A CASE STUDY OF MULTIFUNCTIONAL NON-PNEUMATIC TIRE DESIGN FOR THE VALIDATION OF META-LEVEL DESIGN PARAMETER IN DOMAIN INTEGRATED DESIGN (DID) METHOD

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ABSTRACT

The work introduced two novel multiscale multifunctional tire designs developed using the Domain Integrated Design (DID) method and modelled with the LatticeQuery geometric modelling software. Furthermore, this research validates the meta-level parameter "interaction area" proposed for selecting biological analogy in the DID method. These two use cases were simulated with Abaqus. The concepts covered in this work are an example of multi-functional design. The obtained results validate the meta-level parameter derived from the DID methodology.

Keywords: Bio-inspired design / biomimetics, Computer Aided Design (CAD), Conceptual design, Creativity, Design methods

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Cite this article: Velivela, P. T., Letov, N., Kong, L., Zhao, Y. F. (2023) 'A Case Study of Multifunctional Non-Pneumatic Tire Design for the Validation of Meta-Level Design Parameter in Domain Integrated Design (DID) Method', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.5

1 INTRODUCTION

Strategies inspired by natural systems have inspired engineers and scientists to develop highly efficient and sustainable products and processes. Implementing nature's strategies is not straightforward and often requires a procedural approach for correct emulation. Many frameworks, methods, and tools have been developed to aid such a complex process. A comprehensive study on biomimetics by Wanieck et al. (2017) defines frameworks as a sequence of steps or procedures to be followed while emulating nature's principles. Methods describe the way of performing steps in the emulation process. On the other hand, tools assist in performing steps in the emulation process. The development of various processes for emulating nature's strategies has led to the evolution of multiple terms that define such processes, such as biomimetics, biomimicry, bio-inspiration, bio-replication, and bio-inspired design (Lenau *et al.*, 2018). Bio-inspired design (BID) can be defined as an approach that uses analogies to biological systems to extract innovative solutions to solve difficult or complex engineering problems (Helms *et al.*, 2009; Vattam *et al.*, 2011). A newly developed method called Domain Integrated Design (DID) has been developed to assist engineers and scientists in developing multifunctional and multiscale conceptual designs (Velivela *et al.*, 2021). DID is a method that classifies functional biological functional tissues into Surfaces, Cellular Structures, Shapes, and Cross-sections. The final design concept generated combines those functional features that have been classified into domains.

Figure 1 presents the schematic of the classified domains encompassing the function-performing tissues and their corresponding functions. The surface domain contains the Epidermis/Epithelial and Connective tissue from the animal kingdom and the Epidermis tissue from the plant kingdom. Likewise, the Cellular Structure domain encompasses the Connective tissue from the animal kingdom and Simple permanent tissue from the plant kingdom. The sub-domains of the Cellular structure domain are Shapes and Cross-sections containing the Muscular and Connective tissue from the animal kingdom, Complex permanent tissue from the plant kingdom, and Connective tissue from the animal kingdom, respectively. However, convergent evolution plays a vital role in organisms' development – convergent evolution is defined as the same functionality exhibited by different organisms in radically different ways. For example, the drag reduction function is shown by Penguin's spindle-shaped skeletal structure (Yu *et al.*, 2020), Sharkskin surface denticles (Luo *et al.*, 2015), and Dolphin skin surface ridges (Yu *et al.*, 2020). Meta-level design parameters are proposed to select the relevant biological analogy from organisms that exhibits the same functions effectively such as those listed above. This research validates the proposed meta-level design parameter through a case study on the impact resistance of a multifunctional non-pneumatic bio-inspired tire designed by using the DID method. In the case study, the meta-level design parameter varies across the structure. The proposed parameter would further aid designers in selecting the relevant strategies, especially in the case of convergent evolution from the classified domains, for the correct combination to develop multifunctional designs.

The paper is organized as follows. Section 2 discusses the distinction between DID and current multifunctional bio-inspired design methods and proposes parameters for the selection of biological strategy and discusses the existing non-pneumatic tire designs. Section 3 describes the idea and conceptual design of the multifunctional non-pneumatic bio-inspired tire and discusses the LatticeQuery software for CAD modelling. Section 4 presents the analysis performed on the models and results generated, and Section 5 provides the conclusion.

2 DOMAIN INTEGRATED DESIGN META-LEVEL DESIGN PARAMETERS

Several methods have been developed to emulate multifunctional conceptual designs inspired by biological systems. These methods can be categorized as two types. The first category represents the methods with a single source of biological inspiration. The second category represents the methods that have multiple sources of biological inspiration. The Reduced-function-means (R-FM) (Bhasin *et al.*, 2021) and function-means (Svendsen and Lenau, 2020) methods fall under the first category. On the other hand, Compound Analogical Design (Vattam *et al.*, 2008), System-Of-Systems BID (Tan, Sun, *et al.*, 2019), BioGEN (Badarnah and Kadri, 2015), BioTRIZ (Altshuller, 1996), Trimming method (Zhang *et al.*, 2021), Multi-Body Effects (MBE) (Tan, Liu, *et al.*, 2019), and Multi-Bionics (Ren and Liang, 2009; Tan, Liu, *et al.*, 2019) fall under the second category. Most of the methods in

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the second category follow the principle of problem decomposition into sub-problems and then integrate the biological solutions to each sub-problem into one final design. Multi-Body Effects and Multi Bionics follow the principle of biological coupling, where functionality is achieved as a combination of various factors such as structures, materials, and organism morphologies (Ren and Liang, 2009). BioTRIZ and Trimming methods use the TRIZ techniques for generating multifunctional design concepts. Methods that fall under the first category use a single organism as a source of inspiration for achieving multi-functions.

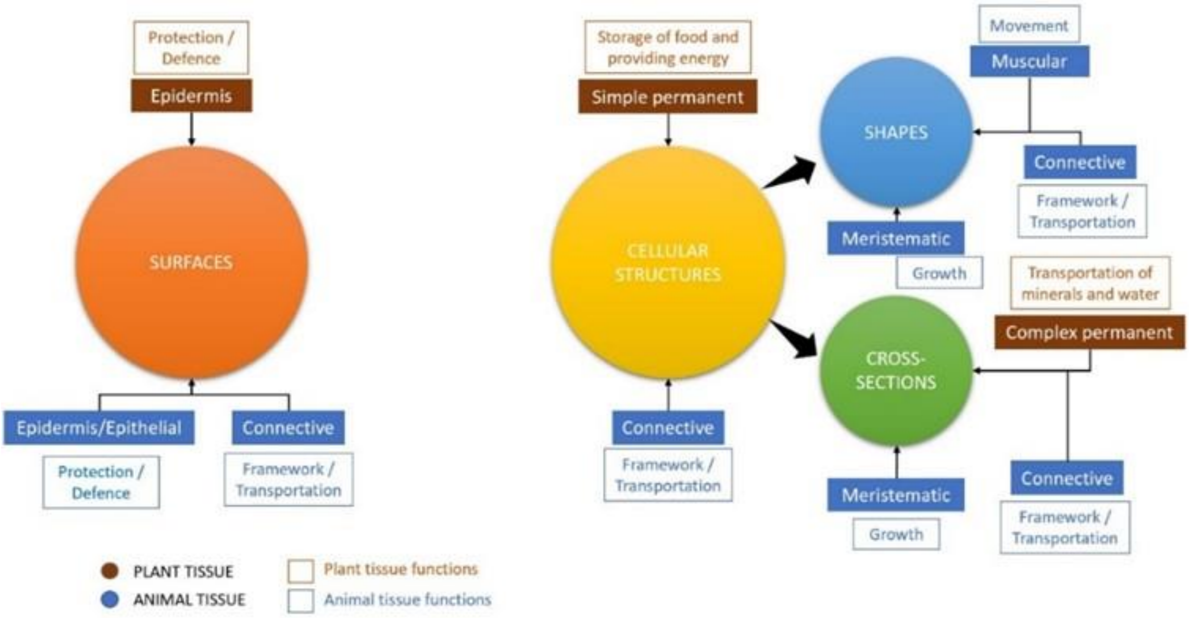

Figure 1. Classification of the functional tissues in animal and plant kingdom into their respective geometric designations named domains

DID is a method developed to facilitate the conceptual design and development of highly efficient products inspired by biological systems. The newly developed non-pneumatic bio-inspired multifunctional tire design is an outcome of using the DID method. The mechanism and application of the DID method provide results superior compared to the previously mentioned methods and are already discussed in the previously published article by the authors on the design of painless sutures (Velivela *et al.*, 2021) and a comparison between other multifunctional bio-inspired design methods and DID (Velivela and Zhao, 2022). As described in Section 1, the method categorizes the function of performing tissues observed in plant and animal kingdoms according to their geometric designations. The categories are named domains; each encompasses the function performing tissues from animal and plant kingdoms. The domains are namely Surfaces, Cellular-Structures, Cross-sections, and Shapes. On the other hand, meta-level design parameters would enhance the ideation process by assisting in selecting a relevant biological analogy.

Figure 2 elaborates the framework of the DID method, where function-performing tissues from multiple biological sources, both from the animal and the plant kingdoms, are classified according to their geometric designations named as domains. This method is used for generating innovative bio-inspired multiscale and multifunctional design concepts. The newly developed non-pneumatic bio-inspired multifunctional tire design proposed for the study in this work is one such concept. In this research, Meta-level design parameters are proposed and validated to select relevant biological analogy for a particular application effectively. In this research, the proposed meta-level design parameters are validated by a case study on the multifunctional bio-inspired non-pneumatic tire design that has effective friction management and is impact resistant. The snakeskin texture for effective friction management and woodpecker and pomelo peel structures for impact resistance inspires the newly developed non-pneumatic multifunctional tire features. A comparison of the impact resistance of a woodpecker's beak-inspired structure to a pomelo peel-inspired structure is simulated for validation of the proposed parameters. Table 1 shows the proposed meta-level design parameters for each domain to assist the designers in selecting the relevant biological analogy under convergent evolution conditions. As described earlier in Section 1, convergent evolution is where distant biological systems exhibit the same functions in radically different ways.

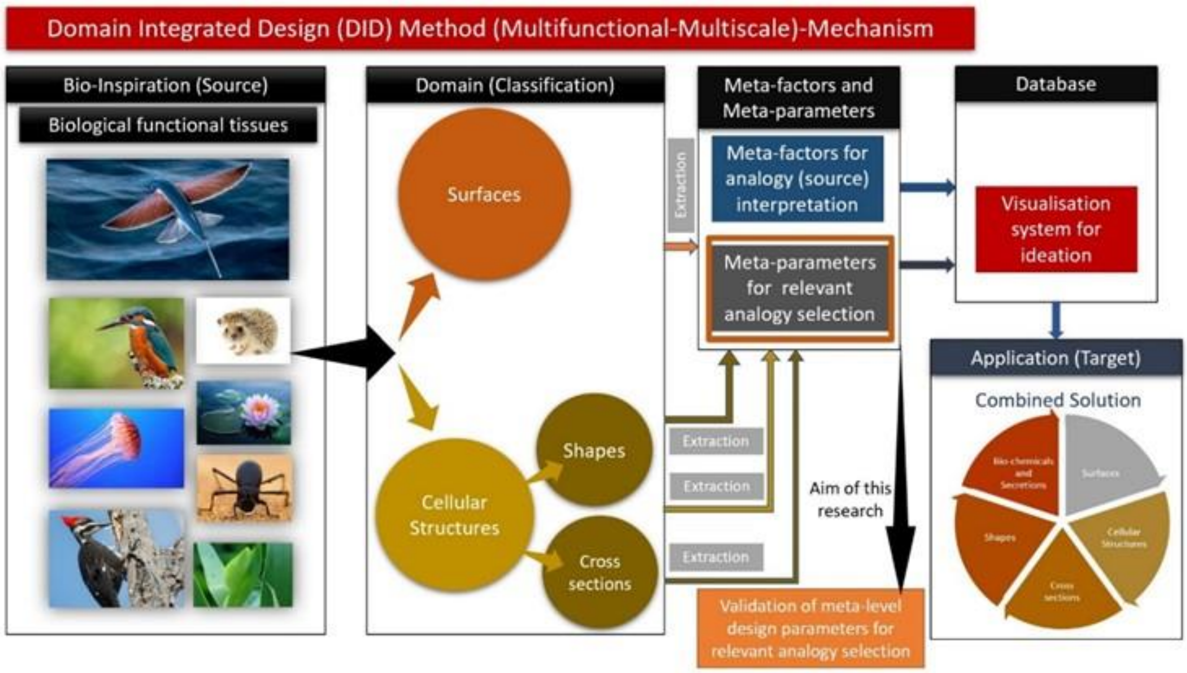

Figure 2. The framework of the Domain Integrated Design (DID) method. The research aims to validate the extracted meta-level design parameter variation for relevant analogy selection

Table 1. The Meta-level design parameters proposed for the selection of relevant biological analogy under convergent evolution

Domain	**Sub-Domain**	**Features**	**Meta-level design factors**
Surfaces	Not Applicable	Micro/Nano	Interaction area and Scale
Cellular Structures	Shapes Cross-sections	Prismatic	Interaction area and Porosity
Cellular Structures	Shapes Cross-sections	Stochastic	Interaction area and Porosity
Cellular Structures	Shapes Cross-sections	Hierarchical	Interaction area and Porosity

Table 2 describes the impact resistance function is solved by two biological systems: pomelo peel and woodpecker’s beak. The pomelo peel and the woodpecker’s beak are classified under the cellular structures domain and represent the stochastic features. However, to select the relevant biological analogy, a hypothesis is derived. The hypothesis is as follows:

- Select features with a higher interaction area and low Porosity for applications with a functional requirement such as adsorption/absorption.

The meta-level design parameter is validated through a case study on the newly developed multifunctional non-pneumatic tire design by using DID method that has effective friction management and impact resistance functions. The proposed meta-level design parameter (Interaction area and Porosity) is proposed to be validated by simulating the impact resistance function of the tire design inspired by Pomelo peel and Woodpecker’s beak, respectively.

The design and development of automotive tires with efficient friction characteristics are essential for passenger transportation and safety. The effective braking distance of an automobile depends upon the change in the friction coefficient according to the change in the speed (Oh and Lee, 2014). However,

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the grip characteristics depend on the elastomer (tire) and surface (road). The tangential contact stresses increase as the friction coefficient. Moreover, they need to be non-pneumatic, have thread blocks, pattern, and shape to overcome obstacles in irregular terrain and be able to take zero-degree turns (Dąbek and Trojnacki, 2016). However, researchers often seek inspiration from biological strategies for designing effective friction management surfaces for advanced applications. Inspired by a cat's soft pad and claws, Vincent et al. (2006) developed a conceptual tire to aid driving in iced and uniced conditions. On the other hand, a mantis shrimp-inspired saddle structure for spokes in a non-pneumatic tire was introduced by Liu and Xu (2022). Likewise, researchers have employed an anti-tetrarchical gradient structure for uniform deformation, resulting in vibration isolation (Wu *et al.*, 2021); the hexagonal honeycomb spokes for high fatigue resistance (Ju *et al.*, 2012); the auxetic materials for shear flexibility (Kolla *et al.*, 2010; Novak *et al.*, 2016); the utilisation of mesostructures for low rolling resistance, high shear flexure and low-energy hysteresis loss (Fazelpour and Summers, 2014). However, one of the prime reasons for advancements in non-pneumatic tire development is the lightweight, high stiffness (impact absorption), and high flexure.

Table 2. Functions, biological system, structure, meta-level design parameter and respective domains

Function	**Biological System**	**Structure**	**Meta-level design parameter**	**Domain**
Efficient friction management	Snakeskin	Microstructure (triangular) on the central ventral and side ventrals (Tiner *et al.*, 2019)	Interaction area and Scale	Surfaces
Impact resistant	Pomelo peel	Porous hierarchical structure (Zhang *et al.*, 2019)	Interaction area and Porosity	Cellular Structures
Impact resistant	Woodpecker's beak	The hyoid bone, carnal bone, and beak bone contain a hierarchical composite structure (Wang *et al.*, 2013)	Interaction area and Porosity	Cellular Structures

3 IDEATION AND CONCEPTUAL DESIGN

A new bio-inspired non-pneumatic multifunctional tire design is developed by using the DID method. Figure 3 shows the schematic sketch of the multi-functional non-pneumatic tire design inspired by snakeskin on the outer surface for effective friction management and woodpecker's beak and pomelo peel for impact resistance. Woodpecker's beak has a varying porosity starting from 30% at the tire interface, 65% in the middle, and 30% at the central region of the tire. Pomelo peel has a varying porosity of 40% at the tire interface, followed by 50% in the middle and 30% at the central region. To evaluate the impact resistance of tires, it is necessary to understand the interaction of the tire and pavement. The tires do not have line contact with the pavement; instead, has a patch. It is observed that in a pneumatic tire, the patch is in the form of an ellipse; for a non-pneumatic tire, the patch is in the form of a rectangle (Kim *et al.*, 2013). The modelling and analysis will be performed on the patches, not the entire tire. The modelling and analysis of snake-inspired texture are not performed. This is because this research aims to validate the meta-level parameter for the selection of correct biological analogy and solve the convergent evolution problem.

Several lattice topologies can be modelled to approximate the original conceptual design. One of the topologies most closely resembling the intended design is the Schwarz Primitive (Schwarz P) surface topology. Geometric modelling is a critical factor affecting a conceptual design's success, such as the novel tire design proposed in this work (Letov and Zhao, 2022). It was decided to use the lattice modelling approach proposed in the preceding work in this stud. This approach allows geometric modelling of lattice structures based on triply periodic minimal surfaces (TPMS) with varying parameters. This framework has been incorporated into the open-source software LatticeQuery. From the industrial analogues of tires, it was found that the tire radius is commonly chosen to be $R = 203$ mm. Since only the point of contact between the tire and the road surface actively participates in the wheel locomotion, a single column in the radial direction can be chosen for the finite element analysis (FEM) simulation. The column for both proposed designs has three regions with different porosities,

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which are sketched in Figure 4. In this sketch, O is the location of the tire axis, and r_I, r_{II}, and r_{III} signify the upper limits of regions I, II, and III, respectively. The three regions are assigned different porosities to represent the natural analogues closely. For the woodpecker-inspired design, the porosities φ_w in regions I, II, and III are $\varphi_{w_I} = \varphi_{w_{III}} = 30\%$, $\varphi_{w_{II}} = 65\%$. For the pomelo-inspired design, the porosities φ_p in regions I, II, and III are $\varphi_{p_I} = 40\%$, $\varphi_{p_I} = 50\%$, $\varphi_{p_{III}} = 30\%$. The column should fit a significant amount of unit cells of the lattice. Thus, it was decided to use the base unit cell size of $u = 3.98$ mm. Woodpeckers are known to have the porous region corresponding to region II elongated in the load direction. Thus, it was decided to have unit cells in the woodpecker region II elongated by 50% in the r-direction.

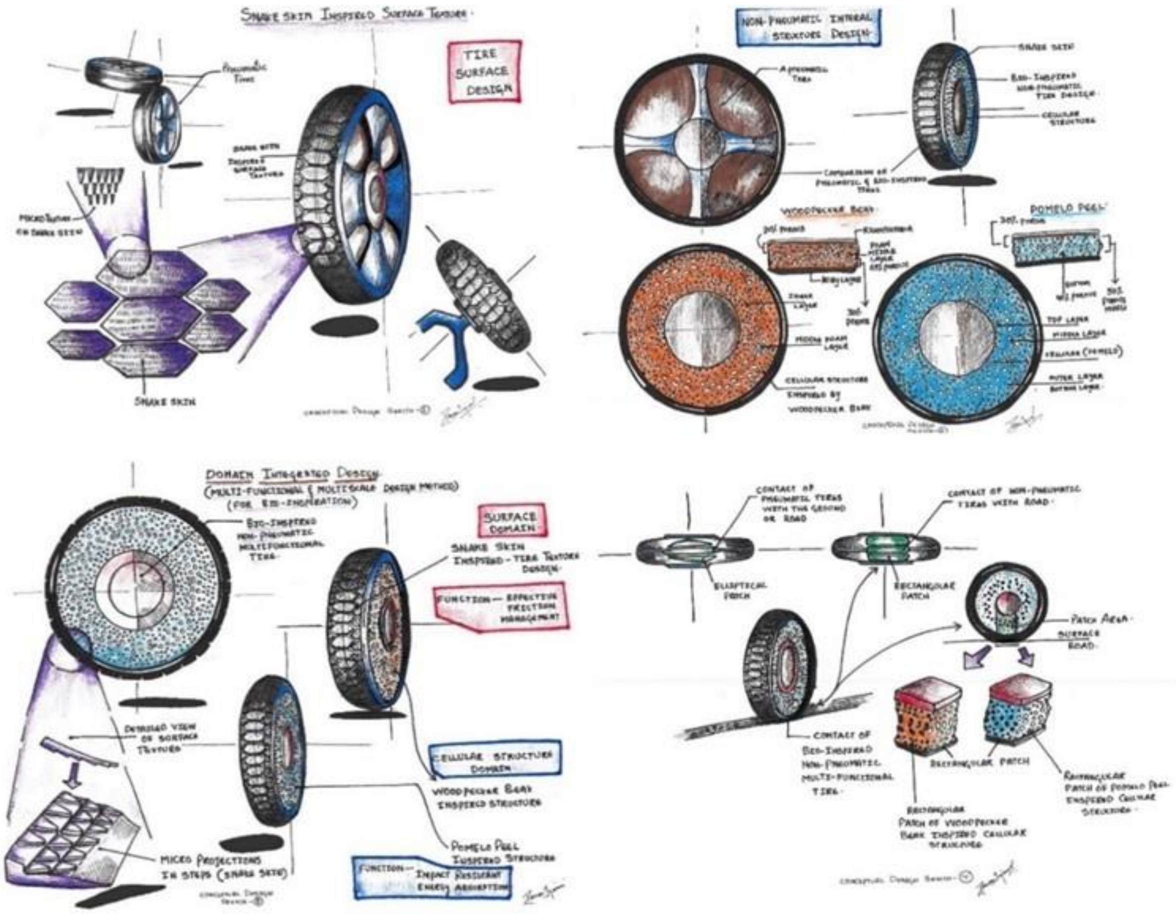

Figure 3. The initial conceptual designs that were produced in the ideation process

LatticeQuery supports setting variable thickness t in a specific direction but not the porosity φ. However, the geometric properties of the Schwarz P surface have been studied well in literature (Gandy and Klinowski, 2000), and these findings were used to estimate its porosity based on thickness t as

$$\varphi = 1 - \rho' = 1 - \frac{At}{V} = 1 - \frac{K(1/4)t}{16K(3/4)u} \tag{1}$$

where ρ' is the relative density of the lattice, $V = u^3$ is the volume of the cubic unit cell, $A = \frac{u^2K(1/4)}{16K(3/4)}$ is the surface area of the Schwarz P surface, and K denotes a complete elliptic integral of the first kind. The 3D print plugin validated the lattice thickness for the Blender computer graphics software, which provided a proper estimate of the volume (Froehlich *et al.*, 2021). It was found that the Porosity $\varphi_{w_I} = \varphi_{w_{III}} = \varphi_{p_I} = 30\%$ can be ensured by $t = 1.34$ mm; $\varphi_{w_{II}} = 65\%$ by $t = 0.61$ mm; $\varphi_{p_{II}} = 50\%$ by $t = 0.89$ mm; and $\varphi_{p_{III}} = 40\%$ by $t = 1.10$ mm.

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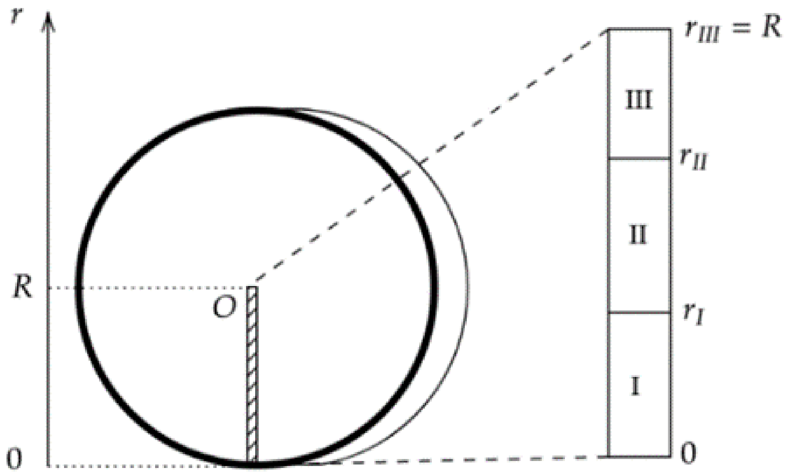

Figure 4. A single column is split into three regions with different porosities

4 RESULTS

The stereolithography (STL) mesh was decided to be simulated with FEM in Abaqus Standard Edition 2021. A contact patch of the tire is commonly subject to loads of $2 \cdot 10^3$ N (Persson, 2011). Since only one column is analysed, it is sufficient to spread this load across $45 \times 11 = 495$ unit cells, resulting in a 4 N load per column. The safety factor for the load on the tire is estimated at 1.125 (Pal Singh, 2010), resulting in a 4.5 N load per column. Elongation was found to be one of the key characteristics that are used to analyse the effectiveness of a tire (Ratrout and Mahmoud, 2006). Rigid polyurethane was chosen as the material for the simulation. Figures 5a and 5b illustrate the result of the FEM simulation for single columns corresponding to the woodpecker- and pomelo-inspired designs, respectively. The maximum values of the magnitude of elongation are 84.77 and 91.20 for the woodpecker- and pomelo-inspired designs, respectively. These values are significantly lower than the estimated elongation at break, which is estimated to be over 200 (Faizah *et al.*, 2019). Note that the region I directly contact the road surface in both cases is the most elongated one. This effect was expected in the conceptual design phase and motivated to provide region I with lower Porosity than the other two regions. Lower porosity results in a higher material interaction area and, thus, lower the deformation.

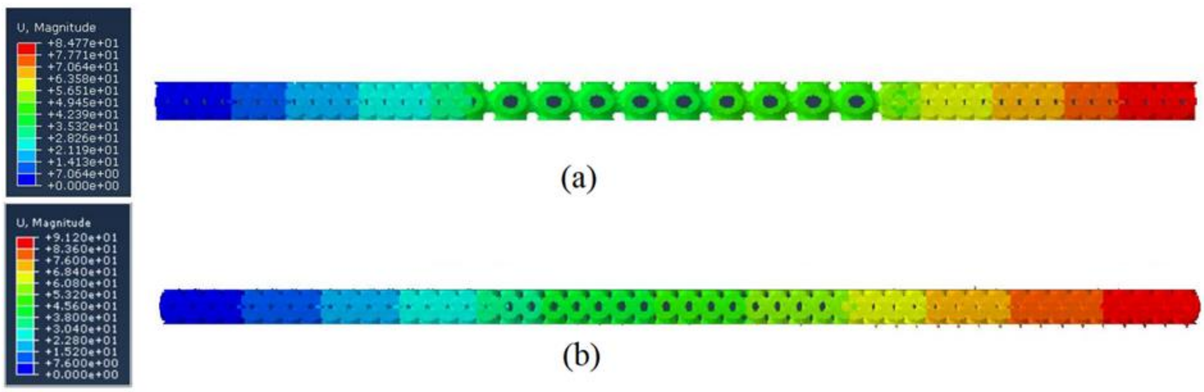

Figure 5. The simulation results show the magnitude of elongation for (a) the woodpecker- and (b) the pomelo-inspired tire designs

It is evident that the woodpecker's beak has a low porosity in region I, which is in direct contact with the road, has a higher interaction area, and thus has a low deformation. This simulation validates the initial hypothesis that is to select the features with a higher Interaction area and low Porosity for the applications involving adsorption/absorption functions. Table 3 compares the Woodpecker's beak and Pomelo peel's interaction area in relation to the Porosity.

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Table 3. Comparison of the impact resistance of Woodpecker's beak and Pomelo peel concerning its Interaction area with the Porosity

Biological System	**Interaction Area**	**Porosity**	**Result**
Woodpecker's Beak	High	Low	High Impact Resistant
Pomelo peel	Medium	Medium	Medium Impact Resistant

5 CONCLUSIONS

The analysis is performed to validate the meta-level parameter "interaction area" proposed for selecting biological analogy in the DID method. Two use cases of novel tire designs were conceptually designed, modelled with LatticeQuery, and simulated with Abaqus. The concepts covered in this work are an example of multifunctional design. The obtained results confirm the initial hypothesis derived from the DID methodology, that is, to select the biological analogy that has a large interaction area for the applications of adsorption/absorption.

Figure 6 describes the overview of the DID method, that is, the classification of the function-performing tissues into their geometric designations named domains. The proposed meta-level design parameters aid in the selection of relevant biological analogy under convergent evolution conditions where distant species exhibit the same functionality. The meta-level design parameters are validated with a case study on the bio-inspired multifunctional non-pneumatic tire design. For future work, it is proposed to conduct experimental tests that would evaluate the tire's mechanical and tribological properties. This experiment could be performed by additive manufacturing tire samples and testing them on a miniature remote control vehicle.

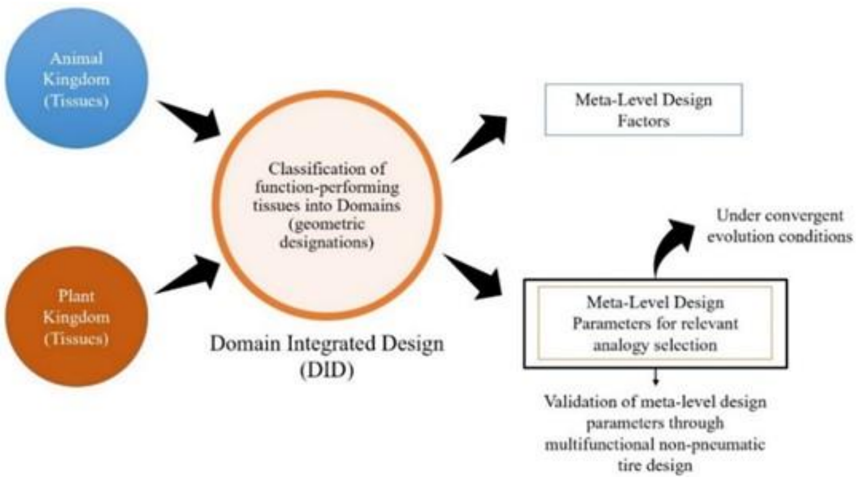

Figure 6. Overview of the DID method and the validation of the meta-level design parameters for the selection of relevant biological analogy

ACKNOWLEDGMENTS

This research work is supported by the Natural Sciences and Engineering Research Council of Canada Discovery Grant RGPIN-2018-05971 and the McGill Engineering Doctoral Award, Canada (MEDA).

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