Journal of Corrosion and Materials *J. Corros. Mater.* (2026) 5(1), 98–112.
www.corromat.com

Topology-Dependent Performance of Additively Manufactured TPMS Materials across Structural, Flow, and Thermal Functions

Marcel Schlaf[1,*]

Department of Chemistry, University of Guelph, Guelph, Ontario N1G 2W1, Canada

[*]Corresponding author: mschlaf@uoguelph.ca

(Received: 27 February 2026. Received in revised form: 11 May 2026. Accepted: 25 May 2026. Published online: 30 June 2026.)

Abstract

TPMS porous architectures offer a way of designing porous and surface-rich light-weight materials based on mathematics, allowing additive manufacturing of the designed materials. The importance of TPMS from a scientific perspective can be found in a core issue of material design, in which the same internal geometry determines fluid access, heat exchange, stiffness, powder removal, fidelity of wall thickness, coatings and environmental stability. In this context, the main question addressed by this study is what should be the choice of TPMS unit topology when mechanical support, permeability, thermal transport and access to the service are taken into account as related design criteria. The approach adopted in the work is to analyze the available literature on TPMS using implicit geometric descriptors, ten design figures and relevant quantified findings reported on TPMS research. Among the data used for the analysis are gyroid superior performance with respect to heat transfer compared to commercial open-cell foam by the factor of 1.07 and ability to dissipate more heat almost twice at the same temperature difference, F-RD structure having 103% higher thermal conductivity and 488% higher stiffness in comparison with stochastic foam at identical porosity, porosity-graded TPMS architectures with reduction of pressure drop by 27.6% while not exceeding 15.7% in heat transfer loss, radial permeability being approximately half the longitudinal one for cylindrical scaffolds, permeability models with prediction differences lower than 5%, and microfabrication processes allowing 5 µm thickness layers or micrometer-size features. The results of the analysis revealed that TPMS choice cannot be limited to porosity or relative density only. It was demonstrated that primitive and gyroid geometries have advantages in case of continuous access and moderate tortuosity, diamond geometries are beneficial in cases with predominance of stiffness and split-merge flow paths, while I-WP or F-RD geometries gain importance in case of internal surface density and heat-conduction pathways.

Keywords: triply periodic minimal surface; porous architecture; additive manufacturing; thermal transport; permeability; lattice materials; service exposure; materials design.

1. Introduction

Material porosity has transitioned from being viewed as an unfortunate feature of an imperfect solid to a useful architectural construct where pores and channels mediate specific functionality. In the realm of additive manufacturing, the geometry of the pore phase can be explicitly designed prior to fabrication rather than being a fortuitous consequence of foaming, sintering or poor consolidation. The porous structure can therefore be configured to be light, permeable, thermally conductive, biocompatible, energy absorbing or environmentally serviceable depending on the distribution of the solid and porous phases. The challenge is that few, if any, of these functions operate independently of each other. An increase in internal surface area that enhances thermal exchange may increase surface exposure to fluids or aggressive species. A constricted pore throat that raises surface area density may impede the flow of powder during consolidation. A wall thickness gradient that minimizes pressure losses may affect local stiffness. Coupling among these functions makes the design of a porous structure an architecture selection problem, rather than a porosity problem.

Triply periodic minimal surfaces provide an elegant basis for the design problem, since they are constructed using implicit field geometry rather than disconnected struts or randomly placed pores. Since Schoen described self-intersecting periodic minimal surfaces, the gyroid, primitive and diamond surfaces have been recognized as canonical examples of bicontinuous geometry in which a periodic interface partitions interwoven domains without sharp nodes or sudden curvature changes [1]. Algorithms for surface extraction from volumetric fields have paved the way for an easy path from implicit representation to discrete geometry [2]. Scaffold designs in the earlier period demonstrated that these surfaces could be converted into fabricable porous materials [3]. Subsequently, computer aided designs allowed for explicit manipulation of TPMS pore architecture for tissue engineering applications [4]. Minimal-surface scaffold studies helped clarify the effect of geometric parameters on biological design requirements [5]. More recently, this implicit design approach has been extended to multiscale additive manufacturing and multidisciplinary applications [6]. Unlike most strut lattice designs, TPMS-based structures can produce continuous surfaces and continuous pores at the same time. While this feature is useful for load carrying, fluid transport and surface-mediated transport, it also means that the resulting structure is sensitive to wall thickness, level set threshold, print orientation, minimum feature size and post-print access.

An important way to think about TPMS materials is to consider the surface as a geometric mediator between processing and function. The mathematical field dictates the location of the wall, additive manufacturing determines how accurately the wall is fabricated, and service environment decides whether the internal passages serve as a useful service conduit or an undesired exposure pathway. This is why TPMS structures cannot be evaluated by their relative density alone. Two porous materials with equal porosity can show quite different permeability if one consists of direct open passages and the other has tortuous split-merge passages. Flow and heat transport evaluations confirm that gyroid and Schwarz-P cells behave differently even in comparable material systems [7]. Two porous bodies with similar cell sizes can exhibit different stiffness if one is a sheet-based and the other a network-based structure. Similar heat-exchanger evaluation studies show that surface geometry affects heat transfer and pressure losses together [8]. Porous gyroid heat sink models further indicate sensitivity to cell size, porosity and choice of material [9]. Foam design space analyses also reveal coupled trade-offs between conductivity, permeability and stiffness [10]. The critical design parameter is thus not simply the quantity of solid, but how it is arranged in the continuous and printable and serviceable domain.

The current study attempts to answer the following research question: How can TPMS porous architectures be selected for additively manufactured materials when load bearing, fluid access, thermal exchange and environmental exposure are considered as coupled requirements rather than independent criteria? The question differs from a collection of TPMS equations, as well as a single criterion-based optimization study. The former is considered only as one aspect of a broader design methodology that also considers construction methods (sheet or network), cell size, grading, surface area, direction dependent permeability and manufacturability. The article uses original figure assets and a quantitative evidence matrix to organize the discussion, but does not generate new experimental data. The contribution of the article is an original, self-standing materials science manuscript that transforms a geometry-based analysis into a design-oriented argument suitable for publication in a journal focused on additively manufactured materials, porous media, heat transfer and environmental-material interaction.

The design logic is summarized in Figure 1. The implicit field is presented first in the workflow because the TPMS equation specifies the possible relationship between wall continuity, open passages and surface density. Additive manufacturing is used to enable the design rather than as a neutral fabrication step, because it influences whether the desired wall thickness and internal passage dimensions are maintained through printing. Performance is then evaluated in terms of mechanical, thermal, permeability and exposure responses. The important point here is that all four responses depend on the same internal geometry. A design that optimizes one response while ignoring the rest can look attractive in a simulation but is likely inappropriate for the material component. The discussion after the figure is thus structured around TPMS as an architecture, process and service system.

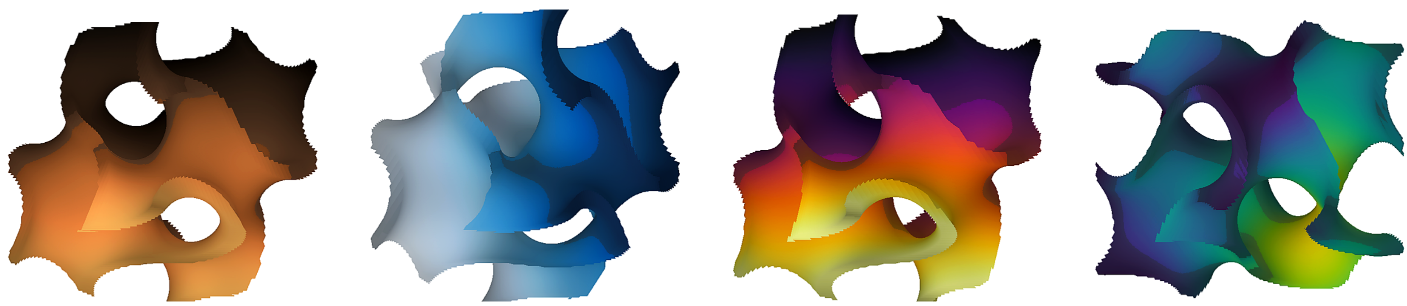

Figure 1: Coupled TPMS service fields.

The importance of this synthesis becomes more evident upon contrasting TPMS materials to conventional cellular solids. The theory of cellular solids elucidates scaling laws between stiffness and strength based on density and structure, but conventional foams tend to have statistical variance in pore diameter and local wall structure [11]. Honeycomb architecture is efficient in two dimensions but does not have comparable channel continuity in three dimensions. Strut lattices are easily manufacturable using digital means, but the joint between struts may concentrate stresses and form thermal dead zones. TPMS geometries are special in that their surfaces are smooth and continuous. This property aids in stress distribution and fluid flow guidance; additionally, the algebraic field provides the ability to modify local topology by adjusting a few parameters. Smoothness of the surface is not enough to guarantee superiority of a TPMS architecture; it needs to be matched to the particular service requirement, which is the core focus of the present manuscript.

The scientific literature has advanced greatly since the scaffold-design work which showed the ability to tune pore network using minimal surfaces for tissue engineering [3]. Computer-aided scaffold design offered the ability to directly control the pore architecture of TPMS scaffolds [4]. Minimal-surface scaffold comparison work established the link between geometry, permeability and biological requirements [5]. Mechanical study demonstrated that polymeric TPMS cellular material possesses architecture-dependent mechanical response [12]. Double-gyroid lattices exhibited typical failure mode and energy-absorption properties under compression [13]. Comparison study of metallic architectures established TPMS strut, skeleton and sheet topology-related mechanical properties [14]. Broader polymeric study confirmed the non-universal nature of mechanical response for different TPMS families [15]. Thermophysical study illustrated the potential of bioinspired TPMS heat exchangers in challenging power cycle conditions [16]. TPMS metal-foam skeletons have been considered in the context of thermal energy storage applications [17]. The connection of TPMS architectural topology to both thermophysical and mechanical properties has been explored via comparison with stochastic foams [18]. Experimental investigation of TPMS-based heat exchangers revealed the effect of geometry on both heat transfer and pressure drop [8]. Multiscale review work provided the overview of TPMS design, fabrication and application requirements in one context [6]. Recent thermophysical reviews point to the important role of fabrication and geometry for energy system performance [19]. Additive manufacturing surveys also draw attention to process limitations and post-fabrication processing [20]. Metallic TPMS lattice reviews establish connections between design considerations, fabrication processes and multifunctionality [21]. The present manuscript extends from this work, but focuses the argument on service-ready selection logic: the architecture of the TPMS should be chosen only after making the balance between transport, heat exchange, structural integrity and internal exposure clear.

2. Evidence Base and Analytical Orientation

The evidence base is comprised of three interrelated tiers. The first tier is mathematical and involves the implicit equations of commercially available TPMS units. The second tier is architectural and includes the figure set describing how the transformation of zero-thickness surfaces into sheet and network structures is performed, how different unit families exist and how homogeneous, graded, heterogeneous and multiscale patterns are formed. The third tier is performance-based and includes specific quantitative measurements that substitute the generalizations like "TPMS increases heat transfer rate" or "TPMS increases permeability." Such measurements include the thermal, hydraulic, mechanical, permeability and manufacturing characteristics of TPMS units described in the TPMS literature and collected in manuscript tables. In other words, the analysis represents a design synthesis rather than a lab report. It assesses the consistency of the evidence, explains where claims are justified and identifies the conditions under which the TPMS unit is suitable.

Such orientation is necessary since many discussions of TPMS overstate its generality. For example, a heat sink made on the basis of gyroid structure having favorable heat-transfer coefficient does not mean that all gyroids perform best in all thermal applications. Or, a high compressive stiffness of diamond lattice does not mean that diamond geometry is always better if transport or de-powdering is needed. Graded porosity pattern reducing the pressure drop can decrease the surface-area density or local stiffness. In other words, the evidence must be treated conditionally. The conditions involve the type of TPMS construction, target relative density, loading direction, Reynolds number/flow regime, heat-transfer boundary conditions, family of materials and manufacturing method itself. The consideration of these conditions explicitly is what transforms the paper from a mere description to the practical framework.

The analytic approach involves following the sequence of steps in the materials-design paradigm. At the first stage, it is necessary to determine the function that is considered as the priority, e.g. stiffness, longitudinal flow, radial flow, heat spreading, heat exchange, tissue ingrowth or environmental access. At the second stage, it is necessary to choose the geometric family compatible with such requirements in terms of channel continuity and surface distribution. At the third stage, it is necessary to decide whether sheet or network construction is optimal for this balance of wall continuity and volume fraction. At the fourth stage, it is necessary to set the threshold value, frequency and wall thickness in order to keep porosity, surface-area density and minimal feature size printable. Finally, at the fifth stage, it is necessary to determine whether the manufacturing technique can allow leaving internal channels open after removing powder, curing, sintering or other post-processing. The sequence of steps is not formulated as an algorithm in the manuscript in order to make it a scholarly narrative but the underlying logic is behind the figures and tables.

Level-set atlas in Figure 2 adds the geometric checkpoint before construction is considered. Panels are arranged according to the threshold state and the unit family. Thus, the reader can see how primitive, gyroid, diamond, I-WP and F-RD surfaces transform from the open to dense configurations. The visual demonstration that changing threshold is not just a cosmetic modification but also means changing throat opening, wall continuity, local curvature and probability of leaving internal channels buildable after printing becomes possible. This interpretation makes the discussion of thermal, hydraulic and service access possible in the future because these responses are rooted in the same topological field.

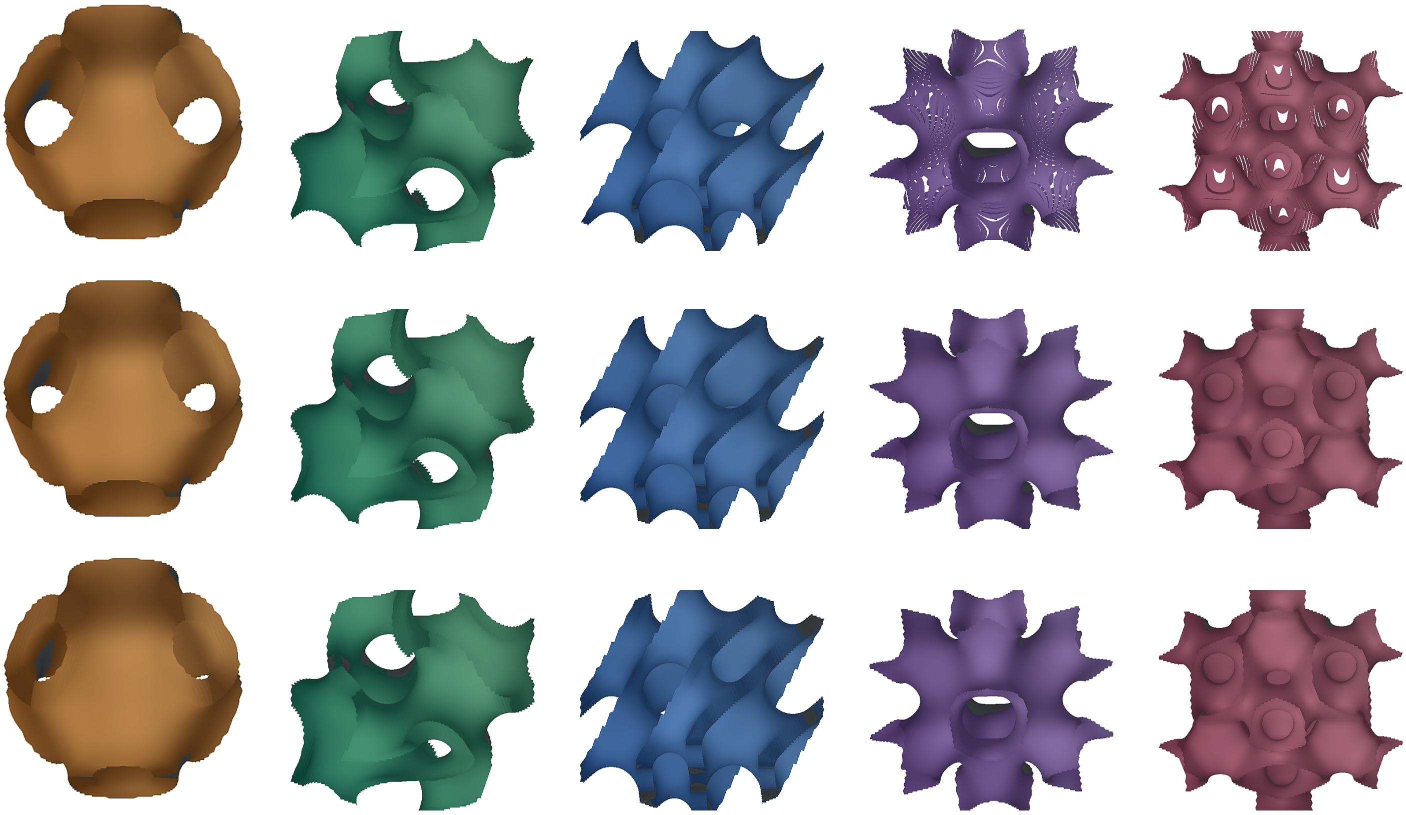

Figure 2: Level-set morphology across TPMS families.

Construction pathway in Fig. 3 shows why the design of TPMS precedes material choice. A zero-thickness mathematical surface turns into a physical architecture only after assigning a finite volume to a solid phase. In the case of a sheet TPMS architecture, the minimal surface is given thickness through offsetting, creating walls on both sides of the original interface. For a network or solid domain TPMS architecture, one side of an implicit field becomes solid phase and the other – void. Two types of construction could be of the same relative density but have different surface areas, thicknesses and loads paths. Practically speaking, a sheet architecture could have large internal surface area and conductive heat transfer channels, while a network could have larger void openings and different load-bearing frames. This figure thus proves the insufficiency of porosity as a criterion.

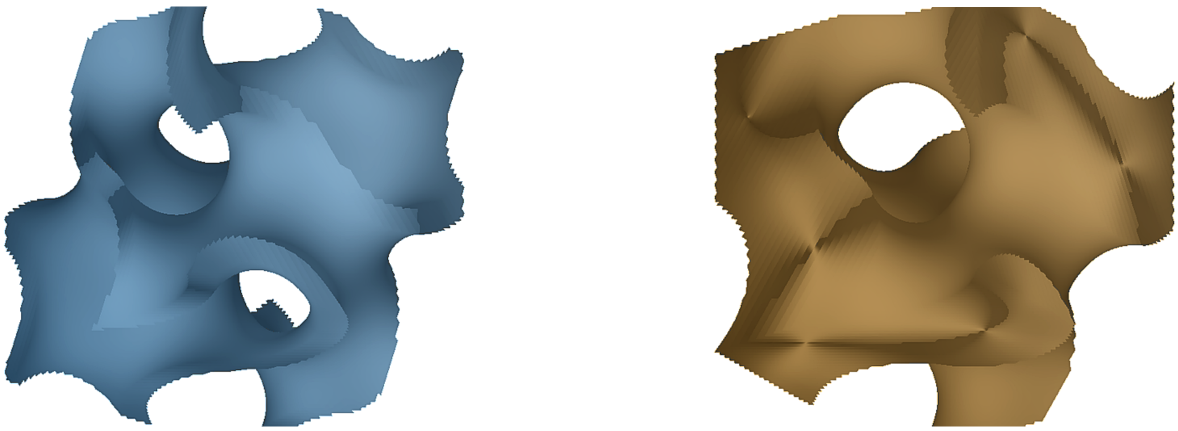

Figure 3: Sheet and network domain assignment.

The implicit functions given in Table 1 are not just for aesthetic purposes; they are used to specify how variations in phase, frequency and threshold affect the underlying physical structure. A variation in C causes the isosurface to change and the local volume fraction to vary. A variation in ω_x, ω_y or ω_z causes the unit cell to stretch and can cause the otherwise isotropic form to become anisotropic. Wall-thickness modification affects the print even though the underlying mathematical isosurface has not changed. These parameters are the key to relating the geometry to materials properties, which is what makes TPMS structures appealing to additive manufacturing. This link is also a risk: if the printer can't handle the smallest wall thickness or can't get the powder out of the holes, the beautiful geometry won't be printed as a useful material.

Table 1: Implicit TPMS descriptors.

Unit family	Representative implicit field	Design relevance
Primitive (P)	$\cos x + \cos y + \cos z = C$	Direct channel connectivity and relatively low tortuosity for access-driven designs.
Gyroid (G)	$\sin x \cos y + \sin y \cos z + \sin z \cos x = C$	Smooth bicontinuous passages with balanced transport and mechanical response.
Diamond (D)	$\sin x \sin y \sin z + \sin x \cos y \cos z + \cos x \sin y \cos z + \cos x \cos y \sin z = C$	Split-merge topology with stiffness and thermal-hydraulic relevance.
I-WP	$2(\cos x \cos y + \cos y \cos z + \cos z \cos x) - (\cos 2x + \cos 2y + \cos 2z) = C$	High surface complexity for thermal and surface-mediated functions.
F-RD	$4 \cos x \cos y \cos z - (\cos 2x \cos 2y + \cos 2y \cos 2z + \cos 2z \cos 2x) = C$	Surface-rich architecture with strong effective-property potential.

Furthermore, the table reveals the reason why the paper does not consider TPMS as one category since although all the primitive, gyroid, diamond, I-WP and F-RD topologies originate from TPMS, they do not necessarily elicit the same engineering reaction. Primitive channels may be desirable for fluid access, but their direct approach is not always able to disrupt the thermal boundary layer for efficient heat exchange. Diamond channels may increase mixing or stiffen but at the expense of additional pressure loss. Gyroid surfaces are generally a good compromise between two extremes, but the same compromise may become unfavorable if there is a need for extremely stiff structures or anisotropic flow. I-WP and F-RD surfaces are useful where there is a need for high surface area, but they have a more complicated structure which may entail more challenging production processes. Hence, the table needs to be interpreted as an algebraic selection tool.

3. Geometry-to-Property Framework

The representative families of TPMS illustrated in Figure 4 are visual evidence of the topological differences described in the mathematical table. Although a geometry based on a smooth surface may seem continuous in any case, these families partition the space in a different way: primitive topology has relatively wide passages, gyroid topology twists asymmetrically, diamond topology makes split-merge networks, while I-WP or F-RD topology gives rise to more complicated surface patterns. They affect the velocity field, thermal boundary layer, deformation modes and probability of feedstock entrapment. A material choice that considers TPMS as equal does not take into account these differences.

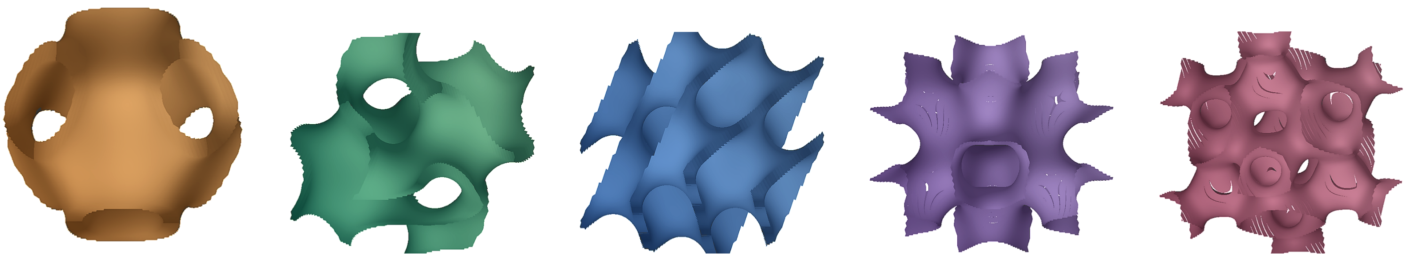

Figure 4: Topology fingerprints of TPMS units.

The interpretation of Figure 4 is related to the mechanics literature. Maskery et al. proved that additively manufactured double gyroid lattices have unique compressive failure and energy absorption characteristics dependent on cell size, relative density and fabrication state [13]. Abueidda et al. found out that TPMS-based cellular materials from a particular mathematical family have different mechanical characteristics [12]. Al-Ketan et al. proved that metal lattice materials created using strut-based, skeletal TPMS and sheet TPMS architectures do not share topology-response relation [14]. All these publications support the hypothesis stated in this work: the architecture family is not a cosmetic variable, but a key determinant of response.

Control parameters of Figure 5 represent the TPMS family translated into material design space. Level-set parameter defines the ratio between the solid and void parts. Spatial frequency defines the cell size and number of repeats in a given volume. Wall thickness determines if the lattice can be manufactured as a load-carrying structure or stays too brittle to manufacture. These parameters are interrelated. Increasing the spatial frequency and keeping constant size of components decrease cell length and may lead to increase in surface-area density. It also decreases pore throat size and may cause clogging with powder. Increasing wall thickness increases stiffness and continuity of the conductivity path, but reduces permeability and may increase pressure drop. Modifying level set parameter may result in creating graded porosity, but if it is excessive, it creates areas of the structure that are outside the printer resolution range. Therefore, the design space in the figure does not only include mathematical parameters of TPMS.

When these parameters are interpreted in the context of effective properties, it becomes possible to find an approach to use this design space. In case of mechanical properties, the relative density and wall continuity influence stiffness, plateau stress and energy absorption ability. In case of fluid transport, the parameters that need to be considered are pore throat size, tortuosity, connectivity and anisotropy which affect permeability and inertial losses. In case of thermal properties, it is necessary to consider the internal surface area, conductivity, flow disruption and pressure drop. Finally, in case of environmental service, it is important to realize that channels responsible for fluid transport may be responsible for cleaning, coating penetration, electrolyte access, oxygen concentration gradients and retention inside the structure.

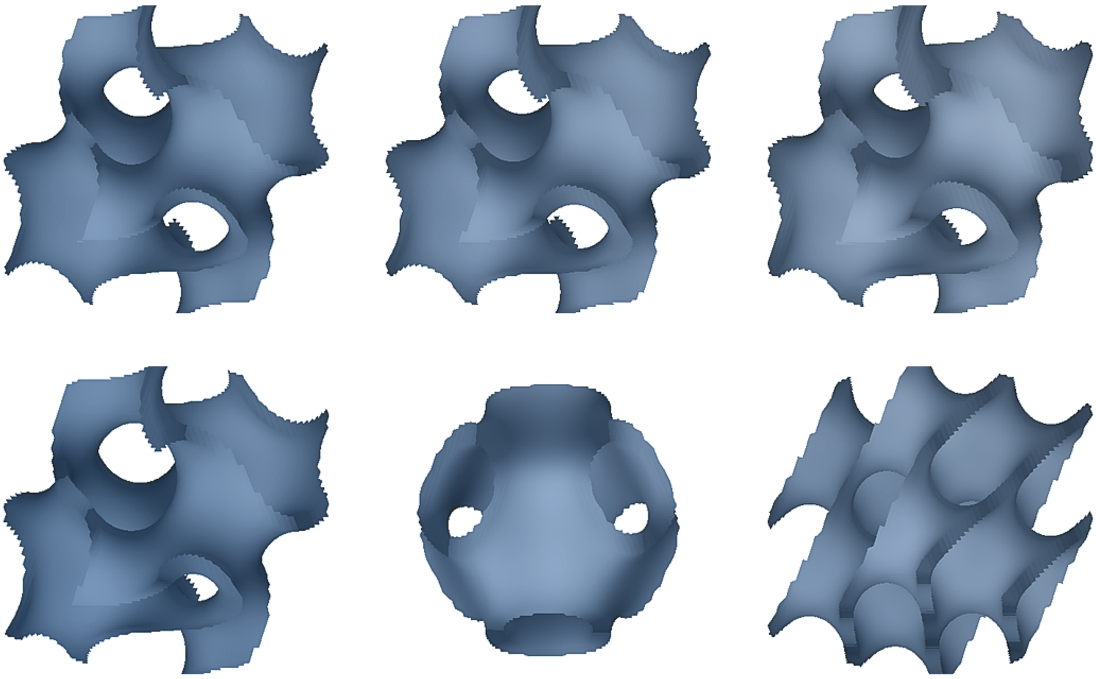

Figure 5: Coupled TPMS control variables.

Architecture classes from Figure 6 provide a framework beyond the scope of a single repeating cell. Uniform TPMS provides the basis for comparative analysis since it features identical units within the component. Graded TPMS adjusts porosity, cell size, or wall thickness to reduce pressure loss or satisfy certain loading conditions. Heterogeneous TPMS uses different unit families depending on the location, for instance, diamond-like structure for stiffness and gyroid-like structure for flow access. Multiscale TPMS introduces hierarchical pore sizes, increasing the area of the surfaces and broadening the range of transport regimes. Each class provides an answer to a particular problem and places additional burden on manufacturing process.

Importance of Figure 6 lies in the separation of topology selection from topology distribution. Choosing the gyroid unit is just the first step. It is necessary to determine whether the chosen topology is going to be uniform, whether the level-set threshold will change along the direction of flow, whether it is going to be changed into other TPMS family close to the load-bearing border, or whether it is going to be included into multiscale hierarchy. This is important since many problems arise not due to the incorrect choice of the TPMS family, but due to the incorrect topology distribution within the component. Heat exchanger might need a lower resistance close to the inlet and higher surface density farther away. Scaffold might need larger pores close to the vascularization zone and higher stiffness close to the fixation surface. Corrosion-resistant porous insert might need open channels for cleaning purposes rather than maximized internal area.

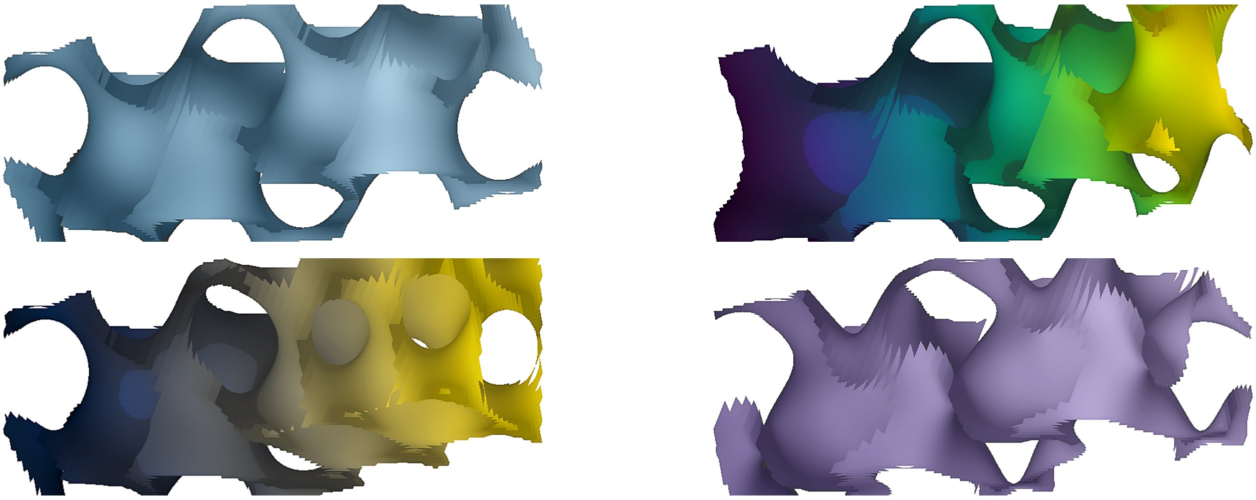

Figure 6: Architecture distribution modes.

4. Selection of Process-Aware TPMS Architecture

Process awareness is the gap between printable-looking TPMS lattice structure and manufacturable additively fabricated material. The minimum wall thickness, unsupported span, surface roughness, closed cavity removal and post-processing constraints are unique for laser powder bed fusion, electron beam melting, binder jetting, vat photopolymerization, projection micro-stereolithography, two-photon polymerization and extrusion-based printing. Several reviews of multiscale TPMS have highlighted the importance of designing geometric structures according to process resolution [6]. Similarly, surveys on additive manufacturing have noted that post-processing and material considerations significantly impact the realized behavior [20]. Reviews on metallic TPMS have pointed out the connection between fabrication constraints and mechanical or multifunctional performance [21]. This implies that a TPMS cell cannot be defined adequately without specifying the process route and minimum manufacturable geometry.

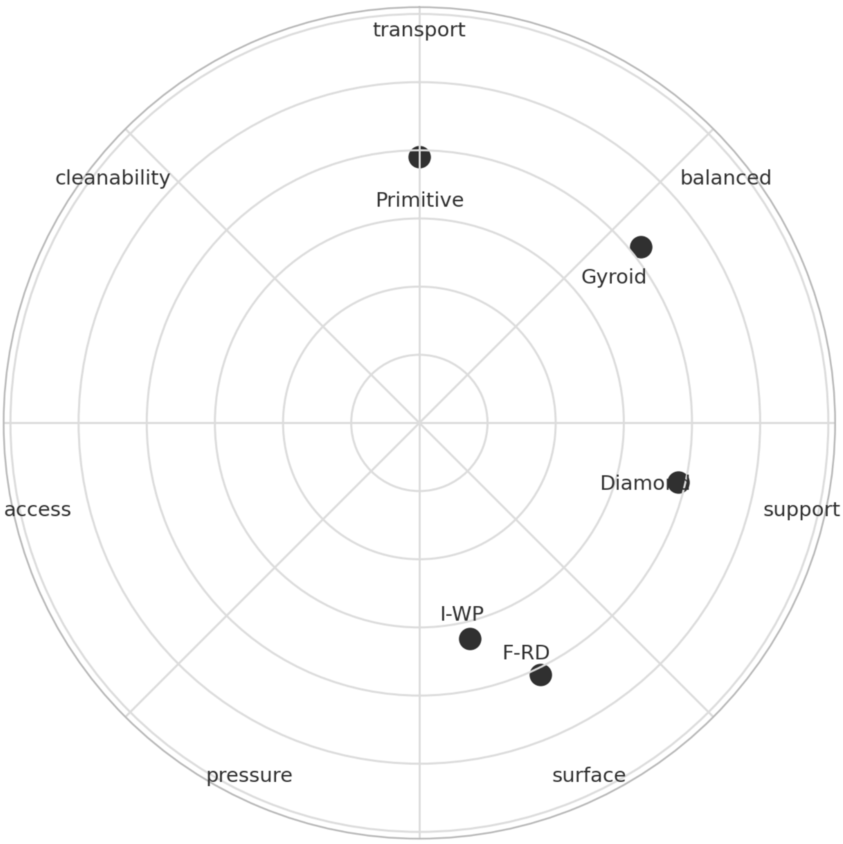

Figure 7: Service-conditioned topology selection.

The selection compass shown in Figure 7 illustrates the compromise between common TPMS families and service goals. Primitive and gyroid cells are located in the transport side of the compass since their open and bicontinuous channels are advantageous when fluid penetration is necessary. The early permeability studies have found out that different TPMS families give rise to different flow resistance [22]. The scaffold optimization has revealed that permeability and elastic modulus must be balanced rather than separately optimized [23]. The diamond cells migrate toward the stiffness side due to split-merge topology that is capable to carry a load and divert the flow path. The mechanical studies have demonstrated that the type of the topology has a great effect on the metallic cellular performance [14]. The I-WP and F-RD TPMS cells are positioned in the region where the internal surface area and thermal response are of primary importance. The simulation results have shown that the change of channel family modifies the transport and heat properties of TPMS cells [7]. The architected foam comparison studies have shown that in certain cases the deterministic topology has superior performance compared to the stochastic ones [18]. Therefore, the compass is qualitative, but not arbitrary.

The compass should be interpreted as a decision tool, not as universal ranking. A primitive cell is a good choice as access structure for certain flows but may be less efficient for highly permeable exchanger with high level of transverse mixing. A diamond cell is attractive from the viewpoint of mechanics, but may be not the optimal choice if the priority is the minimization of pressure drop for highly porous exchangers. Gyroid cells usually provide balanced performance, but it can be outperformed by more specialized surfaces when design goal is well-defined. The I-WP and F-RD cells can deliver strong property improvements, but need careful consideration of local feature quality. Thus, the right selection depends on the service statement. Without such a statement, a claim that one TPMS family is the "best" is incomplete.

Manufacturing constraints also determine the ways how the chosen topology could be manufactured. In case of metal powder bed fusion, the trapped powder is the key issue as long as there are narrow and tortuous internal throats. The rough as-fabricated surface can increase the actual surface area and improve local mixing but also increase the pressure drop, initiate the fatigue cracks or create environmental traps. In photopolymer and ceramic processes, the resin drainage, shrinkage and sintering distortions can modify the designed pore morphology. The projection micro-stereolithography was used to manufacture the sample with layer thickness of 5 μm, while two-photon polymerization is able to make a sample of several hundreds micrometers with feature size of several micrometers. Such possibilities enable microarchitectured applications, but do not eliminate the necessity of surface quality evaluation on scale-dependent level. TPMS cell that is manufacturable at millimeter scale may exhibit other behavior at micrometer scale since the ratio of surface roughness and wall imperfection to feature size increases.

The process-aware selection also implies determination of the acceptable level of geometric grading. Geometric grading can lower the pressure drop and redistribute the mechanical response but the abrupt grading may cause local stress concentration or manufacturing discontinuities. The smooth gradient in the implicit field is always preferred as it preserves the wall continuity. The heterogeneous TPMS cells combining different cell families require special attention at transition regions. The transition should not be considered as a simple boundary between two independent lattices but constructed so as to maintain the contact of walls, opening of pores and absence of unbuildable sliver surfaces. This is the strength of implicit modeling approach since it allows designer to blend the fields but resulting geometry has to be evaluated with respect to manufacturability requirements.

5. Integrated Results and Discussion

The integrated results are presented as a design synthesis and not as a new experimental dataset. Quantitative values are key because they transform general claims into design signals. Cross-functional evidence summary in Figure 8 has several clear messages. Gyroids can improve the average heat-transfer coefficient in comparison to an open-cell foam and permit twice as much heat dissipation with the same temperature difference. F-RD architectures can have much higher effective thermal conductivity compared to stochastic foams at the same porosity. Graded TPMS architectures can reduce pressure drops while keeping heat transfer mostly unchanged. All of these messages suggest the same thing: topology, distribution, directionality and process resolution are at least as important as porosity.

Further analysis of the thermal-flow evidence reveals that the improvement in heat transfer cannot be considered as an additional benefit. Heat-exchanger data shows that the geometry of TPMS structures influences both heat transfer and pressure drop [8]. Experiments using water-cooled TPMS show that increased heat transfer must be assessed based on the operating conditions of the heat exchanger [24]. The gyroid message reveals that the tortuous surface-rich channels help break the thermal boundary layer and thus increase the heat dissipation, yet it comes with a penalty in terms of pressure drop. Modeling of the gyroid heat-sinks shows that cell size, porosity and materials influence the thermal behavior [9]. The F-RD message suggests that the shell-like architected foam can improve stationary thermal conduction by providing the solid network in a more efficient way than stochastic foam. Graded TPMS message suggests that changing the spatial porosity helps decrease the flow resistance, however, the reduction of the surface area relative to the uniform structure reduces the convective heat transfer. Modern TPMS heat-exchangers design research therefore considers geometry and additive manufacturing feasibility simultaneously [25]. Thus, the design message here is that the heat-transfer performance must be assessed in terms of thermal-hydraulic criteria and not only in terms of heat transfer coefficient. The high heat-transfer coefficient, requiring large pumping power, might not be feasible for compact devices, while a lower heat-transfer coefficient with significantly reduced pressure drop might be better.

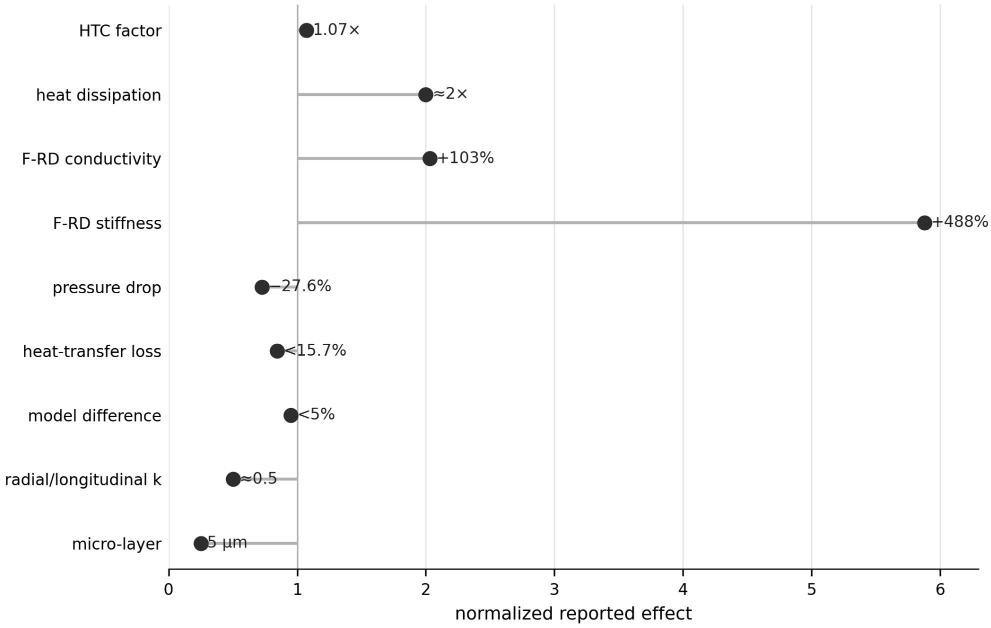

Figure 8: Cross-functional TPMS evidence.

The thermal-hydraulic frontier in Figure 9 illustrates this point explicitly by plotting the TPMS cases in terms of performance rather than in terms of mere comparison. The graded case is considered attractive since it approaches the lower hydraulic penalty regime while maintaining most of the thermal response, while the gyroid and F-RD cases are located in different places in the thermal and effective properties space. The importance of this figure for the results section is that it does not allow discussing heat transfer performance in isolation. A more practical design target is a region where all aspects – thermal gain, pressure penalty, manufacturability and access – are good at the same time.

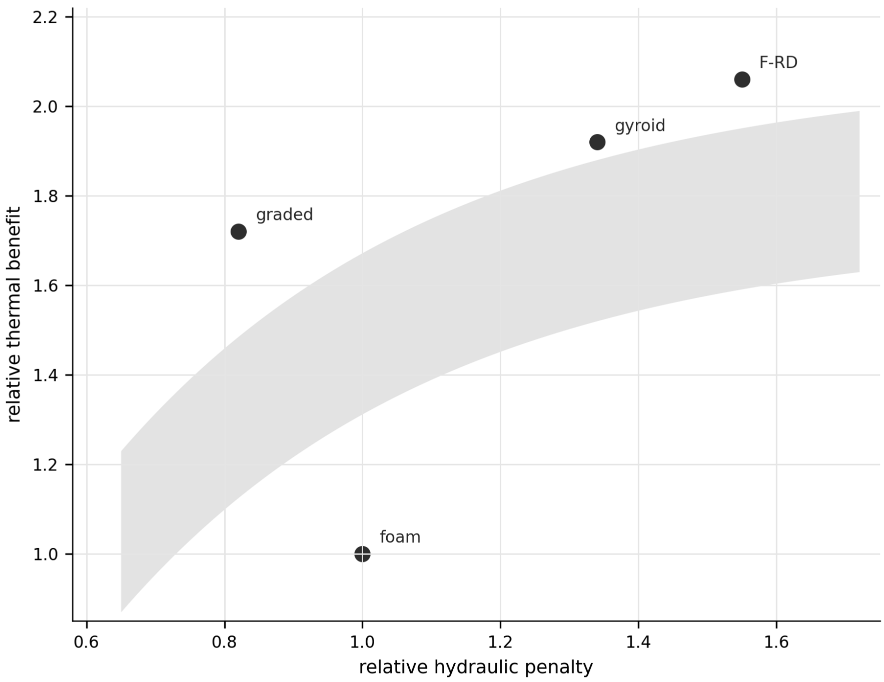

Figure 9: Thermal-hydraulic trade-off frontier.

The evidence matrix in Table 2 documents the observations made in this interpretation. The matrix is intentionally terse, but it plays an important scholarly role: it does not allow making vague claims. The value of 1.07 of gyroid heat-transfer coefficient demonstrates the moderate coefficient advantage, while the claim of approximately doubled heat dissipation shows the system-level benefit at the same temperature difference. The 103% increase in thermal conductivity and 488%

increase in stiffness in F-RD architecture illustrate the possibility to improve both conduction and mechanical response due to efficient solid network arrangement. The 27.6% pressure drop reduction with less than 15.7% heat transfer loss for the graded case illustrates the capability to tune the hydraulic penalty. The directional permeability observation, analytical prediction difference and microfabrication values show that the transport and manufacturability cannot be evaluated in a qualitative way.

Table 2: Evidence matrix.

Design observation	Specific evidence and interpretation
Gyroid heat exchange	Average heat-transfer coefficient reported at 1.07 times that of a commercial open-cell foam, with approximately twice the heat dissipation under the same temperature difference.
F-RD effective properties	Thermal conductivity 103% higher than stochastic foam at equal porosity, with stiffness reported 488% higher in the same comparison.
Porosity grading	Uniform TPMS showed 22% larger surface area than the graded counterpart, while grading reduced pressure drop by 27.6% and limited heat-transfer reduction to less than 15.7%.
Sheet and network comparison	Sheet gyroid provided approximately twice the surface area of network gyroid, while network gyroid and network diamond showed comparable surface areas.
Directional permeability	Cylindrical TPMS scaffolds showed radial permeability approximately half the longitudinal permeability, confirming orientation-sensitive transport.
Permeability modelling	Analytical TPMS permeability models produced prediction differences below 5% in reported comparisons.
Multiscale construction	Four-level TPMS generation was sufficient to create structures with three pore scales.
Microfabrication capacity	Projection micro-stereolithography reached 5 µm layer thickness, while two-photon polymerization produced several-micrometre features in samples a few hundred micrometres wide.

The table illustrates an important finding from the paper: TPMS effectiveness is a matter of topology, distribution, and processing. The superior capability of a gyroid to dissipate heat does not imply that the gyroid is the stiffest topology per se. The superior capability of an F-RD for effective thermal conductivity and stiffness does not imply that the F-RD will have the lowest pressure drop. Graded diamond or TPMS distribution can enhance hydraulic capability, although the decrease in surface area needs to be taken into account when convective heat transfer is the goal. Directional permeability proves that a certain topology tested in one direction of flow is not necessarily equivalent in another direction. The values for manufacturing illustrate that very fine TPMS can be manufactured, although within certain process-specific limits. Therefore, the most important finding is not numerical at all; rather, it is recognizing the decision variables.

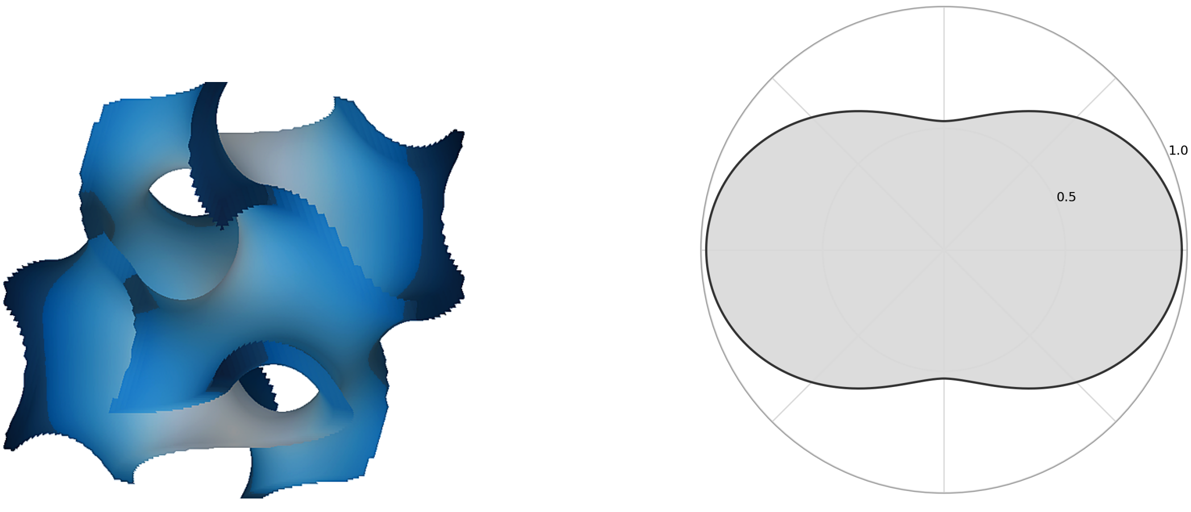

Figure 10: Direction-sensitive permeability response.

Directional permeability is illustrated in Figure 10, since this parameter often decides on the successful operation of the TPMS element. While the cylinder made of TPMS structures can be designed for longitudinal flow, radial transport can control diffusion of nutrients, cleaning process, electrolyte supply or mixing. The reported observation about the fact that radial permeability can be approximately half the longitudinal permeability implies that the conditions at the boundary and the orientation should be taken into account at the design stage. For implantable devices, it can affect the issue of tissue ingrowth and fluid exchange. For filters, it can influence the backwashing or fouling process. For heat exchangers, the cross-flow distribution can be affected. For corroding porous metals, it can determine the possibility of rinsing, coating or passivation of the internal surface. Thus, the permeability parameter is not only a transport metric, but also a service access metric.

The orientation-sensitive interpretation of this parameter is confirmed by the literature data. In the paper by Montazerian et al., the design of minimal-surface scaffold is associated with compromise between permeability and elastic parameters, rather than a single optimum [23]. In the work by Zhianmanesh et al., the permeability of graded porosity scaffolds is analyzed with respect to the change in architecture and porosity distribution [26]. Ma et al. investigated bone-mimicking gyroid structures obtained by the process of selective laser melting and associated mass transport properties with mechanical properties of the structure [27]. Asbai-Ghoudan et al. developed an analytical model of TPMS permeability; the reported accuracy of predictions confirms the applicability of reduced order modeling as a tool prior to simulations or fabrications [28]. The combination of these works proves that permeability should be considered as a directional property, depending on architecture, and not a simple parameter related to porosity.

The manufacturability constraints in Figure 11 illustrate the practical limits of the above results. Even when the TPMS design is correct in mathematical terms and holds promising computational results, it can be still inappropriate for production. The issues of minimum wall thickness, removal of the powder, resin drainage, thermal distortions, as-built roughness and post-processing access define whether the internal geometry stays open. In metallic powder-bed processes, the internal surface can retain partially fused particles, which affects the hydraulic diameter and roughness of the surface. In the case of polymers, the cured resin or support material can be retained in narrow passages. In the case of ceramics and metal-ceramics routes, the sintering shrinkage can affect the throat diameter.

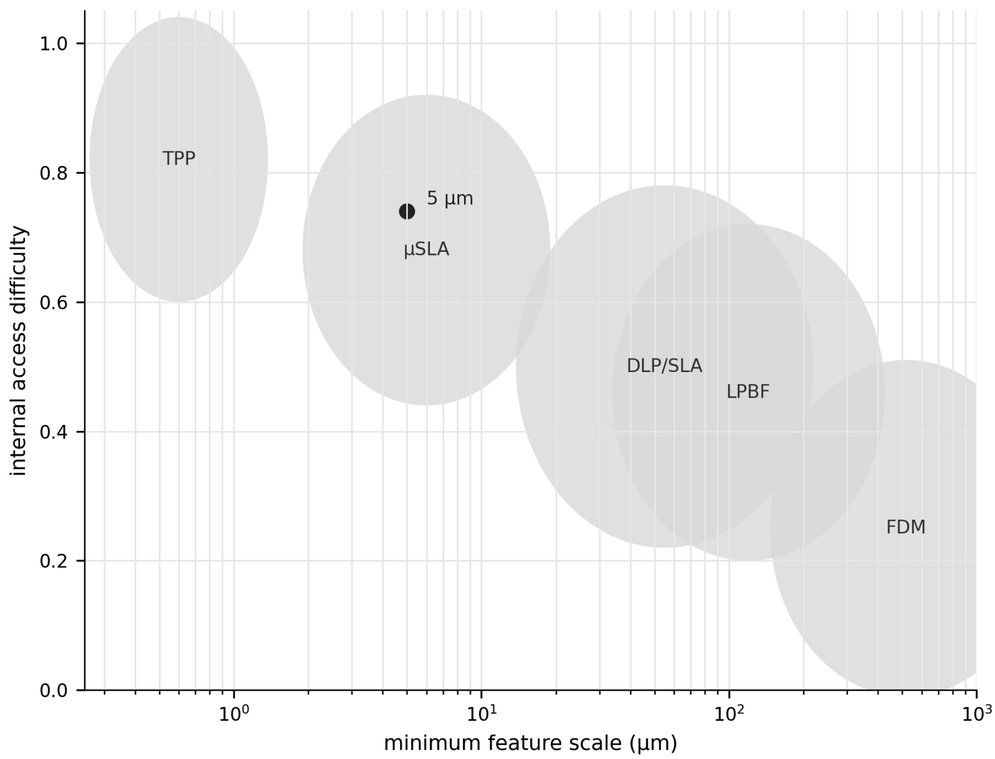

Figure 11: Process window for TPMS realization.

Manufacturing considerations change the role of the wall thickness from a geometrical parameter to a quality control variable. Wall thicknesses that are too low may lead to breakage or distortion during handling, heat treatment and printing. Wall thicknesses that are too large will close passages and limit permeability. Pore sizes that are too small will create high surface area but not allow de-powdering. Rough surface will improve local heat transfer but will also increase pressure drop and sensitivity to fatigue. Recent studies on TPMS heat exchangers hence assess wall thickness, lattice density, material conductivity and pressure drop in combination [25]. Reviews on thermal applications recognize fabrication quality as a factor that influences energy performance [19]. Surveys of additive manufacturing stress the interdependence of geometry, processing and post-treatment [20]. Metallic TPMS reviews extend the same conclusion to the case of multifunctional structural performance [21].

One of the important discussion points here concerns the distinction between local and global performance criteria. A TPMS surface can be locally efficient in terms of high heat transfer through increasing the surface area and disrupting the flow. Globally, however, pressure drop, manufacturability, fouling and cleaning may define the suitability of the design. A locally stiff wall may lead to failure of the component in case the transitions or boundaries are not sufficiently robust. A locally permeable pore may create a functional channel but the material will retain powder or electrolyte if there is no sufficient exit from the channel network. The figures and table thus lead to the service level conclusion that TPMS design evaluation has to consider the path from the digital field to the printed geometry and operated component.

The presented evidence suggests that grading is more than just an aesthetic option. The pressure-drop decrease by 27.6% along with heat-transfer decrease below 15.7% demonstrates that the graded field can redistribute the hydraulic resistance more efficiently than the uniform field at the same average porosity. The result is crucial in the sense that it demonstrates the possibility to use the TPMS architecture to tune the multiphysics trade-offs rather than just maximize one of them. While the uniform surface can offer larger surface area, the graded surface can save on pumping power while preserving the major part of the heat-transfer functionality. In applications where the cost of pumping power is high or pressure limits are stringent, the graded design may prevail over the non-graded design despite the lower local convective coefficient.

The F-RD comparison with stochastic foam is also significant since it connects the thermal and mechanical performance criteria. The 103% increase in thermal conductivity indicates that the solid continuity becomes more effective in the presence of the architected rather than randomly distributed conduction path. The 488% increase in the stiffness proves that the same architected pattern improves mechanical performance. The dual improvement constitutes a strong argument in favor of deterministic porous materials. At the same time, this example warns about the use of stochastic foam analogies when designing additively manufactured components. The random foams may serve as useful benchmarks, but TPMS structures can occupy the different regions of the property space due to the mathematical arrangement of the surfaces and load paths.

The gyroid heat-dissipation example reveals yet another type of advantage. The factor of 1.07 in the average heat-transfer coefficient seems moderate, but almost doubled heat dissipation at the same temperature difference demonstrates that the overall thermal performance is affected by the surface area, contact area, flow distribution and effective geometry rather than the local coefficient. For a designer, this means that the gyroid structures have to be evaluated through the heat removal requirement rather than local Nusselt number. In applications like compact electronic cooling, battery thermal management or recuperative heat exchange, the relevant question is whether the architecture is able to remove the necessary amount of heat at acceptable pressure drop, mass and manufacturability. Gyroids are good candidates because they usually achieve this goal, but the balance has to be proved for the particular boundary condition.

The sheet versus network observation adds another dimension to the problem. The sheet gyroid, being approximately twice the surface area of the network gyroid, may be preferable in cases of catalysis, heat transfer or tissue interactions, but the same doubling of the surface area leads to increased frictional losses or exposure to the environment. Even the network gyroid and network diamond structures with the comparable surface areas may show different performance since the channel topology and tortuosity remains different. Thus, TPMS materials have to be described not only by unit family name but also by construction type and distribution. The phrase like "gyroid lattice" is incomplete if the structure is either sheet-based or network-based and what is the definition of wall thickness and relative density.

The analytical permeability model with the prediction errors below 5% is valuable since it points toward the efficient pre-screening procedure. Full pore-scale computational fluid dynamics becomes costly when many unit families, porosities and grading strategies have to be studied. The reduced-order models allow to rule out the non-suitable candidates before the simulation and printing. However, the reduced order modeling approach has to be applied on condition of manufacturing fidelity. The model created on the basis of the ideal geometry may overestimate the permeability in case of printing roughness that narrows throats and/or trapped particles that stay inside the channels. The optimal workflow includes analytical screening, manufacturability filtering, targeted simulation and experimental validation.

The multiscale construction example demonstrates that four-level TPMS generation can provide three pore scales that is relevant for the applications where macroflow and micro-surface interaction are both necessary. In biomedical scaffolds, hierarchical pores allow tissue migration, vascularization and local fluid exchange. In thermal applications, multiscale architecture allows the conduction, convection and pressure losses to take place on different scales. In environmental materials, the multiscale porosity allows wetting, retention and coating penetration. The drawback is that each additional scale increases the manufacturing sensitivity. A multiscale TPMS has to be accepted not because of biomimetic appearance, but because it can prove that the smallest features are buildable, accessible and stable during service.

The microfabrication evidence proves that the TPMS design can reach very small scales, but stresses the scale-dependent interpretation. Projection micro-stereolithography at the layer thickness of 5 µm and two-photon polymerization with several-micrometre features allows to make the micro-devices and metamaterials that are impossible with the coarser methods. At these scales, however, wall roughness, curing resolution, surface chemistry and size effects become dominant. Micrometre-scale TPMS structure intended for filtration or biomedical interface can not be evaluated through the same assumptions as millimetre-scale metal heat exchanger. The architecture-process-service framework remains relevant, but the relevant failure modes and transport regimes change.

The above results answer the research question by proving that the TPMS unit selection has to be done on the basis of the dominant service coupling. Primitive and gyroid surfaces are suitable for applications where the open transport and balanced performance are critical. Diamond surfaces are more justified for the applications where stiffness, lateral mixing or split-merge flow patterns are desirable. I-WP and F-RD surfaces are relevant for the case where the major objectives are the effective conduction, internal surface density or multiphysics property enhancement. Graded architecture has to be selected if the goal is not the maximization of the local response but the system-level trade-off. Sheet constructions are suitable for applications with the high surface-area and wall-continuity requirements, while the network constructions may be preferred where open void volume and lower blockage are needed. Manufacturing feasibility will then determine which of the above possibilities can be implemented.

6. Service Interpretation of Materials Exposure

The relationship between TPMS porous materials and service exposure is illustrated in Figure 12. The interlinked channels, which help in permeation and thermal conductivity, may turn into channels for environment entry into a TPMS. In an electrochemical, humid or biological environment, a metallic TPMS may experience internal geometrical effects on chemistry, oxygen gradient, wetness-dryness state, deposition and coating coverage. Figure 12 should not be considered as corrosivity information but rather to demonstrate that environmental-material interaction depends on architecture. A porous material that is not cleanable or coatable internally will act differently from a dense material of the same alloy. Similarly, an increased-surface TPMS will need treatment or coating processes considering internal access rather than just aesthetics.

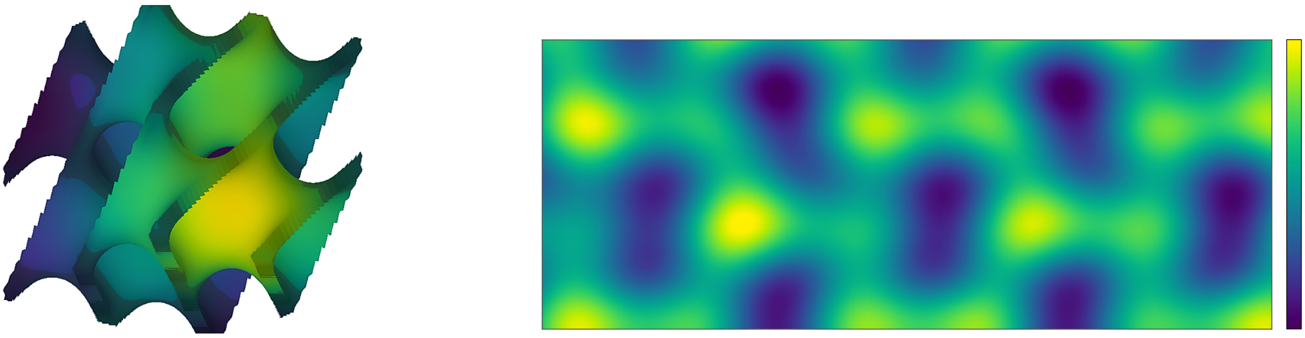

Figure 12: Internal surface-access fields.

Paired service panels confirm that internal accessibility needs to be understood in terms of material properties, rather than a secondary maintenance issue. Rendered TPMS body contains surface regions that are accessible to flowing media, whereas the unfolded field reveals heterogeneous access regions along the internal wall. Open regions in an external view can still have low-access pockets, gradual retention zones or surface regions shielded with coating. This point is important for porous metals, biomedical scaffolds, heat-transfer inserts and filtration supports as increased internal surface area that improves exchange is the same surface area that requires protection, cleaning or inspection during the service.

This exposure consideration is especially important for additively manufactured metals. Roughness of surface, partial melting and presence of residual powder can lead to the development of heterogeneous surfaces. In dense bodies, such surface irregularities are often removed by machining or polishing after fabrication. In TPMS bodies, many of those surfaces become internal and can be difficult to machine or polish. As a result, environmental resistance is tightly bound with architectural features. If the service involves the need of coolant flow through channels, the channels should remain open and chemically stable. If the service requires high resistance to corrosion, the body should be capable of passivation or coating penetration. If the service implies biological integration, surface chemistry and pore accessibility should be suitable for the response of particular tissues. All those considerations depend on geometry before chemical characteristics.

Service consideration also changes the priorities for thermal and permeability performance. The design that maximizes fluid access can maximize exposure to aggressive fluids. The design that minimizes pressure drop can create stagnation regions where undesired species can deposit. The design that increases surface area increases heat exchange, but also increases the amount of area that needs protection. Those are not the reasons to dismiss TPMS materials. They are reasons to specify the environment during the selection of geometry. The most appropriate TPMS architecture for a clean and closed heat exchanger will be different from TPMS architecture for a marine-exposed porous insert, biomedical scaffold or catalytic support.

The robust materials-exposure workflow should thus include three assessments. First is access, that is, whether the fluid, coating, cleaning medium or biological environment can reach the intended internal surfaces. Second is retention, that is, whether the geometry provides regions with slow velocity or stagnation where undesired species can remain. Third is recovery, that is, whether the body can be inspected, flushed, passivated or repaired after the service. Although those assessments are provided narratively, rather than as a list, they represent the issues that need to be considered before TPMS porous component is applied in the critical environment. Currently, TPMS investigations often consider mechanical and thermal properties, but service exposure can determine long-term reliability.

Contribution of the paper to materials science is thus the reframing of TPMS design from a printable geometry to a service-conditioned architecture. Internal surface is not only the area for heat transfer or biological support, but it is also the interface between the material and its environment. This interface is beneficial when reaction, exchange or integration is desired and harmful when corrosion, fouling and clogging dominate. Thus, the same TPMS characteristic can become a benefit or a liability, depending on service conditions. High surface area is a benefit for thermal exchange or catalysis, but a liability for unprotected corrosion exposure. Tortuosity is beneficial for mixing, but is detrimental to cleaning. Smooth continuous walls can reduce stress concentrations, but manufacturing residues can negate this benefit. Those conditional interpretations are the reason for integration of topology, process and service in a single manuscript.

7. Conclusion

The research question is about selection criteria for TPMS porous architectures when structural support, fluid transport, heat exchange and service access are coupled. The answer is that TPMS selection needs to be topology-resolved, construction-specific, process-aware and service-conditioned. Unit family should not be chosen based on visual preferences and porosity alone. Primitive and gyroid structures are defendable for transport-dominant and balanced multifunctional designs, diamond structures are defendable for applications where stiffness and split/merge pathways are important, and I-WP or F-RD structures are defendable where surface density, conduction pathways and effective-property improvement are key. Sheet and network constructions should be differentiated since they can produce different surface areas and load paths despite equal porosity.

Evidences provided above demonstrate that TPMS materials can outperform stochastic or conventional porous materials under appropriate conditions. Gyroid structure can provide improved heat transfer coefficient and approximately double heat dissipation under matched temperature difference. F-RD architecture can provide much higher effective thermal conductivity and stiffness than stochastic foam with equal porosity. Porosity gradient can substantially reduce pressure drop, while keeping substantial heat exchange. Directionality, accuracy of analytical models, multiscale construction and microfabrication capability further show that practical TPMS design space is wide but conditional. The conclusion is not that one structure type is superior everywhere. The conclusion is that each TPMS family occupies a particular region in coupled materials-performance space.

In case of additively manufactured materials, the final decision should incorporate the printing technology, minimum wall thickness, internal-channel accessibility, surface roughness and post-processing possibility. In case of service environments, the internal passages should be evaluated not just as performance-improving, but as exposure passages. Therefore, this manuscript confirms the necessity of the integrated architecture-process-service framework for TPMS porous materials. Such a framework is more reliable than the ranking based on single property since it bridges the mathematical surface with the printed geometry and further with the conditions under which the material will be used.

Conflict of Interest

The author declares no conflict of interest.

References

[1] Schoen, A. H. (1970). Infinite periodic minimal surfaces without self-intersections (Vol. 5541). National Aeronautics and Space Administration.
[2] WE, L. (1987). Marching cubes: A high resolution 3D surface construction algorithm. Computer graphics, 21(1), 7-12.
[3] Rajagopalan, S., & Robb, R. A. (2006). Schwarz meets Schwann: design and fabrication of biomorphic and durataxic tissue engineering scaffolds. Medical image analysis, 10(5), 693-712.
[4] Yoo, D. J. (2011). Computer-aided porous scaffold design for tissue engineering using triply periodic minimal surfaces. International Journal of Precision Engineering and Manufacturing, 12(1), 61-71.
[5] Kapfer, S. C., Hyde, S. T., Mecke, K., Arns, C. H., & Schröder-Turk, G. E. (2011). Minimal surface scaffold designs for tissue engineering. Biomaterials, 32(29), 6875-6882.
[6] Feng, J., Fu, J., Yao, X., & He, Y. (2022). Triply periodic minimal surface (TPMS) porous structures: from multi-scale design, precise additive manufacturing to multidisciplinary applications. International Journal of Extreme Manufacturing, 4(2), 022001.
[7] Kaur, I., & Singh, P. (2021). Flow and thermal transport characteristics of Triply-Periodic Minimal Surface (TPMS)-based gyroid and Schwarz-P cellular materials. Numerical Heat Transfer, Part A: Applications, 79(8), 553-569.
[8] Iyer, J., Moore, T., Nguyen, D., Roy, P., & Stolaroff, J. (2022). Heat transfer and pressure drop characteristics of heat exchangers based on triply periodic minimal and periodic nodal surfaces. Applied Thermal Engineering, 209, 118192.
[9] Samson, S., Tran, P., & Marzocca, P. (2023). Design and modelling of porous gyroid heatsinks: Influences of cell size, porosity and material variation. Applied Thermal Engineering, 235, 121296.
[10] Stallard, S., Jiang, H., Chen, Y., Bergman, T. L., & Li, X. (2023). Exploring the design space of the effective thermal conductivity, permeability, and stiffness of high-porosity foams. Materials & Design, 231, 112027.
[11] Lee, W. E. (2000). 'Cellular solids, structure and properties'. Materials Science and Technology, 16(2), 233.

[12] Abueidda, D. W., Bakir, M., Al-Rub, R. K. A., Bergström, J. S., Sobh, N. A., & Jasiuk, I. (2017). Mechanical properties of 3D printed polymeric cellular materials with triply periodic minimal surface architectures. Materials & Design, 122, 255-267.
[13] Maskery, I., Aboulkhair, N. T., Aremu, A. O., Tuck, C. J., & Ashcroft, I. A. (2017). Compressive failure modes and energy absorption in additively manufactured double gyroid lattices. Additive Manufacturing, 16, 24-29.
[14] Al-Ketan, O., Rowshan, R., & Al-Rub, R. K. A. (2018). Topology-mechanical property relationship of 3D printed strut, skeletal, and sheet based periodic metallic cellular materials. Additive manufacturing, 19, 167-183.
[15] Maskery, I., Sturm, L., Aremu, A. O., Panesar, A., Williams, C. B., Tuck, C. J., ... & Hague, R. J. (2018). Insights into the mechanical properties of several triply periodic minimal surface lattice structures made by polymer additive manufacturing. Polymer, 152, 62-71.
[16] Li, W., Yu, G., & Yu, Z. (2020). Bioinspired heat exchangers based on triply periodic minimal surfaces for supercritical CO2 cycles. Applied Thermal Engineering, 179, 115686.
[17] Qureshi, Z. A., Al-Omari, S. A. B., Elnajjar, E., Al-Ketan, O., & Al-Rub, R. A. (2021). Using triply periodic minimal surfaces (TPMS)-based metal foams structures as skeleton for metal-foam-PCM composites for thermal energy storage and energy management applications. International Communications in Heat and Mass Transfer, 124, 105265.
[18] Wang, F., Jiang, H., Chen, Y., & Li, X. (2021). Predicting thermal and mechanical performance of stochastic and architected foams. International Journal of Heat and Mass Transfer, 171, 121139.
[19] Gado, M. G., Al-Ketan, O., Aziz, M., Al-Rub, R. A., & Ookawara, S. (2024). Triply periodic minimal surface structures: Design, fabrication, 3D printing techniques, state-of-the-art studies, and prospective thermal applications for efficient energy utilization. Energy Technology, 12(5), 2301287.
[20] Hossain, M. S., Hossain, M. M., & Nilufar, S. (2025). An Overview of Additive Manufacturing of Triply Periodic Minimal Surface (TPMS) Structures. Polymers, 17(24), 3307.
[21] Li, J., Wang, L., He, X., Liang, J., & Dong, C. (2025). Additively manufactured metallic TPMS lattice structures: design strategies, fabrication, multifunctional properties, and applications. npj Advanced Manufacturing, 2(1), 45.
[22] Jung, Y., & Torquato, S. (2005). Fluid permeabilities of triply periodic minimal surfaces. Physical Review E—Statistical, Nonlinear, and Soft Matter Physics, 72(5), 056319.
[23] Montazerian, H., Davoodi, E., Asadi-Eydivand, M., Kadkhodapour, J., & Solati-Hashjin, M. (2017). Porous scaffold internal architecture design based on minimal surfaces: a compromise between permeability and elastic properties. Materials & Design, 126, 98-114.
[24] Li, W., Li, W., & Yu, Z. (2022). Heat transfer enhancement of water-cooled triply periodic minimal surface heat exchangers. Applied Thermal Engineering, 217, 119198.
[25] Liu, J., Cheng, D., Oo, K., McCrimmon, T. L., & Bai, S. (2024). Design and additive manufacturing of TPMS heat exchangers. Applied Sciences, 14(10), 3970.
[26] Zhianmanesh, M., Varmazyar, M., & Montazerian, H. (2019). Fluid permeability of graded porosity scaffolds architectured with minimal surfaces. ACS Biomaterials Science & Engineering, 5(3), 1228-1237.
[27] Ma, S., Tang, Q., Feng, Q., Song, J., Han, X., & Guo, F. (2019). Mechanical behaviours and mass transport properties of bone-mimicking scaffolds consisted of gyroid structures manufactured using selective laser melting. Journal of the mechanical behavior of biomedical materials, 93, 158-169.
[28] Asbai-Ghoudan, R., de Galarreta, S. R., & Rodriguez-Florez, N. (2021). Analytical model for the prediction of permeability of triply periodic minimal surfaces. Journal of the Mechanical Behavior of Biomedical Materials, 124, 104804.