasets in future research iterations.

The construction and analysis of TRL curves led to the underlining of one main development pattern, which is stagnation around concept validation. This phenomenon happens from TRL 2 to TRL 5, associating high effort to the validation of TRLs 3 and 4.

Biomimetic development slow down appears to be linked to both generic upscaling struggles and biomimetic-specific barriers, namely on the technical aspect of the approach (difficult manufacturability, complexity of biological mechanism, scale differences between biology and engineering), but also on the business side of things (uncertainty of market, complex ROI prediction . . .).

Hypothesis around biomimetics development patterns were elaborated thanks to the data acquired through the framework. Future work could test if upscaling troubles do start earlier (as soon as POC obtention), for biomimetic innovations, and could dive on which troubles exactly. Another hypothesis revolves around the amount and quality of existing knowledge on the chosen biological model, and on how it influences development.

Although pilot results are promising, they should be nuanced as they indicate tendencies rather than support statements on biomimetic development patterns and their influencing factors. Indeed, relying on a small dataset, sigmoid curves are sensitive to noise and PCA loses relevance.

The proposed framework can be optimised and should consider bridging the following limitations when applied to bigger and more representative datasets.

One clear limit the framework carries is that only time was used as a reference to assess advancement along the TRL scale. It could be interesting to add "allocated resources" along development to see the impact they might have on it. Indeed, the number and availability of people working on the project, the allotted budget, the management and organisational structure, all certainly play a role in the advancement of a project, and influence development.

Another addition could be on the analysis of the data provided by the framework, specifically the qualitative, subjective data acquired through the interviews. A lot of worthwhile feedback relies in the transcripts of interviews, and the use of thematical analysis and triangulation tools would render this data fit for statistical analysis and would substantially strengthen the identification of influencing (boosting or hindering) factors around biomimetic development.

Improvements on the framework could deal with its current stativity. Indeed, TRL curves provide a linear, time-based view but fail to capture iterative loops, parallel developments, or pivots, which are common in biomimetic projects. The incorporation of dynamic modelling or systems mapping to represent feedback cycles and non-linear progress could be interesting. The framework is static in the way that it is descriptive and works in a reactive manner by mapping past trajectories of existing projects. Once a strong baseline of biomimetic development tendencies, all the way to market residence, is built, prospective studies and forecasting of risks and bottlenecks would be a strong addition.

Nevertheless, now that the struggles of validating POCs, and upscaling are being brought to light, the question is rather on what could be done to lift the identified bottlenecks. Feedback from interviewees opens the door to methodological works with the expressed struggle of understanding the biological mechanism and the lack of information around it, particularly to be able to build a basic replica of the function of interest. There seems to be a gap in methodology to transfer from a concept to a prototype. One lead that could be investigated on this topic is the integration of parametric modelling to help with concept projection and reduce iterative cycles.

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