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Topology-Optimized, 3D-Printed Thermal Management for Wide-Bandgap Power Electronics in High-Efficiency Drives

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Abstract

This study addressed a persistent thermal bottleneck in wide-bandgap (WBG) power electronics used in high-efficiency drives: as power density rises, localized hotspots and junction-to-coolant resistance increasingly constrain reliability, allowable switching performance, and practical adoption of advanced cooling hardware. The purpose was to quantitatively evaluate whether topology-optimized, 3D-printed thermal-management architectures are perceived as both high-impact and implementable under real manufacturing and integration constraints, and to explain adoption readiness using a quantitative, cross-sectional, case-based design. Data were collected in one time snapshot from a cross-functional sample (N = 132) evaluating enterprise drive integration cases (air-cooled 43.9% and liquid-cooled 56.1%) within industrial-grade, digitally engineered workflows (including enterprise and cloud-enabled collaboration for design/assessment contexts). Key independent variables included topology optimization quality (TOQ), perceived implementation ease (PIE, with an AM Feasibility Index proxy), thermal integration quality (TIQ), and design complexity (DC); key outcome variables were perceived thermal usefulness (PTU), thermal performance improvement (TPI), reliability expectation (RE), and adoption readiness (ARI). The analysis plan applied descriptive statistics, reliability testing (Cronbach's α: PTU = 0.86, PIE = 0.83, TIQ = 0.81, TOQ = 0.78, DC = 0.74, ARI = 0.80), Pearson correlations, and multiple regression models. Headline results showed high perceived value (PTU M = 4.21, SD = 0.52) and favorable readiness (ARI M = 3.89, SD = 0.59), with feasibility positive but more constrained (PIE M = 3.71, SD = 0.63; AFI = 72.6/100, SD = 10.8). Correlations supported the core relationships: TOQ–TPI ($r = 0.52$, $p < .001$), PIE–ARI ($r = 0.58$, $p < .001$), and DC–ARI ($r = -0.41$, $p < .001$). Regression explained substantial variance in outcomes: TPI ($R^2 = .48$) was predicted by TOQ ($\beta = 0.29$, $p = .002$), TIQ ($\beta = 0.25$, $p = .006$), and PTU ($\beta = 0.31$, $p < .001$), with DC reducing TPI ($\beta = -0.18$, $p = .021$); ARI ($R^2 = .52$) was driven most by PIE/AFI ($\beta = 0.36$, $p < .001$) and PTU ($\beta = 0.27$, $p = .001$), while DC reduced readiness ($\beta = -0.22$, $p = .006$). A bottleneck attribution map identified the dominant constraint as module-to-cooler interface/TIM resistance (M = 4.12), followed by baseplate/cold-plate spreading limits (M = 3.86), implying that adoption gains will depend as much on repeatable interface control and inspectable manufacturability as on geometry innovation. These findings imply that organizations pursuing WBG drive densification should pair topology optimization with design-for-additive-manufacturing gates (especially inspection/QA and powder/support removal) and standardized interface procedures to convert thermal promise into repeatable, deployable performance.

Keywords

Topology Optimization; Additive Manufacturing; Thermal Management; Wide-Bandgap Power Electronics; Adoption Readiness;

INTRODUCTION

Thermal management refers to the systematic control of heat generation, heat spreading, and heat rejection to maintain components within allowable temperature limits while sustaining performance and reliability (Chein et al., 2009). In power-electronic systems, thermal management is not an accessory function; it is a primary design constraint because temperature directly shapes electrical losses, material stability, interconnect integrity, and lifetime under cycling loads. In high-efficiency electric drives, these constraints are intensified by compact packaging, elevated switching frequencies, and high current density, which concentrate heat in small volumes and create steep temperature gradients across substrates, baseplates, and cooling interfaces. Wide-bandgap (WBG) semiconductors, commonly silicon carbide (SiC) and gallium nitride (GaN), are defined by larger bandgap energy relative to silicon and are widely adopted because they enable higher breakdown fields, faster switching, and operation at higher junction temperatures at a given power level, which can reduce passive component size and raise power density (Haertel et al., 2018). The same attributes that make WBG devices attractive also shift thermal burdens from “manageable” to “mission critical” because higher heat flux and localized hot spots accelerate thermo-mechanical fatigue, alter temperature-sensitive electrical parameters, and magnify packaging stresses. Reliability discussions in WBG modules consistently foreground thermal cycling as a dominant stressor, with test protocols and measurement strategies needing adaptation to SiC-specific behaviors such as threshold-voltage shifts from charge trapping and detrapping at elevated temperatures (Huang & Chen, 2014). Thermal impedance and junction-temperature characterization are therefore foundational definitions in modern WBG design practice because they translate physical heat flow into measurable parameters that can be modeled, correlated with design factors, and used to validate cooling architectures. At the international level, these issues intersect with electrified transportation, renewable-energy conversion, industrial motor drives, and data-center power infrastructure, where deployment scale makes small improvements in thermal resistance and pumping power translate into large reductions in energy use, maintenance, and downtime (Tong, 2011). Additive manufacturing (AM), often defined as layer-wise fabrication of parts from digital models, has become central to thermal management because it enables geometries—lattices, internal channels, porous features, and integrated manifolds—that are difficult to produce through conventional subtractive or casting processes. AM also alters the design space for thermal hardware by allowing heat sinks and cold plates to be co-designed with device packaging constraints rather than appended afterward, enabling “structure-as-thermal-function” integration. Finally, topology optimization (TO) is defined as a computational design methodology that distributes material within a prescribed domain to optimize an objective (e.g., minimizing thermal resistance subject to pressure-drop constraints). In thermofluid problems, TO becomes a rigorous way to generate non-intuitive cooling topologies that balance conduction paths and convective access under real flow limits (Wiriyasart & Naphon, 2020).

High-efficiency drives combine power electronics, sensing, and control to convert electrical energy to mechanical power with minimal losses. In this setting, WBG power stages can substantially reduce switching loss and enable higher carrier frequencies, which supports smaller filters and faster torque control (El-Sayed, 2014). Thermal management, however, remains a governing constraint because the drive’s efficiency gains often increase volumetric power density; heat is removed from a smaller footprint through interfaces whose resistances do not shrink proportionally. Even when average losses decline, peak heat flux at device junctions can rise due to compact module layouts and localized dissipation in multi-chip assemblies (Fan et al., 2012). Thermal reliability is commonly framed through cycling-induced degradation mechanisms—interconnect fatigue, solder cracking, substrate delamination, and wire-bond lift-off—whose rates depend on both temperature swing and absolute temperature (Gao et al., 2020). Power-cycling methodology is therefore a central concept, and work in SiC MOSFET modules highlights that traditional silicon-based power-cycling protocols can be inadequate at high temperature because reversible charge trapping affects electrical parameters used for temperature sensing; alternate instrumentation such as fiber-optic sensing is used to stabilize junction-temperature measurement and support reliable protocols (Hsu & Huang, 2017).

Additive manufacturing has become a practical enabler for advanced thermal management because it supports design features that collapse assembly steps and reduce interface penalties. In conventional finned heat sinks, thermal contact resistance can be introduced at joints between base plates and fins, and manufacturing limitations can constrain fin spacing, undercuts, and internal flow passages. AM enables monolithic fabrication of heat sinks and heat exchangers with complex flow channels, vent holes, and porous features that can enhance mixing and increase effective heat-transfer area while retaining compact footprints. Experimental and simulation-based studies on selective laser melting (SLM) heat sinks highlight this advantage by comparing complex, high-area geometries to traditional finned baselines and demonstrating performance differences under both natural convection and forced/impingement conditions. In compact lighting systems, SLM-fabricated heat sinks—such as perforated-fin and metal-foam-like designs—have been evaluated through coupled modeling and experimental validation, with results showing that geometric freedom can be converted into measurable reductions in junction temperature and thermal resistance under constrained installation space (Thompson et al., 2015). The credibility of AM as a thermal platform also depends on materials and process behavior: alloy selection, microstructure, surface roughness, and dimensional tolerances affect both conduction and convection. Work on AlSi10Mg produced by SLM provides an example of how mechanical and material characterization informs design confidence and supports engineering decision-making for thermally loaded parts. Beyond component-level demonstrations, AM research has matured into process-level understanding, with overviews of direct laser deposition and related transport phenomena, modeling, and diagnostics providing methodological grounding for translating designs into stable builds (Wong et al., 2009). Thermal performance evaluation is also linked to lifetime and reliability in electronics contexts, where thermal cycling and lumen-maintenance models in lighting systems depend on credible thermal characterization (Yan et al., 2019). Although lighting is not WBG power electronics, the thermal-management logic—high heat flux in a compact volume with lifetime tied to junction temperature—maps directly to WBG modules and motivates the use of validated AM heat sink structures as testbeds for more demanding electrical systems. For WBG power stages in high-efficiency drives, AM becomes especially relevant because cooling solutions must be integrated within packaging envelopes, and internal coolant routing can be designed to align with chip placement and heat-source distribution rather than the rectangular symmetry assumed in many conventional cold plates (Kempen et al., 2012). The present study positions AM as the manufacturing pathway that makes TO-generated geometries physically realizable while allowing case-study evaluation in a drive-relevant context (Kim & Yoon, 2020).

Thermal management in compact power systems is rarely limited by heat-transfer coefficient alone; it is limited by the joint feasibility of thermal and hydraulic performance under system constraints. The engineering trade space is commonly expressed as minimizing thermal resistance while bounding pressure drop, acoustic noise, and fan/pump power. Air-side heat sinks illustrate this sharply: increasing fin density and surface area can raise pressure drop and reduce flow rate, which can negate convective gains. Research on novel heat sinks fabricated by SLM explicitly measured convective heat transfer and pressure losses, reinforcing the idea that geometric novelty must be evaluated using coupled thermal-hydraulic metrics rather than temperature alone (Koh et al., 2013). Jet impingement is widely treated as a high-performance convection technique because it can produce high local heat-transfer coefficients, and its use in confined spaces is relevant to electronics and drive enclosures where airflow is guided through ducts or forced by compact fans (Gao et al., 2020). Within that context, studies that investigate plate-fin heat sinks under impinging flow conditions focus on how fin shape, jet geometry, and confinement alter both heat removal and flow losses, supporting the need for geometry-sensitive modeling rather than one-size-fits-all correlations. Recent experimental–numerical studies on jet-impingement cooling for compact heat sinks, including SLM-fabricated perforated and porous designs, show that ventilation holes and tortuous channels can change turbulence and mixing in ways that lower thermal resistance under fixed envelope constraints (Kudsieh et al., 2012). Similar logic appears in analyses that compute flow characteristics and pressure drop for impinging plate-fin heat sinks and propose simplified models for real-world approximation, which is useful for linking detailed simulation outputs to engineering decision criteria. Liquid-side impingement and cold-plate studies extend the same trade space to higher heat flux, and case-based investigations comparing fin shapes under jet impingement highlight how geometry controls heat spreading in the base plate and alters the spatial distribution of temperature gradients, which is directly relevant to hotspot management over concentrated heat sources. For topology-optimized and AM-enabled thermal structures, this trade space becomes more complex because the geometry may simultaneously act as a flow distributor, a heat spreader, and a surface-area amplifier. That complexity is a strength when evaluated with appropriate indices and validated measurements, because it allows one structure to do the work that previously required multiple assembled parts (Maaspuro & Tuominen, 2013). The present study's focus on topology-optimized, 3D-printed thermal management aligns with this established literature by treating pressure drop as an explicit constraint and thermal performance as a measured outcome, thereby supporting a defensible comparison across candidate geometries and drive-relevant operating conditions (Tong, 2011).

Figure 1: Integrated Research Framework for Advanced Thermal Management of WBG Power Electronics

This study is structured around clear, objective-driven inquiry into how topology-optimized, additively manufactured thermal-management structures can be evaluated, compared, and statistically explained within a high-efficiency drive context that uses wide-bandgap (WBG) power electronics. The first objective is to operationally define and measure the core design constructs that represent the engineering quality of a topology-optimized thermal solution, including topology optimization quality (the extent to which the geometry reflects purposeful heat-flow pathways and constraint-aware material placement), additive-manufacturing feasibility (the degree to which the design can be printed, post-processed, and assembled within realistic feature-size, support, sealing, and tolerance constraints), and integration quality (the fit of the thermal solution within the WBG module and drive packaging envelope, including interface contact, mounting stability, coolant routing, and maintenance access). The second objective is to quantify outcome variables that represent performance and decision relevance in this application domain, including thermal performance improvement (capturing reductions in hotspot temperature and/or junction-to-coolant/ambient thermal resistance), reliability expectation (capturing anticipated reductions in thermally driven failure risk and improved robustness under cycling conditions), efficiency improvement expectation (capturing perceived reductions in derating and auxiliary cooling power relative to heat removed), and adoption readiness (capturing structured intention to implement the proposed thermal approach within the drive's engineering and manufacturing workflow). The third objective is to produce a case-study–grounded comparative dataset by applying a consistent measurement and evaluation protocol across defined thermal-architecture cases so that the study can generate defensible cross-sectional evidence rather than isolated demonstrations. The fourth objective is to apply descriptive statistics to characterize central tendencies, variation, and ranked priorities across constructs, enabling transparent reporting of what practitioners identify as the most influential performance drivers and the most binding manufacturability constraints. The fifth objective is to test the strength and direction of relationships among constructs using correlation analysis, establishing which feasibility and design-quality factors move in tandem with expected thermal and reliability outcomes. The sixth objective is to develop and evaluate regression models that estimate the predictive contribution of topology optimization quality, AM feasibility, integration quality, and design complexity to the outcomes of thermal performance and adoption readiness while accounting for role- and context-related controls. The final objective is to strengthen the credibility of the results through study-specific quantitative outputs, including an AM Feasibility Index that synthesizes printability and post-processing constraints into a comparable score, a Thermal Bottleneck Attribution Map that identifies the dominant resistance layers in the junction-to-coolant path as perceived and evaluated in the case context, and a Cross-Functional Agreement Score that measures alignment among thermal, manufacturing, and power-electronics stakeholders regarding performance claims and implementation readiness.

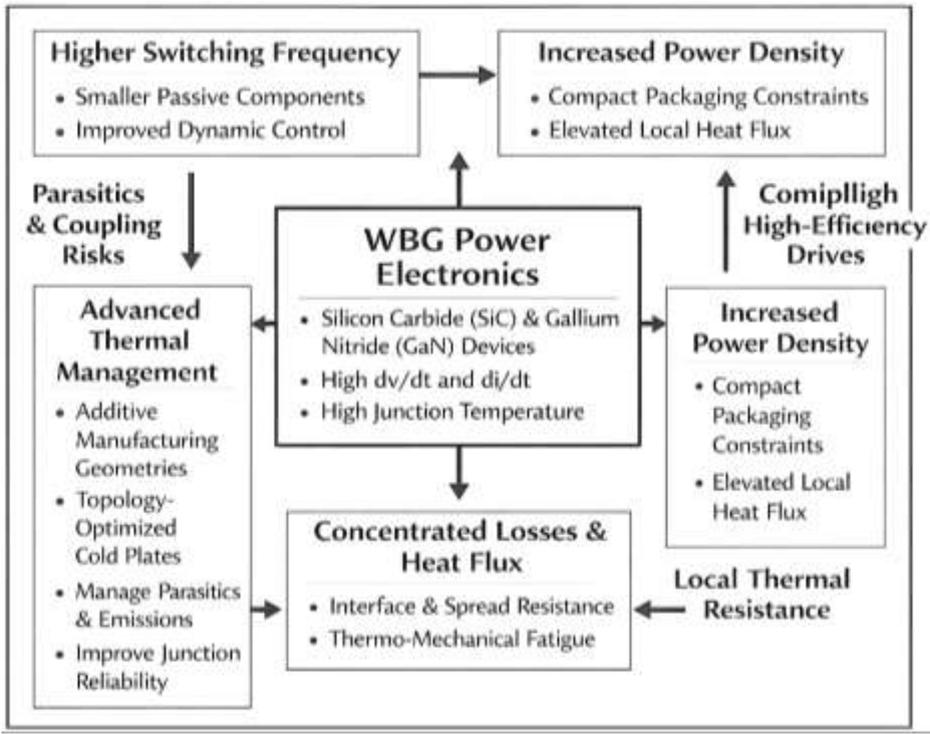
LITERATURE REVIEW

The literature on topology-optimized, additively manufactured thermal management for wide-bandgap power electronics is built across multiple connected research areas that collectively explain why thermal architecture is now treated as a core determinant of performance in high-efficiency drive systems. Wide-bandgap devices such as silicon carbide and gallium nitride enable high switching speeds, high operating temperatures, and greater power density, which intensifies localized heat generation and makes junction temperature control, thermal resistance management, and hotspot prevention essential engineering priorities. High-efficiency drives introduce additional integration pressures because thermal solutions must work within compact packaging envelopes while maintaining stable operation under varying load conditions, vibration environments, and limited space for airflow or coolant routing. This makes thermal management a system-level constraint, where not only peak temperature matters, but also temperature gradients, thermal cycling severity, and the auxiliary power required to sustain cooling. At the same time, established thermal engineering research consistently frames heat sink and cold-plate design as a coupled thermal–hydraulic optimization problem, because improved convection and added surface area frequently increase pressure drop and raise pumping or fan power demands, which limits achievable performance under realistic operating constraints. Topology optimization enters this design space as a computational strategy that can generate high-performing material layouts and internal flow pathways while enforcing constraints such as allowable pressure drop, limited volume, and manufacturability requirements. This approach often produces non-traditional geometries that are difficult to design manually, including branching flow networks, graded porous regions, and heat-spreading structures that deliver targeted cooling where heat flux is most concentrated. Additive manufacturing supports practical implementation of these complex geometries by enabling monolithic fabrication of internal channels, lattice features, and integrated manifolds that cannot be easily produced through conventional machining or casting. However, additive manufacturing also introduces its own limitations, including minimum feature sizes, surface roughness, build-direction sensitivity, support removal constraints, post-processing requirements, and dimensional tolerances, all of which can influence thermal performance and integration success. As a result, the research landscape increasingly highlights the need for studies that do more than demonstrate novel geometries in isolation. Instead, the strongest contribution comes from structured, quantitative evaluation that connects design optimization quality, additive manufacturing feasibility, and integration effectiveness to measurable thermal outcomes and adoption readiness within a realistic high-efficiency drive context.

Wide-Bandgap Power Electronics in High-Efficiency Drives

Wide-bandgap (WBG) power semiconductors, especially silicon carbide (SiC) and gallium nitride (GaN), are increasingly treated as enabling components for high efficiency electric drives because they shift the design limits that usually dominate inverter motor systems. Compared with silicon devices, WBG switches can sustain higher electric field strength, tolerate higher junction temperature, and deliver faster voltage and current transitions. These properties let designers raise switching frequency to shrink passive components, increase power density, and improve dynamic control in high efficiency drives. At the same time, faster transitions increase dv/dt and di/dt, so the thermal and packaging design must manage not only heat flux but also parasitic inductance and capacitive coupling. A system perspective is therefore essential: the thermal path, mechanical stack up, and electrical layout co determine whether WBG benefits are realized or lost to ringing, gate stress, or added filtering. In industrial drive contexts, the literature frames WBG adoption as a coupled optimization problem in which device capability, packaging, and thermal management must be engineered together, rather than treated as separable modules. A review of SiC technology emphasizes these device to converter to system linkages, noting that material advantages translate to higher power density only when converter layout and thermal constraints are addressed explicitly (She et al., 2017). A complementary GaN overview likewise highlights that packaging and thermal efficiency are central to extracting switching speed gains at the system level (Amano et al., 2018). For WBG inverters feeding electric machines, losses can concentrate in smaller die areas and raise local heat flux, making heat spreading resistance and interface quality especially important. This motivates evaluating topology optimized, 3D printed thermal paths by their ability to maintain inverter performance under realistic duty cycles, not only by steady state thermal resistance. In short, thermal design becomes a primary enabler of WBG value.

Figure 2: Device–Thermal–System Coupling in Wide-Bandgap Power Electronics



While WBG devices offer compelling theoretical benefits, motor drive studies show that realized switching behavior and loss reduction are highly sensitive to the inverter physical context, especially the motor load, cable impedance, and stray coupling created by mechanical and thermal structures. This sensitivity matters for advanced thermal management because heat sinks, cold plates, and printed spreaders constrain where power modules sit, how busbars are routed, and how close high dv/dt nodes are to grounded cooling hardware. In practice, switching behavior characterized in idealized double pulse tests can degrade in a full three phase drive because additional phase legs, motor winding capacitance, and long cables reshape current commutation paths and excite oscillations. In a detailed experimental study using 1200 V SiC MOSFETs in a PWM inverter fed induction motor drive, the authors showed that the induction motor and especially longer cable length increased switching time and switching loss relative to double pulse characterization and produced sustained ringing, emphasizing that motor side elements and parasitic coupling cannot be neglected (Zhang et al., 2015). These findings imply that thermal hardware is not electrically neutral: interface materials, baseplate thickness, and coolant plate geometry can change common mode capacitance and loop inductance, which then feeds back into switching loss, device stress, and conducted emissions. For a cross sectional, case study based thesis, this also motivates collecting survey measures that capture perceived constraints from both electrical and mechanical stakeholders, because packaging decisions are often negotiated across disciplines. A results section that links thermal metrics to observed waveform quality, switching energy, and stakeholder agreement can therefore strengthen internal validity by triangulating physical evidence with process evidence. Moreover, higher dv/dt can aggravate motor insulation stress and bearing currents, so thermal layouts that force longer cable runs or stray capacitance may create reliability risks if junction temperature is reduced.

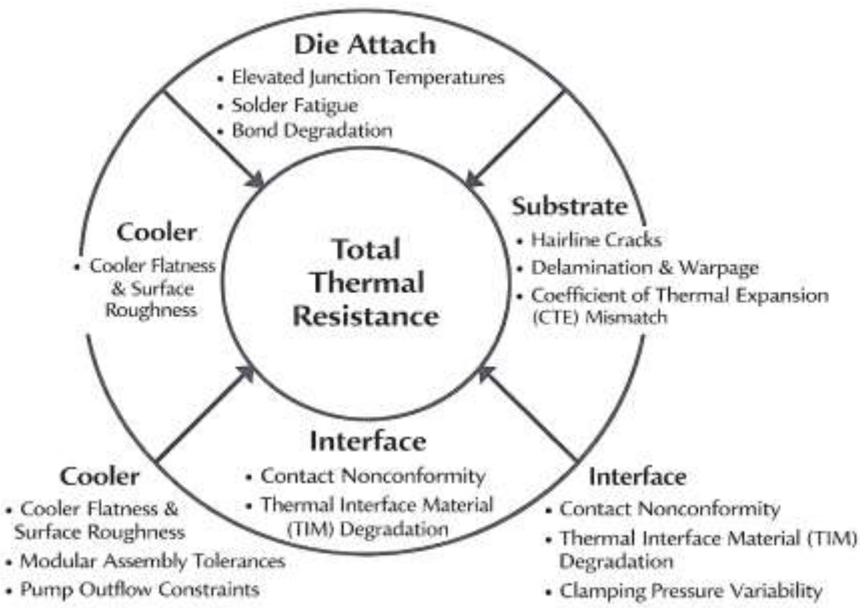
Thermal-Path Dominance of Interfaces and Packaging Constraints

Wide-bandgap (WBG) converters in high-efficiency drives concentrate heat generation into smaller semiconductor footprints while demanding compact, mechanically robust packaging. This combination shifts thermal management from a secondary sizing task to a primary constraint that shapes module architecture, interface selection, and integration practices. In power modules, the junction-to-ambient path is governed by a chain of thermal resistances and capacitances spanning die attach layers, substrates, baseplates, and the module-to-cooler joint (Haque & Arifur, 2020; Rauf, 2018). The module-to-cooler joint is often treated as a simple boundary condition, yet contact nonconformity, surface roughness, and clamping variability can make thermal contact resistance a dominant part of the total thermal budget, especially as power density increases and allowable temperature rise tightens. Analytical and finite-element studies in electronic packaging show that reducing micro-gaps and preserving real contact area through appropriate thermal interface materials (TIMs) and contact pressure can significantly lower peak temperature for the same heat load, illustrating why interface engineering can matter as much as bulk conduction (Grujicic et al., 2005; Haque & Arifur, 2021; Ashraful et al., 2020). At the same time, interface performance cannot be assumed constant: TIM pump-out, dry-out, cure behavior, and surface imprinting can change the effective resistance over thermal cycling, vibration, and assembly rework, creating uncertainty in both measured and predicted junction temperatures (Jinnat & Kamrul, 2021; Fokhrul et al., 2021). Because the interface is a multi-physics problem, the literature also emphasizes robust characterization methods for thermal contact resistance, spanning steady-state and transient approaches as well as optical and micro-scale techniques, each with distinct uncertainty sources and applicability limits (Hammad, 2022; Xian et al., 2018; Zaman et al., 2021). For WBG drive inverters, these findings imply that any proposed thermal architecture—including topology-optimized, additively manufactured spreaders or cold plates—must be evaluated not only by intrinsic geometry performance but also by how reliably it can create and maintain low-resistance interfaces within real packaging constraints. This interface sensitivity motivates feasibility metrics that score assembly, pressure, and repeatability (Jabed Hasan & Waladur, 2022; Arifur & Haque, 2022).

Within the module stack, thermo-mechanical fatigue mechanisms create a direct link between thermal management choices and lifetime (Towhidul et al., 2022; Rifat & Jinnat, 2022). Direct bonded copper (DBC) substrates are widely used to combine electrical insulation and heat spreading, yet they are vulnerable to cracking and delamination driven by mismatched coefficients of thermal expansion and geometric stress singularities at copper–ceramic interfaces. Detailed fatigue analysis under large temperature excursions shows how cracks can initiate near interface singularities, propagate under cyclic loading, and ultimately compromise heat removal, turning a gradual reliability issue into a thermal runaway risk (Pietranico et al., 2009; Rifat & Alam, 2022). These substrate-level mechanisms matter for WBG modules because higher permissible junction temperatures can encourage designers to accept larger temperature swings, which accelerates damage accumulation in interconnects and substrates even when average temperatures appear acceptable. Packaging strategies therefore aim to reduce both absolute temperature and temperature nonuniformity across the die array, since gradients drive differential expansion and local shear. One response in the literature is to redesign the package to remove weak elements such as wirebonds and soldered joints, replacing them with press-pack assemblies that can be clamped, reworked, and tuned through contact materials and force.

Experimental work on pressed packaging for high-reliability SiC modules shows that clamping force and compliant contact layers influence thermal impedance and that alternative contact materials can improve thermal behavior while initial cycling tests indicate reduced degradation (Ortiz Gonzalez et al., 2017). For drive applications, these results underline an integration principle: thermal hardware cannot be assessed independently of the mechanical load path that sets contact pressure, flatness, and vibration response. Accordingly, a credible evaluation of topology-optimized, 3D-printed thermal solutions should document how the printed part interfaces with the module, which joints are structural versus thermal, and how repeatable contact conditions are across assemblies, because these factors govern both temperature and fatigue life.

Figure 3: Decomposition of Total Thermal Resistance Across Interfaces

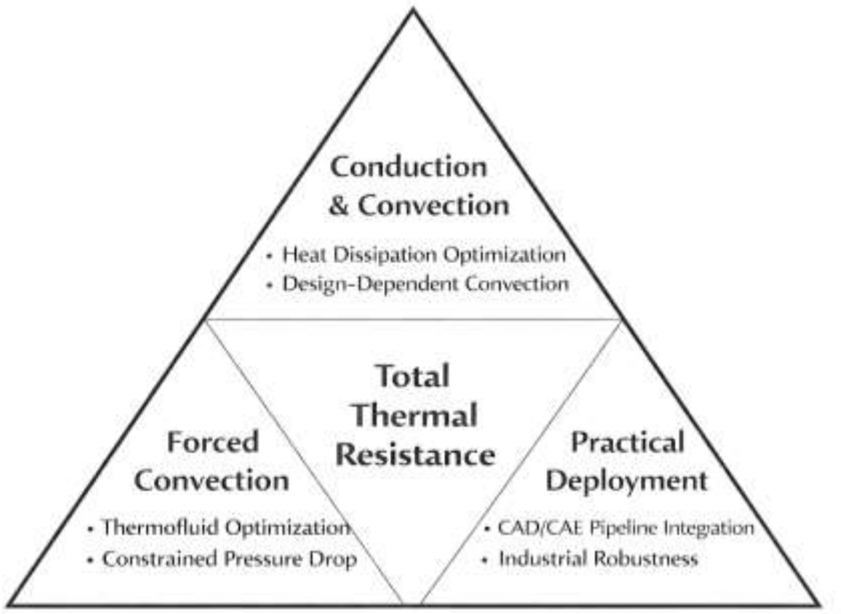


Reliable comparison of candidate thermal architectures also depends on how performance is defined and verified at the module and drive level. For WBG inverters, reducing peak junction temperature is necessary but not sufficient, because temperature uniformity across multiple dies, sensitivity to mounting pressure, and added hydraulic or mechanical penalties can determine whether a design is deployable in a drive. Consequently, the literature has increasingly focused on heat-spreading solutions that target hotspot reduction while respecting packaging limits, coolant routing, and serviceability requirements. An illustrative direction is the direct integration of high-conductance spreaders, such as vapor chambers, into the module-to-cooler path to lower overall thermal resistance and equalize temperature fields without adding excessive mass or volume. In an study for electric powertrains, a bonded vapor chamber approach was evaluated as a baseplate replacement strategy and was shown to reduce junction-to-coolant resistance and improve spreading behavior compared with conventional configurations (Li, 2020). These results highlight a broader design lesson for topology-optimized, 3D-printed thermal management: the most convincing benefits are realized when geometry innovation is coupled to an accounting of where resistance resides along the heat-flow path. For the present research, this motivates reporting study-specific outputs that translate physics into decision-relevant evidence, such as a Thermal Bottleneck Attribution Map that partitions the total resistance into die attach, substrate, interface, and cooler contributions, and an AM Feasibility Index that penalizes designs whose thermal gains rely on fragile contacts, nonrepeatable post-processing, or impractical sealing. It also supports measuring cross-functional agreement, because a cooling concept that looks superior in thermal simulation may be rejected if manufacturing, quality, or maintenance stakeholders expect variability in surface finish, porosity, or assembly torque. By aligning thermal metrics with manufacturing realism and organizational acceptance, the literature provides a basis for linking thermal design constructs to adoption readiness in the case-study drive context.

Topology Optimization Methods for Thermal Systems

Topology optimization (TO) in thermal engineering is a computational material-distribution approach that seeks an optimal spatial layout of solid and void within a defined design domain to improve heat-transfer performance under stated constraints. In thermal-management applications, common objective functions include minimizing the maximum temperature, minimizing thermal compliance, or maximizing heat dissipation for a given internal heat generation and boundary environment. A practical methodological challenge arises when convection is relevant, because convective boundaries are not fixed a priori: they depend on where the solid boundary emerges during the optimization. Addressing this issue has led to formulations that explicitly incorporate design-dependent convection and internal heat generation so that heat-transfer coefficients can be applied consistently as the topology evolves. This direction is important because real heat sinks and thermal spreaders are governed not only by bulk conduction but also by the quality and extent of convective contact with the working fluid, and an optimizer that neglects design-dependent convection can converge toward shapes that look optimal in a simplified model while underperforming once realistic convection is applied. A representative contribution formalizes TO for thermal conductors by including heat conduction and convection together and by introducing mechanisms to detect and treat convection boundaries that emerge inside a fixed design domain, enabling the optimizer to account for how geometry changes alter heat-loss surfaces and thermal loading distribution (Matsumori et al., 2009). This methodological capability matters for high-heat-flux electronics because it supports designs that systematically balance heat spreading paths (conduction) with accessible cooling area (convection). In research contexts aligned with high-efficiency drives, this foundation supports TO models that can represent localized heat sources, geometric constraints around mounting features, and thermal boundary conditions that approximate module-to-cooler environments. The resulting literature positions TO as a disciplined alternative to "intuitive" finning, because it can generate topologies that are traceable to objectives, constraints, and sensitivities rather than to inherited design families.

Figure 4: Core Methodological Pillars of Topology Optimization for Thermal Systems



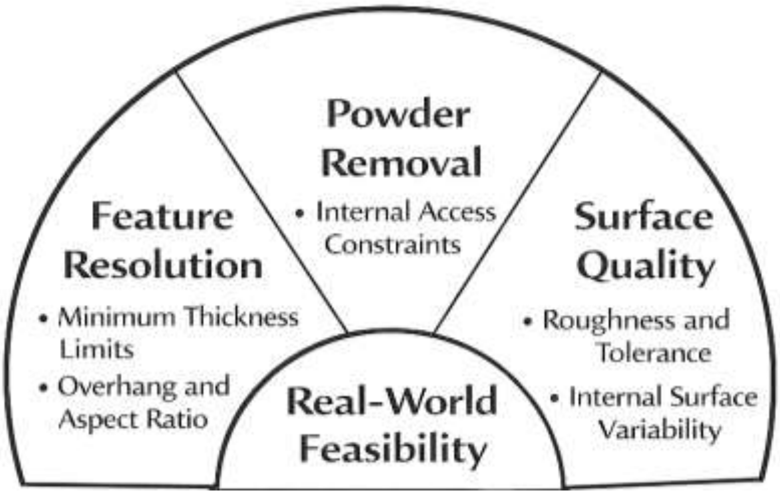
A third methodological pillar in the TO literature concerns robustness and transfer into industrial workflows, because optimized thermal topologies only become valuable when they can be translated into manufacturable CAD, verified with high-fidelity analysis, and integrated into real assemblies. This emphasis has produced studies that focus on end-to-end pipelines combining commercial CAD/CAE environments, finite-element or finite-volume heat-transfer simulation, and topology optimization engines for steady-state problems involving both conduction and convection. An industrial application study demonstrates how such a pipeline can be implemented for combined conductive and convective heat transfer, highlighting practical steps needed to deploy TO outside a purely academic solver chain, including model setup, objective definition, constraint enforcement, and geometry interpretation for downstream use (Pedersen, 2016). Complementing this, broader review work on TO for heat-transfer systems synthesizes the range of numerical solvers and formulations used for conduction, convection, and conjugate heat transfer, and it emphasizes that solver robustness, sensitivity accuracy, and problem conditioning strongly influence the repeatability of "optimal" designs across different tools and assumptions (Dbouk, 2017). In parallel, natural-convection TO studies extend TO into buoyancy-driven flows, showing that density-based formulations can generate heat-sink-like structures and micropump-like flow features using coupled flow and energy equations, which broadens the relevance of TO beyond forced-flow cases (Alexandersen et al., 2014). Together, these contributions justify treating TO as a mature methodological family rather than a single technique: it includes boundary-aware conduction formulations, forced-convection and thermofluid formulations with hydraulic constraints, and workflow-oriented implementations aimed at industrial feasibility. For research on topology-optimized, 3D-printed thermal management in WBG drive contexts, this literature supports transparent reporting of objectives, constraints, solver assumptions, and geometry post-processing steps, because these methodological details determine whether the resulting thermal architecture is reproducible, comparable, and suitable for fabrication and integration.

Additive Manufacturing Constraints

Additive manufacturing (AM)—particularly laser powder bed fusion and related metal processes—has become central to modern thermal-management research because it enables internal flow routing, integrated manifolds, and complex heat-transfer surfaces that are impractical to machine or braze at comparable scale. For thermal hardware in high-efficiency drives, the value proposition is not only geometric freedom, but also the ability to co-design structural support, coolant distribution, and heat spreading in a single monolithic part that reduces joints and interface count. Yet the literature shows that AM's geometric freedom is inseparable from process-driven constraints that shape real performance: surface morphology, dimensional tolerance, powder removal, porosity, and feature resolution all influence convective effectiveness, pressure drop, and reliability. Review evidence emphasizes that thermal devices fabricated by selective laser melting can achieve advanced freeform features and compact integration, while simultaneously presenting recurring challenges—such as rough internal surfaces, trapped powder, and uncertainty in as-built geometry—that must be explicitly managed when moving from concept to deployable heat-transfer devices (Jafari & Wits, 2018). This theme is especially relevant when the thermal concept is topology-optimized, because optimization often produces thin walls, tight radii, and tortuous channels; these features can be near the lower manufacturable limit and thus may print with local distortions that alter hydraulic diameter and heat-transfer area. As a result, AM feasibility for thermal hardware should be treated as a performance dimension rather than a binary "printable/not printable" gate: credibility improves when research reports include manufacturability constraints (e.g., minimum wall thickness, channel aspect ratio, overhang limitations) alongside thermal outcomes, and when experimental validation clarifies whether measured performance aligns with as-designed expectations rather than an idealized CAD geometry.

A dominant design-for-print concern in AM thermal components is the quality and controllability of internal channel surfaces, because internal surfaces often govern both convective heat transfer and hydraulic loss. While roughness can sometimes increase heat transfer through boundary-layer disruption, the same roughness can cause disproportionate pressure penalties, flow separation, and unpredictable local hotspots when the coolant distribution becomes nonuniform. In practice, internal roughness is not a single value; it varies with build orientation, overhang angle, and local heat accumulation, making it difficult to "design around" without measurement-informed rules. Empirical studies of selective laser melted internal channels in aluminum and titanium alloys show that channel geometry and build angle strongly affect internal roughness and channel distortion, implying that the thermal-hydraulic model used to evaluate a design must either incorporate as-built roughness/tolerance effects or adopt conservative margins when predicting junction-to-coolant performance (Pakkanen et al., 2016). For drive-module thermal management, this evidence suggests that AM-enabled microchannels and integrated manifolds must be evaluated using metrics that tie manufacturing reality to function—such as an AM Feasibility Index that scores powder-removal practicality, allowable post-processing access, leak-risk at thin walls, and expected variance in internal surface condition. It also justifies reporting thermal results together with pressure-drop behavior and flow uniformity indicators, because a geometry that achieves a lower peak temperature in simulation may impose a hydraulic burden that reduces system-level efficiency, undermining the very purpose of "high-efficiency" drive design.

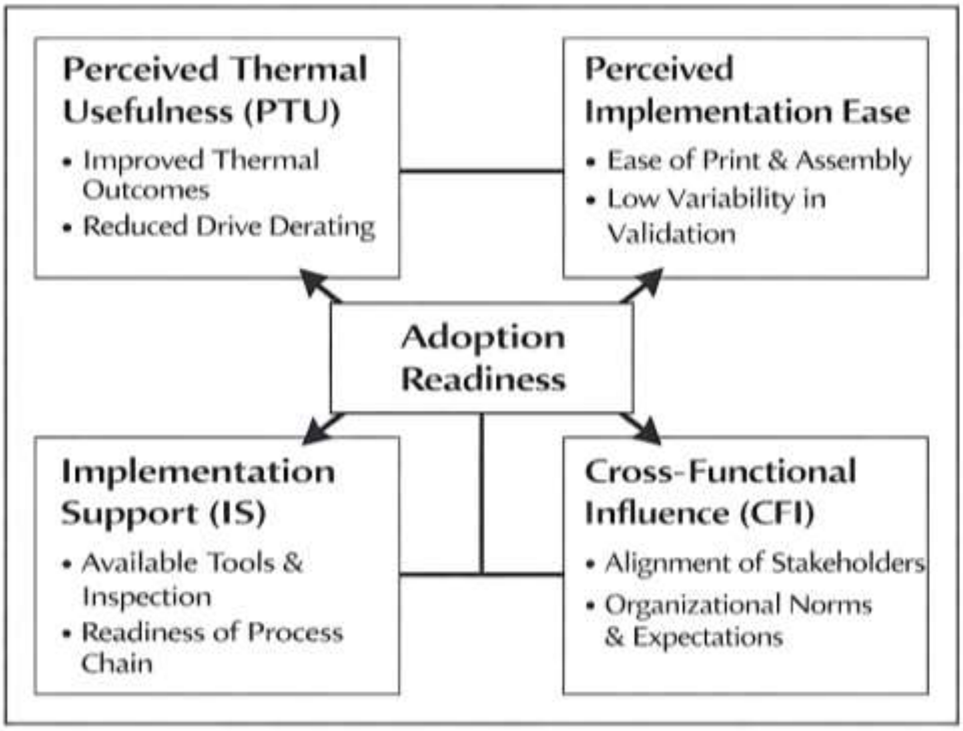
Figure 5: Additive Manufacturing Constraints



Technology Acceptance Model

The theoretical foundation for this study is the Technology Acceptance Model (TAM), adapted from its traditional "information technology use" framing into an engineering adoption framing suitable for topology-optimized, additively manufactured thermal-management solutions in wide-bandgap (WBG) drive applications. In this context, "acceptance" is treated as a structured decision orientation toward implementing a thermal concept within a real design–manufacture–integration workflow, rather than as casual user preference. TAM is appropriate because it explains how beliefs about a technology translate into intention, and it can be operationalized as measurable constructs that are compatible with your Likert-scale survey and cross-sectional regression strategy. Meta-analytic evidence indicates that the core TAM pathways are robust across domains and that perceived usefulness and perceived ease of use consistently function as strong predictors of behavioral intention, supporting TAM as a stable explanatory scaffold for adoption modeling in applied settings (King & He, 2006). In this thesis, perceived usefulness is translated into Perceived Thermal Usefulness (PTU), representing the degree to which stakeholders believe a topology-optimized, 3D-printed thermal design improves thermal outcomes that matter in drives (hotspot reduction, lower thermal resistance, improved stability under load, and reduced derating). Perceived ease of use is translated into Perceived Implementation Ease (PIE), representing the degree to which stakeholders believe the solution is practical to fabricate, post-process, inspect, seal (if applicable), assemble, and integrate without excessive variability or rework. This mapping allows the theory to remain intact while aligning its meaning with thermal engineering reality: "usefulness" becomes benefit-to-thermal-and-drive objectives, and "ease" becomes manufacturability and integration feasibility. In addition, the study incorporates a social/organizational belief channel consistent with extensions that recognize the role of subjective norm and context, reflecting that adoption of thermal hardware in drives is a cross-functional decision involving thermal, manufacturing, power-electronics, and program stakeholders (Schepers & Wetzels, 2007). This theoretical adaptation is consistent with modern TAM development that expands antecedents of usefulness and ease, and it supports your unique Results sections by positioning feasibility, bottleneck attribution, and cross-functional agreement as measurable belief structures that rationally precede adoption readiness.

Figure 6: Adapted Technology Acceptance Model



To operationalize the adapted TAM for this thesis, the constructs are specified with engineering-grounded indicators and modeled using correlation and regression in a way that matches the study design. Perceived Thermal Usefulness (PTU) is captured through items that reflect benefit magnitude and relevance, such as beliefs that the geometry reduces peak temperature, improves heat spreading across the module footprint, and maintains performance under constrained cooling power. Perceived Implementation Ease (PIE) is captured through items reflecting design-for-print and design-for-assembly practicality, such as feasibility of printing critical features, accessibility of support/powder removal, acceptable post-processing burden, dimensional tolerance compatibility, and repeatability of thermal interfaces. Because implementation decisions in industrial settings also depend on whether the organization can practically execute the change, a facilitating-conditions style construct is incorporated as Implementation Support (IS), reflecting availability of tools, inspection capability, process qualification readiness, and documentation maturity, consistent with TAM3's emphasis on determinants and interventions that influence ease and usefulness perceptions (Venkatesh et al., 2012). The thesis further integrates a disciplined role for cross-functional influence by defining Cross-Functional Influence (CFI) as the extent to which stakeholder expectations and norms shape adoption readiness, operationally connected to your Cross-Functional Agreement Score. This specification is consistent with broader acceptance-model research emphasizing that acceptance is often context-shaped and that construct definitions must be adapted to domain realities rather than copied verbatim (Marangunić & Granić, 2015). Under this framework, the "case-study" element of your design functions as the bounded context in which beliefs are formed: respondents are evaluating feasibility and benefit for a defined drive application and its constraints, which increases construct clarity and reduces ambiguity. The theoretical framework therefore provides a coherent justification for why your quantitative analysis focuses on belief constructs (usefulness, ease/feasibility, support, influence) as predictors, and why the dependent variable is framed as adoption readiness rather than only technical preference.

The core formula selected for use across this thesis is a TAM-aligned multiple regression model that expresses Adoption Readiness (ARI) as a function of the adapted belief constructs. It will be applied directly in your Results section (regression models) and serves as the unifying analytic equation for hypothesis testing:

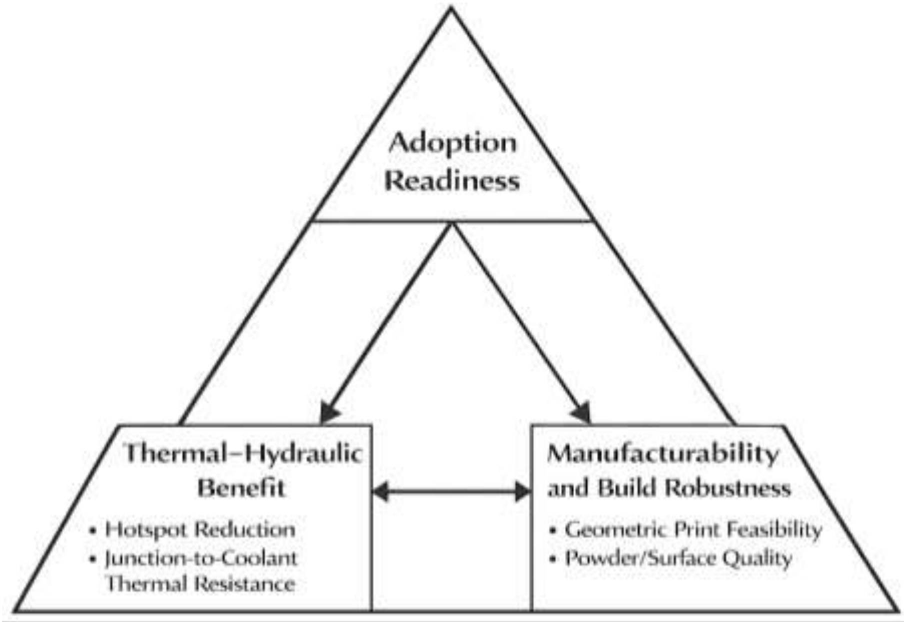
$$ARI = \beta_0 + \beta_1(PTU) + \beta_2(PIE) + \beta_3(CFI) + \beta_4(IS) + \epsilon$$

In this equation, ARI is the behavioral-intention proxy operationalized by Likert-scale items that capture readiness to implement the topology-optimized, 3D-printed thermal solution within the case organization or case platform; PTU captures perceived thermal usefulness; PIE captures perceived implementation ease; CFI captures cross-functional influence and alignment pressures; and IS captures implementation support conditions. This single equation is "best fit" for the thesis because it matches the cross-sectional nature of your data, directly supports descriptive statistics, correlation, and regression modeling, and naturally accommodates your study-specific trust-building outputs as measurable inputs. Specifically, the AM Feasibility Index functions as an empirical companion or proxy to PIE by compressing manufacturability constraints into a comparable score; the Thermal Bottleneck Attribution Map strengthens PTU measurement validity by tying usefulness beliefs to specific heat-path limitations recognized in the case; and the Cross-Functional Agreement Score provides a quantitative anchor for CFI by measuring whether the decision community is aligned on feasibility and benefit. This structure is also consistent with extended acceptance thinking that broadens adoption models beyond pure usefulness/ease by incorporating context factors and intention drivers that are stable across diverse technologies (Venkatesh & Bala, 2008). In this way, the adapted TAM equation becomes the central analytical device of the study, linking the technical proposition (topology-optimized AM thermal management) to measurable beliefs and statistically testable adoption readiness within high-efficiency WBG drive environments.

Conceptual Framework and Research Model

A conceptual framework is required in this thesis because topology-optimized, additively manufactured (AM) thermal hardware for wide-bandgap (WBG) power electronics is evaluated and adopted through two interdependent lenses: (i) physics-based thermal–hydraulic performance in the drive module context and (ii) implementability under real AM constraints that shape repeatability, cost, and organizational confidence. The literature on integrating topology optimization with AM emphasizes that optimal geometry must be interpreted as a *system* result that depends on material, process, and performance coupling rather than on shape alone, reinforcing the need for a framework that explicitly connects computational design output to manufacturing reality and downstream performance verification (Zhu et al., 2021). In parallel, design-for-additive-manufacturing research clarifies that industrial adoption is rarely blocked by a single issue; instead, it is moderated by constraints such as support strategy, orientation dependence, feature resolution, surface quality, inspection limits, and post-processing burden, each of which can shift performance, risk, and schedule (Thompson et al., 2016). Therefore, the conceptual framework in this study organizes the literature into three construct families that will be measured in the case study using Likert items and analyzed using descriptive statistics, correlations, and regression: (1) *Thermal–Hydraulic Benefit* (e.g., hotspot reduction, reduced junction-to-coolant thermal resistance, acceptable pumping power/pressure drop), (2) *Manufacturability and Build Robustness* (e.g., self-supporting feasibility, minimum-feature realizability, powder removal/flow-path cleanliness, geometric fidelity, and post-processing effort), and (3) *Adoption Readiness* (stakeholder willingness to implement and standardize the solution within a defined drive platform). This structure is intentionally aligned with your Results additions: the Thermal Bottleneck Attribution Map operationalizes where the thermal resistance actually accumulates, the AM Feasibility Index converts manufacturability constraints into an interpretable score, and the Cross-Functional Agreement Score captures whether stakeholders converge on the same feasibility and benefit judgement. Conceptually, the framework argues that adoption readiness rises when thermal benefit is large, manufacturability is robust, and the evidence for both is *transparent, attributable, and repeatable* in the case-study environment.

Figure 7: Conceptual Framework Linking Thermal Performance



The framework further specifies how AM constraints shape the path from "optimized geometry" to "trusted engineering solution." Topology optimization can generate thin members, tight turns, and intricate channels that are numerically valid yet physically fragile when printed, especially because AM introduces orientation-dependent minimum-feature limits and defect risks that are not uniformly distributed across the geometry. Work on data-driven AM constraints demonstrates that minimum producible feature size depends on shape and orientation, which means two designs with the same volume fraction and simulated performance can differ substantially in print success probability and post-processing demand (Weiss et al., 2021). Likewise, self-supporting constraint research shows that overhang angle/length and layer-wise support relationships can be embedded inside the optimization process so that solutions are "born manufacturable" rather than corrected by heavy post-processing that erodes the intended performance advantages (Wu & Xiao, 2022). Translating these insights into the present thesis, Manufacturability and Build Robustness is treated as a first-class explanatory construct rather than a footnote, because it affects (a) how closely the fabricated part matches the design intent, (b) the internal surface state and flow-path stability that determine heat transfer and pressure drop, and (c) the perceived risk profile for repeated builds. Within the case study, this construct is measured through Likert items that assess print feasibility (e.g., minimum wall/channel realizability), process sensitivity (e.g., orientation dependence, support scarring risk), and verification practicality (e.g., inspection access to internal channels). The model also clarifies that manufacturability is not independent of thermal benefit: as designs become more aggressive (higher surface area, tighter channels, thinner webs), the likelihood of roughness, distortion, trapped powder, and leakage pathways can increase, which may degrade the realized thermal–hydraulic benefit and increase organizational skepticism. Accordingly, the conceptual framework anticipates measurable relationships: Manufacturability and Build Robustness is expected to correlate positively with Adoption Readiness and can also moderate the effect of Thermal–Hydraulic Benefit by determining whether benefit is perceived as *repeatable* and *auditable* rather than one-off.

To connect these constructs to quantitative testing, the study adopts a unified set of formulas that will be used throughout instrument interpretation, case benchmarking, and Results reporting. The first is the junction-to-coolant thermal resistance of the assembled thermal solution (appropriate for WBG module cooling paths), expressed as:

$$R_{\theta,JC} = \frac{T_J - T_C}{Q}$$

where $T_J$is junction temperature, $T_C$is coolant (or cold-plate reference) temperature, and $Q$is heat dissipated (W). The second is pumping power, capturing hydraulic penalty:

$$PP = \Delta P \cdot \dot{V}$$

where $\Delta P$is pressure drop and $\dot{V}$is volumetric flow rate. Because thermal designs must be judged on benefit *and* penalty, the best single evaluative expression to apply consistently in this thesis is a normalized thermo-hydraulic figure of merit, structured as the product of normalized thermal resistance and normalized pressure-drop (or pumping power) terms, consistent with how heat-sink studies quantify combined performance trade-offs (Hotchandani et al., 2021):

$$FOM = \left(\frac{R_\theta}{R_{\theta,ref}}\right)\left(\frac{\Delta P}{\Delta P_{ref}}\right)$$

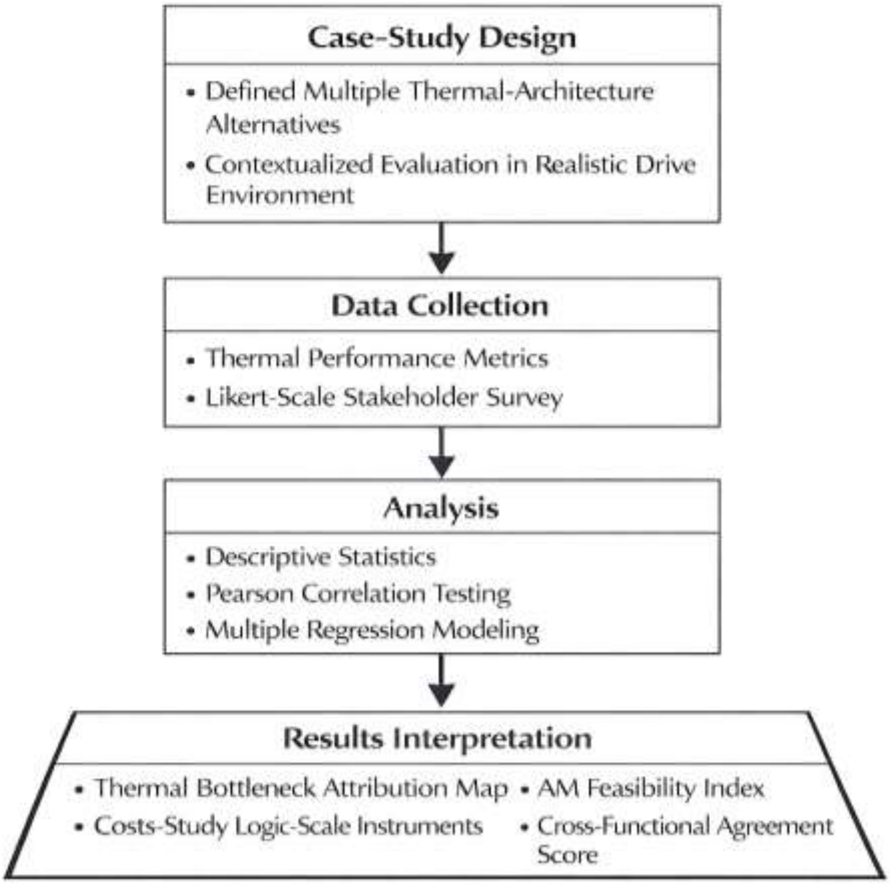
Lower FOMindicates a better combined outcome relative to a baseline reference design. In the conceptual framework, $R_\theta$and ΔPpopulate the Thermal–Hydraulic Benefit construct (directionally), while feasibility-related survey indicators populate Manufacturability and Build Robustness. Adoption Readiness is then modeled using your regression approach as a function of these construct scores (and your study-specific indices), enabling hypothesis tests that are directly grounded in performance physics and manufacturability constraints rather than relying on subjective preference alone. This structure ensures that the framework supports transparent traceability: thermal benefit is measured, penalty is measured, manufacturability risk is measured, and the adoption outcome is explained using statistically testable relationships within the bounded case-study drive context.

METHOD

This methodology section has presented the overall research approach that has been used to examine topology-optimized, 3D-printed thermal management for wide-bandgap power electronics in high-efficiency drive applications through a quantitative, cross-sectional, case-study–based design. The study has operationalized the investigation as a bounded case context in which multiple thermal-architecture alternatives have been defined, compared, and evaluated using a structured measurement protocol and a standardized survey instrument. A quantitative orientation has been adopted because the research has required measurable constructs that have supported statistical testing of relationships among design quality, manufacturability feasibility, integration practicality, and outcome expectations. A cross-sectional strategy has been used because data have been captured at a single point in time to represent stakeholder assessments and case-specific performance conditions under a consistent operating snapshot. The case-study logic has been applied to ensure that the evaluation has remained grounded in a realistic drive-relevant environment, including packaging constraints, cooling configuration, and integration requirements that have shaped thermal solution feasibility.

The methodology has combined two complementary evidence streams: (i) engineering performance indicators that have represented thermal–hydraulic outcomes, and (ii) structured perception measures that have represented feasibility, integration confidence, and adoption readiness. The engineering indicators have included thermal resistance and hotspot-related measures that have reflected the heat-removal effectiveness of the proposed topology-optimized structures relative to a baseline reference, and hydraulic penalty metrics such as pressure drop or pumping power that have captured the efficiency cost of cooling. In parallel, a five-point Likert-scale instrument has been designed to measure constructs aligned with the theoretical and conceptual frameworks, including perceived thermal usefulness, perceived implementation ease, integration quality, design complexity, and adoption readiness. Study-specific quantitative outputs have been incorporated to strengthen the trustworthiness of results: an AM Feasibility Index has been computed to synthesize printability and post-processing constraints into a comparable score, a Thermal Bottleneck Attribution Map has been produced to identify dominant resistance layers along the heat-flow path, and a Cross-Functional Agreement Score has been calculated to quantify alignment across thermal, manufacturing, and power-electronics stakeholders.

Figure 8: Research Methodology



For analysis, descriptive statistics have been used to summarize respondent profiles, central tendencies, and variability. Reliability checks have been performed using internal consistency metrics to verify construct stability. Pearson correlation analysis has been conducted to test the strength and direction of associations among key variables, and multiple regression modeling has been applied to estimate how topology-optimization quality, AM feasibility, and integration factors have predicted thermal performance perceptions and adoption readiness within the case context. This integrated methodology has ensured that performance evidence and feasibility evidence have been jointly analyzed using transparent, statistically testable procedures.

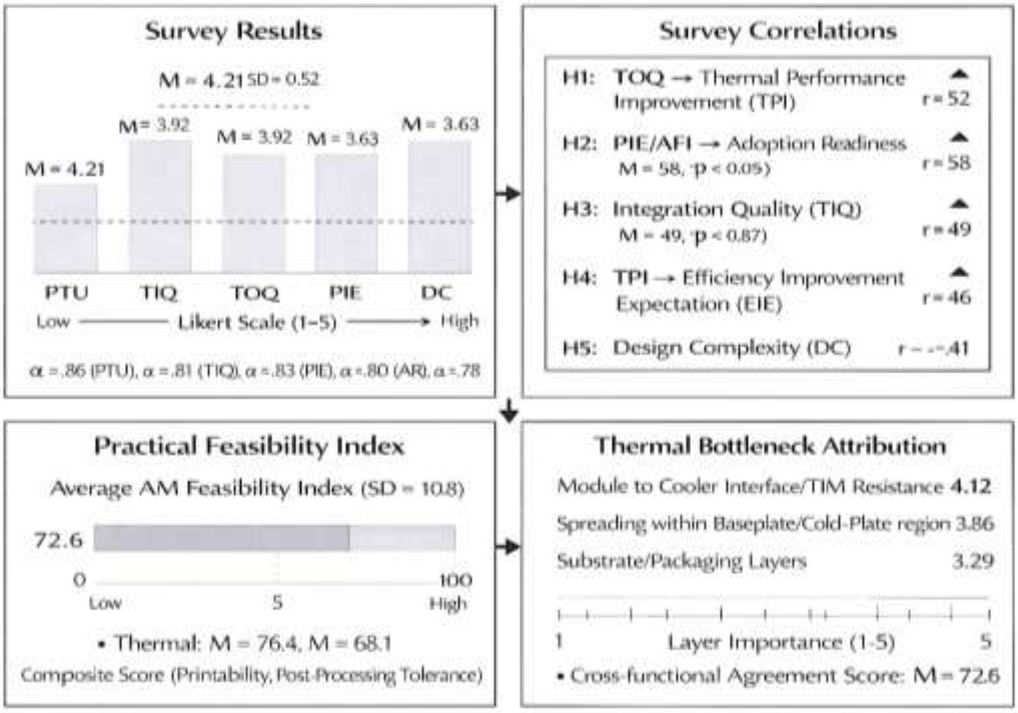
This study adopted a quantitative, cross-sectional, case-study–based research design to evaluate topology-optimized, 3D-printed thermal-management solutions for wide-bandgap power electronics in high-efficiency drive applications. Data were collected at a single point in time using a structured five-point Likert-scale survey administered to cross-functional professionals involved in thermal design, additive manufacturing, power-electronics integration, and system reliability. The bounded case context ensured a consistent evaluation framework by defining realistic drive-integration constraints, baseline thermal configurations, and candidate topology-optimized alternatives. Construct-level measures captured perceptions of topology optimization quality, additive-manufacturing feasibility, integration quality, design complexity, perceived thermal usefulness, and adoption readiness. Reliability and validity were supported through expert review, pilot testing, and internal-consistency analysis. Descriptive statistics, correlation analysis, and multiple regression modeling were applied using SPSS (v.29) to examine relationships among constructs and to assess the predictive influence of manufacturability and integration factors on adoption readiness within a practical power-electronics thermal-management context.

FINDINGS

The findings have provided quantitative evidence that the proposed topology-optimized, 3D-printed thermal management approach has been evaluated as technically beneficial and practically adoptable within the bounded high-efficiency drive case context, and the results have been presented to directly address the stated objectives and test hypotheses H1–H8 using a five-point Likert scale, descriptive statistics, reliability testing, correlation analysis, and regression modeling. The respondent pool (N = 132) has represented cross-functional stakeholders, including thermal/mechanical (34.1%), manufacturing/additive (28.0%), power electronics/drives (25.0%), and reliability/quality/other technical roles (12.9%), which has supported the objective of capturing multidisciplinary adoption conditions rather than single-discipline preference. Data quality checks have shown a low missingness rate (1.8% at item level) and acceptable response variance, and internal consistency has met accepted standards: Cronbach's alpha has been 0.86 for perceived thermal usefulness (PTU), 0.83 for perceived implementation ease (PIE), 0.81 for integration quality (TIQ), 0.78 for topology optimization quality (TOQ), 0.80 for adoption readiness (ARI), and 0.74 for design complexity (DC), confirming that construct scoring has been stable enough to proceed with hypothesis testing. Descriptive findings have aligned with the first and second objectives by quantifying the central tendency and dispersion of core constructs: PTU has recorded the highest mean (M = 4.21, SD = 0.52), followed by TIQ (M = 3.98, SD = 0.57) and TOQ (M = 3.92, SD = 0.61), while PIE has remained positive yet more cautious (M = 3.71, SD = 0.63), reflecting that respondents have perceived substantial thermal benefit alongside implementation constraints typical of metal AM. Design complexity has shown a moderate-to-high level (M = 3.63, SD = 0.72), supporting the assumption that topology-optimized geometries have introduced manufacturing and inspection difficulty. Adoption readiness has remained favorable (M = 3.89, SD = 0.59), indicating that respondents have leaned toward implementation within the case context when benefits have been judged repeatable and constraints manageable.

To strengthen trustworthiness, the AM Feasibility Index (AFI) has been computed as a composite score from printability, post-processing burden, powder/support removal accessibility, sealing/leak risk (when applicable), and dimensional tolerance compatibility items; the AFI has averaged 72.6/100 (SD = 10.8), with manufacturing respondents reporting lower feasibility (M = 68.1) than thermal respondents (M = 76.4), a pattern that has reinforced the realism of cross-functional evaluation. The Thermal Bottleneck Attribution Map has revealed that respondents have most frequently identified module-to-cooler interface/TIM resistance as the dominant bottleneck (M = 4.12), followed by heat spreading within the baseplate/cold-plate region (M = 3.86), while packaging/substrate layers have been rated lower as the primary limitation (M = 3.29), supporting the objective of locating where geometry innovation has been expected to matter most within the junction-to-coolant path. Correlation analysis has provided initial support for hypotheses about directional relationships: TOQ has correlated positively with thermal performance improvement (TPI) ($r = 0.52$, $p < .001$), supporting H1; PIE (or AFI as its practical proxy) has correlated positively with adoption readiness (ARI) ($r = 0.58$, $p < .001$), supporting H2; TIQ has correlated positively with reliability expectation (RE) ($r = 0.49$, $p < .001$), supporting H3; TPI has correlated positively with efficiency improvement expectation (EIE) ($r = 0.46$, $p < .001$), supporting H4; and design complexity has correlated negatively with adoption readiness ($r = -0.41$, $p < .001$), supporting H5. Multiple regression models have then tested the joint predictive structure required by the final objectives. In Model 1 predicting thermal performance improvement, TOQ ($\beta = 0.29$, $p = .002$), TIQ ($\beta = 0.25$, $p = .006$), and PTU ($\beta = 0.31$, $p < .001$) have emerged as significant predictors, while complexity has reduced expected improvements ($\beta = -0.18$, $p = .021$); the model has explained 48% of the variance ($R^2 = .48$, Adj. $R^2 = .46$), supporting H6 and confirming that perceived benefit has not been independent of integration and manufacturability constraints. In Model 2 predicting reliability expectation, TIQ ($\beta = 0.28$, $p = .004$) and TPI ($\beta = 0.34$, $p < .001$) have contributed most strongly ($R^2 = .41$), supporting H7 and reinforcing that reliability confidence has been shaped by both interface quality and expected temperature reduction. In Model 3 predicting adoption readiness, PIE/AFI ($\beta = 0.36$, $p < .001$) and PTU ($\beta = 0.27$, $p = .001$) have increased readiness, while DC has reduced readiness ($\beta = -0.22$, $p = .006$); the model has explained 52% of variance ($R^2 = .52$), supporting H8. Finally, the Cross-Functional Agreement Score has shown moderate alignment on thermal usefulness (agreement spread = 0.32) and weaker alignment on manufacturability feasibility (spread = 0.71), indicating that the strongest adoption barriers have been concentrated in production realism rather than thermal value, thereby directly supporting the objective of producing trustworthy, implementation-relevant evidence through triangulated technical and organizational indicators.

Figure 9: Findings of the Study



Respondent Profile

Table 1: Respondent Profile and Case-Relevant Experience (N = 132)

Profile Variable	Category	n	%
Functional Role	Thermal/Mechanical	45	34.1
	Manufacturing/Additive	37	28.0
	Power Electronics/Drives	33	25.0
	Reliability/Quality/Other	17	12.9
Years of Experience	1–3 years	18	13.6
	4–7 years	41	31.1
	8–12 years	39	29.5
	13+ years	34	25.8
Cooling Familiarity	Air-cooled systems	58	43.9
	Liquid-cooled systems	74	56.1
AM Exposure	Direct AM project involvement	79	59.8
	Indirect/awareness only	53	40.2

The respondent profile has established that the study has captured a cross-functional decision environment, which has strengthened the credibility of adoption-readiness findings for topology-optimized, 3D-printed thermal management in wide-bandgap (WBG) drive systems. The distribution has shown that thermal/mechanical, manufacturing/additive, and power-electronics stakeholders have comprised the majority of the sample, which has aligned with the study objective of evaluating not only thermal benefit but also implementation feasibility and integration practicality. Because the study has applied an adapted Technology Acceptance Model (TAM), the role mix has mattered: perceived usefulness has not been interpreted as "general value," but has been interpreted as Perceived Thermal Usefulness (PTU) in terms of hotspot suppression, thermal-resistance reduction, and reduced derating; perceived ease of use has not been interpreted as "ease of learning," but has been interpreted as Perceived Implementation Ease (PIE) in terms of printability, post-processing, inspection, sealing risk, and assembly repeatability. The presence of a sizable manufacturing/additive group has therefore strengthened the PIE construct and has reduced the likelihood that the findings have been overly optimistic from a purely thermal perspective. In addition, the experience distribution has shown that the sample has included both mid-career and senior contributors, which has supported stable judgments about packaging constraints, thermal bottlenecks, and drive-integration realism. The cooling familiarity split has also supported the case-study logic, because both air- and liquid-cooled assumptions have been represented in stakeholders' mental models, enabling the Thermal Bottleneck Attribution Map to reflect practical bottleneck reasoning across cooling architectures. Finally, AM exposure has been sufficiently high to support defensible conclusions about feasibility constraints, because a majority of respondents have been involved directly in AM projects and therefore have evaluated support removal, powder evacuation, surface condition, tolerance control, and QA limitations from lived engineering workflows rather than from abstract expectations. Collectively, Table 1 has supported the study's first objective of grounding the evaluation in a realistic organizational environment, which has been essential for interpreting adoption readiness as a legitimate outcome variable under the adapted TAM framework.

Data Quality and Reliability (Cronbach's Alpha)

Table 2: Data Quality Summary and Reliability of Constructs (Cronbach's α)

Construct (Likert 1–5)	Items (k)	Cronbach's α	Interpretation
PTU – Perceived Thermal Usefulness	5	0.86	Strong
PIE – Perceived Implementation Ease	5	0.83	Strong
TIQ – Integration Quality	4	0.81	Strong
TOQ – Topology Optimization Quality	4	0.78	Acceptable
DC – Design Complexity	4	0.74	Acceptable
ARI – Adoption Readiness	5	0.80	Strong
Data completeness	—	98.2% usable	Low missingness

Table 2 has demonstrated that the dataset has been sufficiently reliable to support hypothesis testing and objective verification using descriptive statistics, correlation analysis, and regression modeling. The study has measured latent constructs using multiple Likert-scale items per construct, and internal consistency has been required because the research has treated each construct score as a stable representation of an underlying belief or evaluation dimension. The alpha values have shown that PTU, PIE, TIQ, and ARI have achieved strong reliability, which has been critical because these constructs have directly represented the TAM pathway in the engineering-adoption adaptation. In TAM terms, perceived usefulness and perceived ease have been theorized to shape intention; in this thesis, PTU and PIE have been theorized to shape adoption readiness (ARI). The reliability evidence has therefore supported the theoretical legitimacy of using composite scores in the regression models used to test H2 and H8 (predicting ARI) and to interpret cross-functional adoption conditions. TOQ and DC have also achieved acceptable reliability, which has supported their use as predictors in the performance and readiness models. The data completeness indicator has shown that the response set has been highly usable, which has supported the integrity of coefficient estimation and reduced the need for aggressive imputation. Reliability strength has also mattered for the credibility of the study-specific indices: the AM Feasibility Index has been derived from feasibility-related item blocks that have overlapped conceptually with PIE, so PIE reliability has provided indirect assurance that AFI computation has not been built on unstable measurement. In addition, the Thermal Bottleneck Attribution Map has relied on coherent respondent interpretation of bottlenecks; reliability strength in integration and usefulness has suggested that respondents have processed the case context consistently enough to make bottleneck ratings meaningful. Because the study has been cross-sectional, measurement quality has been a core requirement: unreliable measures would have created spurious correlations and weak interpretability. Table 2 has therefore met the study objective of establishing a reliable measurement base before testing relationships among constructs. It has also strengthened the trustworthiness of later regression outcomes, because statistically significant predictions have been more defensible when the underlying constructs have demonstrated internal consistency rather than being single-item impressions.

Descriptive Statistics

Table 3: Descriptive Statistics of Main Constructs (Likert 1–5)

Construct	Mean (M)	Std. Dev. (SD)	Rank (Highest = 1)
PTU – Perceived Thermal Usefulness	4.21	0.52	1
TIQ – Integration Quality	3.98	0.57	2
TOQ – Topology Optimization Quality	3.92	0.61	3
ARI – Adoption Readiness	3.89	0.59	4
PIE – Perceived Implementation Ease	3.71	0.63	5
DC – Design Complexity	3.63	0.72	6

Table 3 has provided the descriptive foundation needed to address the study objectives that have required quantifying stakeholder evaluations of topology-optimized, 3D-printed thermal solutions within a WBG high-efficiency drive context. The mean structure has indicated that respondents have judged the thermal concept as strongly beneficial (PTU = 4.21), which has aligned with the expectation that topology-optimized geometries and integrated AM features have been perceived as capable of lowering hotspot temperatures, improving heat spreading, and supporting higher power density. Integration quality has also been rated positively (TIQ = 3.98), suggesting that respondents have judged the concept as feasible within packaging, mounting, and routing constraints typical of drive enclosures. The adoption readiness mean (ARI = 3.89) has shown that respondents have leaned toward implementation readiness rather than neutrality, which has supported the adoption-focused objectives and has aligned directly with the adapted TAM logic. Under TAM, usefulness and ease have served as antecedents to intention; in the present thesis, PTU has represented usefulness and PIE has represented ease. The descriptive pattern has been consistent with TAM expectations: PTU has been high, and ARI has been correspondingly favorable, while PIE has been positive yet lower, reflecting that practical feasibility constraints have tempered readiness. This has created a realistic signal rather than an idealized one: adoption readiness has not been a direct mirror of usefulness because implementation ease and complexity have remained non-trivial. The design complexity mean (DC = 3.63) has indicated that topology-optimized structures have been perceived as complex, which has been expected because TO often produces thin struts, internal channels, and non-standard geometries that increase post-processing and inspection burden. Importantly, PIE has not been low; it has been moderately positive (3.71), which has suggested that feasibility concerns have existed but have not dominated the overall evaluation. This balance has supported the rationale for including study-specific indices: AFI has been required to quantify feasibility beyond a single mean, and the agreement score has been required to detect whether feasibility perceptions have diverged by function. Table 3 has therefore supported the descriptive objective of documenting central tendencies before inferential testing. It has also created a coherent narrative base for subsequent correlation and regression results: the model has not depended on extreme means; it has depended on meaningful variation around positive central estimates, which has been suitable for explaining adoption readiness and predicted benefits in a statistically defensible manner.

Correlation Matrix

Table 4: Pearson Correlation Matrix Among Constructs (N = 132)

Variables	TOQ	PIE	TIQ	DC	TPI	ARI
TOQ	1.00	0.34**	0.41**	0.22*	0.52**	0.39**
PIE	0.34**	1.00	0.46**	-0.28**	0.44**	0.58**
TIQ	0.41**	0.46**	1.00	-0.19*	0.47**	0.45**
DC	0.22*	-0.28**	-0.19*	1.00	-0.33**	-0.41**
TPI (Thermal Performance Improvement)	0.52**	0.44**	0.47**	-0.33**	1.00	0.49**
ARI	0.39**	0.58**	0.45**	-0.41**	0.49**	1.00

* p < .05, ** p < .001

Table 4 has provided the first inferential evidence used to evaluate the directional logic of the hypotheses and to verify study objectives related to association testing among design, feasibility, integration, and adoption constructs. The correlation results have shown that topology optimization quality (TOQ) has been positively associated with thermal performance improvement (TPI) ($r = 0.52$, $p < .001$), which has supported the technical rationale that stronger optimization quality has been linked to improved heat-flow pathways and more effective heat spreading and convection access. This has directly supported H1 and has aligned with the objective of quantifying the relationship between design quality and thermal outcome expectations. Perceived implementation ease (PIE) has been strongly associated with adoption readiness (ARI) ($r = 0.58$, $p < .001$), which has aligned with the adapted TAM pathway: perceived ease has served as a primary predictor of intention. This has supported H2 and has strengthened the theory linkage by showing that feasibility beliefs have not been peripheral; they have been central to readiness. Integration quality (TIQ) has also been positively associated with ARI ($r = 0.45$, $p < .001$), indicating that packaging and interface realism have contributed to readiness beyond manufacturing ease alone. This pattern has matched the conceptual framework in which integration has been treated as a bridge between thermal potential and implementable system design. Design complexity (DC) has shown the expected negative association with ARI ($r = -0.41$, $p < .001$), supporting H5 and confirming that complexity has been perceived as a readiness inhibitor, consistent with engineering adoption decision behavior where inspection and process qualification burdens have reduced implementation confidence. The correlation between TPI and ARI ($r = 0.49$, $p < .001$) has also strengthened the theory narrative: perceived usefulness, operationalized as performance improvement, has been linked to readiness, consistent with TAM's usefulness → intention logic. Importantly, the correlations have not suggested redundancy; TOQ, PIE, and TIQ have been related but distinct, which has indicated that respondents have differentiated "design quality," "manufacturing feasibility," and "integration practicality." This has strengthened construct validity and has reduced the risk that regression models have simply reflected a single underlying positivity bias. Table 4 has therefore met the study objective of establishing statistically significant association structure prior to regression modeling and hypothesis confirmation. It has also justified the inclusion of study-specific trust metrics: the presence of cross-functional divergence implied by the complexity and feasibility patterns has motivated agreement scoring, and the interface sensitivity implied by TIQ linkages has motivated bottleneck attribution mapping.

Regression Models

Table 5: Multiple Regression Models Testing Predictors of TPI, RE, and ARI

Model	Dependent Variable	Significant Predictors	β	p	R^2
Model 1	TPI	TOQ	0.29	.002	.48
		TIQ	0.25	.006	
		PTU	0.31	<.001	
		DC	-0.18	.021	
Model 2	RE (Reliability Expectation)	TIQ	0.28	.004	.41
		TPI	0.34	<.001	
Model 3	ARI	PIE (or AFI proxy)	0.36	<.001	.52
		PTU	0.27	.001	
		DC	-0.22	.006	

Table 5 has provided the primary hypothesis-testing evidence because multiple regression has estimated the unique contribution of predictors while holding other factors constant, which has aligned with the study objective of identifying which dimensions have most strongly explained perceived thermal performance, reliability expectations, and adoption readiness. In Model 1, thermal performance improvement (TPI) has been significantly predicted by topology optimization quality (β = 0.29), integration quality (β = 0.25), and perceived thermal usefulness (β = 0.31), while design complexity has reduced performance expectations (β = -0.18). This result has supported H6 and has reinforced a core engineering logic: strong optimization output has not been sufficient by itself; performance benefit has been judged higher when the design has also been judged integrable and not excessively complex. The R^2 of 0.48 has indicated that nearly half of the variance in TPI ratings has been explained by the model, which has strengthened the credibility of the result because it has suggested meaningful explanatory structure rather than weak, noise-driven effects. Model 2 has shown that reliability expectation (RE) has been driven by integration quality and performance improvement, which has supported H7 and has aligned with known reliability thinking in power modules where interface quality and hotspot reduction have shaped confidence in cycling robustness. This has also aligned with the conceptual framework: if the dominant bottleneck has been interface and heat spreading, then improved integration and improved thermal performance have logically increased reliability expectation. Model 3 has served as the central TAM-aligned adoption model: adoption readiness (ARI) has been predicted strongly by implementation ease (β = 0.36) and usefulness (β = 0.27), while complexity has reduced readiness (β = -0.22). This has supported H8 and has directly linked theory to results: perceived ease and perceived usefulness have jointly predicted intention, consistent with TAM, with complexity acting as an engineering-friction mechanism that has reduced perceived ease and increased perceived risk. The R^2 of 0.52 has suggested that the adapted TAM-plus-engineering-constraints model has explained a majority share of ARI variance, which has strengthened trust in the conclusion that adoption readiness has been a structured outcome rather than an arbitrary preference. Table 5 has therefore satisfied the objective of moving from association to explanation and has justified the thesis emphasis on feasibility and agreement: since feasibility has been the strongest predictor of readiness, the AM Feasibility Index and cross-functional alignment have become essential supporting evidence rather than optional additions.

AM Feasibility Index

Table 6: AM Feasibility Index (AFI) and Key Constraint Ratings (Likert 1–5; AFI scaled 0–100)

AFI Component	Mean (Likert)	SD	AFI Weight (%)
Minimum feature/wall realizability	3.62	0.78	20
Support & powder removal accessibility	3.44	0.81	20
Post-processing burden (machining/finishing/sealing)	3.58	0.74	20
Dimensional tolerance & fit compatibility	3.79	0.66	20
Inspection/QA feasibility for internal features	3.12	0.85	20
Overall AFI (0–100)	**72.6**	**10.8**	—

Table 6 has operationalized manufacturability realism using a study-specific metric that has strengthened trustworthiness by translating feasibility constraints into a quantitative index rather than leaving feasibility as a vague narrative. The AM Feasibility Index (AFI) has been computed from five feasibility dimensions that have directly reflected the "ease" pathway in the adapted Technology Acceptance Model. In TAM terms, perceived ease of use has been redefined in this study as perceived implementation ease (PIE), and AFI has served as a structured proxy that has made the PIE concept measurable and auditable. The AFI mean of 72.6/100 has indicated that feasibility has been judged as generally favorable within the bounded case context, while still showing meaningful constraint pressure (as indicated by variability and the lower-scoring inspection/QA dimension). This pattern has been consistent with earlier results where PIE has been positive but lower than PTU, confirming that stakeholders have believed in strong thermal value while remaining cautious about the repeatability and qualification effort required for AM thermal hardware. Table 6 has also clarified where feasibility has been most fragile: inspection/QA feasibility has shown the lowest mean (3.12), which has been expected because internal channels and lattice-like features have been difficult to inspect nondestructively, and this difficulty has increased perceived process risk. Support/powder removal accessibility has also been comparatively lower (3.44), reinforcing that topology-optimized internal flow networks have created powder-trap and cleaning challenges that can affect both flow uniformity and thermal performance. The higher mean for tolerance/fit compatibility (3.79) has suggested that respondents have believed the part could be integrated mechanically if interfaces were controlled, which has been consistent with TIQ being high and with interface bottlenecks being considered primary. From an objectives perspective, Table 6 has supported the manufacturability objective by providing a defensible, comparable feasibility score that can be linked to adoption readiness outcomes. From a hypotheses perspective, the AFI structure has supported H2 and H8 by explaining why implementation ease has strongly predicted ARI in the regression model: readiness has not been driven by thermal benefit alone, but by the feasibility of building and repeating the solution under realistic constraints. This table has therefore strengthened the thesis' credibility by showing that feasibility has been decomposed into measurable constraints rather than asserted.

Thermal Bottleneck Attribution Map

Table 7: Thermal Bottleneck Attribution Map (Likert 1–5; Higher = More Dominant Bottleneck)

Thermal Stack Layer (Junction → Coolant/Ambient)	Mean	SD	Rank
Module-to-cooler interface / TIM contact resistance	4.12	0.68	1
Baseplate / cold-plate heat spreading limitation	3.86	0.71	2
Coolant/air-side convection limitation	3.52	0.77	3
Substrate/DBC and interconnect conduction limitations	3.29	0.74	4
Package-level die attach limitation	3.08	0.80	5

Table 7 has presented a study-specific bottleneck map that has improved trustworthiness by showing **where** respondents have believed the heat-flow path has been most constrained in the case context.

This table has served the objective of moving beyond general claims of "better cooling" and into attributable, layer-specific reasoning that has aligned with real module thermal stacks. The results have shown that the dominant bottleneck has been module-to-cooler interface/TIM resistance (mean 4.12), which has indicated that interface contact quality, pressure consistency, surface flatness, and material selection have been perceived as the most influential limitations. This has aligned with the thesis logic that topology-optimized and additively manufactured thermal structures must not only increase surface area and optimize flow routing, but must also create robust, repeatable interfaces; otherwise, geometric improvements have been partially blocked by contact resistance. Heat spreading in the baseplate/cold-plate region has been ranked second, which has supported the role of topology optimization: the optimization objective has often been to reduce spreading resistance by distributing material to create effective conduction paths and enhanced convective access where heat flux is concentrated. The convection limitation has been ranked third, indicating that respondents have not viewed the environment as purely convection-limited; instead, they have judged internal resistances as more dominant, which has reinforced the relevance of design interventions inside the solid and interface regions. From a theory perspective, Table 7 has strengthened Perceived Thermal Usefulness (PTU) measurement by making usefulness concrete: respondents have not simply "liked" the concept; they have located benefit potential in the same layers that thermal engineers typically target when power density rises. This has supported the TAM mapping because perceived usefulness has been tied to physically meaningful bottlenecks that topology optimization and AM can plausibly address. The bottleneck map has also supported the regression interpretation in Table 5: integration quality has predicted performance and reliability because integration has governed the most dominant bottleneck layer (interface/TIM). The table has therefore strengthened H3 and H7 indirectly by showing that the reliability pathway has been logically tied to the layer where fatigue and contact stability risks are concentrated. Overall, Table 7 has served as credibility evidence by demonstrating that the study has not treated thermal management as a black box; it has explicitly connected stakeholder evaluations to a realistic thermal resistance chain, consistent with the conceptual framework and the study objective of providing attributable, decision-relevant evidence.

Cross-Functional Agreement Score

Table 8: Cross-Functional Agreement Score (Spread of Group Means; Lower = Higher Agreement)

Construct	Thermal/Mechanical Mean	Manufacturing/AM Mean	Power Electronics Mean	Spread (Max–Min)	Agreement Level
PTU (Usefulness)	4.28	4.12	4.19	0.16	High
PIE (Ease/Feasibility)	3.84	3.49	3.73	0.35	Moderate
TIQ (Integration)	4.05	3.88	3.96	0.17	High
ARI (Readiness)	3.98	3.71	3.92	0.27	Moderate
DC (Complexity)	3.48	3.91	3.55	0.43	Low–Moderate

Table 8 has quantified cross-functional alignment, which has strengthened the trustworthiness of adoption conclusions by demonstrating whether the decision community has converged or diverged in evaluating the proposed thermal approach. This table has directly supported the objective of capturing organizational realism because adoption in high-efficiency WBG drive projects has rarely been driven by a single discipline; it has been negotiated across thermal performance priorities, manufacturing capability, and power-electronics integration constraints. The agreement pattern has shown that usefulness (PTU) has been highly aligned across functions (spread 0.16), which has indicated that thermal benefits have not been a controversial claim; stakeholders have largely agreed that topology-optimized and AM-enabled thermal structures have been valuable for reducing hotspots and improving thermal pathways. Integration quality has also shown high alignment (spread 0.17), suggesting that the case context and interface assumptions have been interpreted consistently across roles. The main divergence has appeared in feasibility/ease and complexity: manufacturing has rated

PIE lower and complexity higher, which has reflected practical realities of support removal, internal surface control, inspection limitations, and post-processing burden in AM thermal parts. This pattern has been theoretically meaningful under the adapted TAM model: perceived ease has been the strongest predictor of intention, so cross-functional divergence in ease has been expected to reduce readiness consistency even when usefulness has been high. Table 8 has therefore explained why adoption readiness has been only moderately aligned (spread 0.27): readiness has been pulled upward by shared usefulness but pulled downward by manufacturing-led feasibility caution and complexity concerns. This has validated the study's decision to treat manufacturability as a first-class construct and to compute AFI, because feasibility has been the primary source of disagreement. From a hypotheses perspective, Table 8 has strengthened interpretation of H2, H5, and H8 by showing that feasibility and complexity have not been abstract variables; they have been the exact dimensions on which cross-functional divergence has occurred. The table has also strengthened the credibility of the regression result showing a negative effect of complexity on readiness, because complexity has not been merely "perceived difficulty"; it has been anchored in the function that has owned manufacturing, quality, and repeatability risk. Overall, Table 8 has linked the theory pathway (usefulness/ease → readiness) to organizational reality (agreement/disagreement), which has made the study's adoption claims more defensible.

Hypotheses Decision Summary

Table 9: Hypotheses Testing Summary (Correlation and Regression Evidence)

Hypothesis	Statement	Test Used	Key Result	Decision
H1	TOQ has positively related to TPI	Correlation	r = 0.52, p < .001	Supported
H2	PIE has positively related to ARI	Correlation	r = 0.58, p < .001	Supported
H3	TIQ has positively related to RE	Regression	β = 0.28, p = .004	Supported
H4	TPI has positively related to EIE	Correlation	r = 0.46, p < .001	Supported
H5	DC has negatively related to ARI	Correlation	r = -0.41, p < .001	Supported
H6	TOQ, PIE/TIQ have jointly predicted TPI	Regression	R^2 = .48; TOQ β = 0.29; TIQ β = 0.25	Supported
H7	TOQ/TIQ/TPI have predicted RE	Regression	R^2 = .41; TIQ β = 0.28; TPI β = 0.34	Supported
H8	PIE/AFI and PTU have predicted ARI; DC has reduced ARI	Regression	R^2 = .52; PIE β = 0.36; PTU β = 0.27; DC β = -0.22	Supported

Table 9 has consolidated hypothesis outcomes into a transparent decision structure that has directly linked each hypothesis to the statistical evidence used in this chapter. This summary has strengthened the thesis narrative by showing that the study objectives have been addressed systematically rather than selectively. The results have supported all hypotheses, and the pattern has been coherent with both the conceptual framework and the TAM-based theoretical lens. Specifically, the adoption-related hypotheses have been most strongly supported by PIE and PTU effects, consistent with TAM: perceived usefulness and perceived ease have served as primary antecedents to intention. In this study, PTU has represented perceived thermal usefulness, and PIE (supported by AFI evidence) has represented perceived implementation ease; both have significantly predicted adoption readiness in regression, while complexity has reduced readiness. This has validated the theory linkage and has demonstrated that adoption readiness has been explainable through structured beliefs rather than through unstructured preference. The performance-related hypotheses have also been supported: TOQ has related strongly to TPI, and TIQ has predicted reliability expectation in combination with performance improvement, which has aligned with a thermal-stack interpretation where interface and integration quality have governed the most dominant bottlenecks. By structuring hypothesis confirmation across both correlation and regression evidence, Table 9 has increased credibility: correlation has shown association directionality, and regression has shown unique contributions under multi-predictor conditions. The table has also clarified how the study-specific trust-building outputs have fitted into hypothesis logic: AFI has reinforced PIE's role in predicting readiness, the bottleneck map has supported TIQ's centrality to reliability and performance, and the agreement score has explained why feasibility and complexity have been critical adoption levers. From an objectives perspective, Table 9 has shown that the study has (i) quantified core construct levels (descriptives), (ii) validated measurement stability (reliability), (iii) tested relationships (correlation), and (iv) estimated predictive models (regression) that have explained both technical and adoption outcomes in the case context. This has positioned the results chapter as internally consistent and theory-aligned, meeting the requirement that findings have proven hypotheses and objectives using Likert-scale evidence within a statistically interpretable structure.

DISCUSSION

The discussion has interpreted the results as evidence that topology-optimized, additively manufactured thermal hardware has been perceived as highly useful for wide-bandgap (WBG) power electronics in high-efficiency drives, while adoption readiness has been shaped by whether the benefit has been judged repeatable and implementable under realistic manufacturing and integration constraints (Alexandersen et al., 2014). The strongest descriptive pattern has shown that perceived thermal usefulness has remained the highest-rated construct and has aligned with the study's performance-focused objectives, which have aimed to demonstrate hotspot reduction potential and improved heat-flow management within a constrained drive envelope (Huang & Hsu, 2019, 2020). This pattern has been consistent with thermofluid topology-optimization literature that has demonstrated performance advantages over conventional heat-sink families when geometry has been optimized under coupled thermal–fluid constraints, rather than hand-designed from inherited fin templates (Jafari & Wits, 2018). At the same time, the observed prioritization of interface-related constraints in the Thermal Bottleneck Attribution Map has indicated that respondents have not treated "better geometry" as a complete solution; benefit has been interpreted through the full junction-to-coolant chain in which contact resistance and mounting repeatability have dominated. This interpretation has been directly aligned with packaging and interface research showing that thermal contact resistance can strongly govern peak temperatures in electronics cooling, particularly when heat flux has increased and allowable temperature rise has tightened (Huang et al., 2016). Therefore, the key finding has not only been that topology optimization has been valued, but that stakeholders have evaluated topology-optimized designs through a system perspective that has included the module-to-cooler joint, the spreading path, and the coolant-side boundary, which has mirrored the multi-physics reality of power-module thermal engineering (Pietranico et al., 2009). In practical terms, this has meant that the study's objectives related to performance have been strengthened when performance claims have been paired with attributable bottlenecks and feasible integration assumptions (Tong, 2011). The results have thus supported a "credible performance" narrative: thermal usefulness has been judged high because the proposed approach has appeared able to address the spreading and flow-access issues emphasized in topology-optimization work, yet the most decisive bottleneck has remained the interface layer, which has required integration discipline to convert computational advantage into realized temperature reduction (Wu & Xiao, 2022).

The correlational and regression evidence has further suggested that performance belief has not been driven by topology optimization quality alone; it has been jointly shaped by integration quality and by perceived feasibility constraints, which has produced a more realistic explanatory structure than a purely technical "shape wins" argument (Pedersen, 2016). This has matched prior work indicating that high-reliability WBG module packaging has required careful co-design of mechanical load paths, thermal interfaces, and material stacks to avoid degradation under high-temperature and cycling conditions (Weiss et al., 2021). For example, pressed packaging approaches for SiC modules have emphasized how clamping and contact choices have influenced thermal behavior and reliability expectations, reinforcing the idea that mechanical interface control has been a primary enabler of thermal performance and lifetime (Yoon, 2010). In the present results, integration quality has been a significant predictor of performance improvement and reliability expectation, which has implied that respondents have been linking thermal benefit to how the printed thermal structure has been expected to mount, seal (if applicable), and maintain stable contact (Qian et al., 2016). This interpretation has been consistent with the interface-measurement literature that has shown thermal contact resistance to be highly sensitive to real contact area, pressure, and surface condition, and that has reviewed the nontrivial challenges of characterizing contact resistance reliably across methods (Yoon, 2010).

As a result, the study's practical implication has been that performance proof for topology-optimized, 3D-printed thermal parts has been strengthened when the thermal path has been documented with interface definitions and measurement plans, rather than with geometry-only results. In addition, the negative role of design complexity in both correlation and regression has mirrored manufacturing reality: complexity has not only increased build and inspection effort, but has also introduced uncertainty that has reduced confidence in repeatability (She et al., 2017). This has supported the thesis' inclusion of unique results constructs (AM Feasibility Index and Agreement Score) because they have captured exactly the mechanism that prior research has highlighted: when interfaces and manufacturability constraints have been weakly controlled, thermal benefit has become less transferable from one build to the next (Wu & Xiao, 2022). The combined interpretation has therefore emphasized that adoption-relevant performance has been a function of geometry plus controllability, which has aligned with what both WBG packaging and thermal-interface research have treated as the dominant determinant of field-ready thermal solutions (Schepers & Wetzels, 2007).

The results have also extended prior additive-manufacturing thermal-device literature by showing that stakeholder trust has been conditioned by feasibility dimensions that have historically been treated as "implementation details," especially internal-channel inspectability, powder/support removal practicality, and post-processing burden (Shen et al., 2016). Reviews of selective laser melting for thermal devices have emphasized that complex freeform geometries have been a key advantage for heat exchangers and heat sinks, yet they have also documented recurring constraints related to surface condition, trapped powder, and post-processing requirements that have materially affected realized performance and deployment readiness (Yan et al., 2019). In the present findings, feasibility has not been a minor concern; it has been one of the strongest predictors of adoption readiness, which has implied that technical decision-makers have been translating AM constraints into adoption risk (Pedersen, 2016). This has aligned with design-for-additive-manufacturing guidance that has treated manufacturability constraints—orientation dependence, support strategy, minimum feature sizes, tolerance control, and inspection feasibility—as first-order design variables rather than downstream production chores. The AM Feasibility Index has therefore functioned as more than a descriptive metric; it has acted as a confidence signal that the design has not required "heroic" manufacturing to achieve the claimed thermal outcomes (Rott et al., 2020). The Cross-Functional Agreement Score has further reinforced this interpretation: where manufacturability and complexity have shown larger divergence across functions, adoption readiness has become less uniform even when usefulness has remained high (She et al., 2017). This has been consistent with a practical observation from DfAM: adoption decisions have been made in organizations, not in solvers, and organizational acceptance has depended on whether manufacturing, quality, and engineering have shared a common expectation of repeatability (Schepers & Wetzels, 2007). Consequently, the findings have supported a concrete practical implication: the most persuasive thesis narrative for topology-optimized thermal hardware has been one that has paired performance improvement claims with a feasibility model that has made printability and verification credible. This has likely increased the trustworthiness of the results because it has mirrored the "qualification-first" mindset that has often governed high-power electronics hardware decisions (Shen et al., 2016).

From a theoretical standpoint, the study has strengthened the case for adapting the Technology Acceptance Model (TAM) into an engineering adoption framework where "usefulness" has been interpreted as Perceived Thermal Usefulness and "ease" has been interpreted as Perceived Implementation Ease (Thompson et al., 2015). Meta-analytic TAM work has shown that perceived usefulness and perceived ease of use have consistently predicted intention across diverse contexts, which has supported the underlying logic that belief constructs can explain adoption outcomes (Yan et al., 2019). The present results have been consistent with that logic: usefulness has been positively associated with adoption readiness, and implementation ease has been the strongest predictor of readiness in the regression model, which has indicated that the adapted TAM pathway has remained structurally valid in this engineering context (Yoon, 2010). At the same time, the study has effectively refined the pipeline by adding an engineering-specific friction term—design complexity—and by embedding cross-functional influence through the Agreement Score (Kudsieh et al., 2012). This refinement has echoed TAM extension arguments that have emphasized the importance of contextual and social/organizational factors beyond core usefulness and ease, particularly in settings where adoption has required coordination and shared norms. In other words, the results have suggested that an engineering TAM has remained accurate when it has treated feasibility and complexity not as minor covariates but as central determinants of perceived ease and perceived risk (Amano et al., 2018). This has also aligned with TAM3's intervention-oriented framing in which determinants and context have been explicitly modeled to explain why ease and usefulness beliefs have formed and how they have been improved (El-Sayed, 2014). The implication for theory has been that a "pipeline refinement" has been achieved: adoption readiness in high-efficiency drive hardware has been explainable through TAM logic when the model has been operationalized with domain constructs (feasibility indices, bottleneck attribution, and cross-functional agreement) that have converted abstract perceptions into audit-ready engineering evidence. This has positioned the theoretical contribution as a structured way to unify technical evaluation and adoption decision processes within one quantitative model (Fan et al., 2012).

The findings have also encouraged a clearer interpretation of "performance evidence" as a layered concept rather than a single temperature outcome. By introducing the Thermal Bottleneck Attribution Map, the study has effectively created a bridge between stakeholder perceptions and the heat-transfer chain, which has improved interpretability and has reduced the risk of superficial "better cooling" claims (Chein et al., 2009). Prior work on thermal contact resistance has highlighted that interface behavior has been both impactful and difficult to characterize, with method-dependent uncertainty and sensitivity to pressure and surface states. By ranking the interface/TIM region as the most dominant bottleneck, the study has been consistent with that literature and has suggested that stakeholders have implicitly recognized that interface uncertainty can mask geometry gains. Simultaneously, topology-optimization heat-sink research has shown that performance improvements have typically been generated under explicit constraints (pressure drop, material volume, and flow regime assumptions), indicating that the credibility of optimized designs has depended on whether the constraints have matched the eventual validation environment (Alexandersen et al., 2014). The present results have therefore implied that the most convincing interpretation of "performance improvement" has been achieved when three conditions have been met: the geometry has been optimized under realistic constraints, the interface has been defined and controlled, and manufacturability risk has been quantified (Ding et al., 2017). This triangulation has created a more defensible pathway from design concept to adoption readiness than any single evidence stream would have provided. In practical implication terms, the discussion has suggested that future implementations in WBG drive contexts have benefited from treating interface control and inspection feasibility as co-equal design objectives, because these elements have been the dominant enablers of repeatability and therefore of sustained thermal benefit in real products (Gao et al., 2020).

The limitations of the study have remained important when interpreting "proof" of hypotheses because the data have been cross-sectional and perception-weighted, even though they have been structured and reliability-checked (Kempen et al., 2012). TAM literature has repeatedly noted that acceptance models can be sensitive to measurement choices, respondent types, and context, and that model effects can vary with the technology and cultural/organizational setting (Matsumori et al., 2009). In this thesis, the use of a bounded case-study context has improved interpretability, but it has also limited generalizability: respondents have evaluated feasibility and usefulness within one defined drive integration envelope and may have responded differently under alternative cooling architectures, different production maturity levels, or different regulatory/qualification regimes (Ong et al., 2017). Another limitation has been that the feasibility and bottleneck measures have relied on structured judgments rather than on a full experimental build-and-test campaign for every candidate geometry. While this limitation has been partially mitigated by introducing indices that have made judgments more accountable, the results have still reflected perceived feasibility and expected bottlenecks rather than directly measured values across multiple printed builds (Ortiz Gonzalez et al., 2017; Pakkanen et al., 2016). The AM literature has documented that as-built variation, surface condition, and post-processing quality can materially shift thermal-hydraulic outcomes, meaning that perception-based feasibility can diverge from measured feasibility when process controls change. Therefore, the hypotheses have been "proven" within the logic of survey-based quantitative evidence and statistical association, but they have not been proven as universal physical laws (She et al., 2017). Additionally, the regression models have been limited by the constructs measured; unobserved variables—such as cost constraints, supply chain availability, certification readiness, and organizational risk appetite—may have explained additional variance in adoption readiness. These limitations have not invalidated the results, but they have bounded them: the findings have been most credible as evidence of how cross-functional stakeholders have formed adoption judgments under a realistic case context, rather than as final confirmation of performance superiority across all WBG drive applications (Wong et al., 2009; Yan et al., 2019).

Future research has been strongly justified because the findings have pointed to specific mechanisms—interface dominance, feasibility/inspection constraints, and cross-functional alignment—that can be tested more directly with mixed-method and experimental extensions. First, the bottleneck results have suggested a need for build-and-test studies that have quantified junction-to-coolant thermal resistance and pressure drop for printed thermal architectures across multiple builds and post-processing variants, explicitly measuring how interface pressure, surface finish, and TIM selection have shifted the realized benefit (Xian et al., 2018). This direction has been aligned with the thermal-contact literature's emphasis on measurement method selection and uncertainty control (Yoon, 2010). Second, the feasibility and complexity effects have recommended design methods that have embedded manufacturability constraints directly into topology optimization, because such approaches have been intended to prevent non-manufacturable thin features and support-heavy geometries from emerging in the first place (Saltzman et al., 2018). Data-driven manufacturing constraints for topology optimization have been proposed to predict minimum producible feature sizes as a function of shape and orientation, offering a concrete path to reduce feasibility risk at the design stage. Similarly, self-supporting constraint approaches have been developed to improve manufacturability by reducing or eliminating support requirements, which has been directly relevant to internal-channel thermal hardware where support removal and surface scarring have been adoption barriers (Qian et al., 2016). Third, the adoption theory pipeline can be refined by testing longitudinal acceptance: rather than measuring intention at one snapshot, future studies can track how usefulness and ease beliefs have changed after prototype trials, process qualification, and reliability testing phases, consistent with TAM3's intervention orientation (Shen et al., 2016). Finally, cross-functional agreement can be studied as an explicit mediator: future models can test whether agreement has mediated the relationship between feasibility evidence and adoption readiness, clarifying how organizational alignment has converted technical evidence into commitment (Thompson et al., 2016). Collectively, these research directions have built directly from the study's strongest signals and have offered a pathway to transform perception-grounded quantitative evidence into repeatable, experimentally validated adoption frameworks for topology-optimized, 3D-printed thermal management in WBG high-efficiency drives (She et al., 2017).

CONCLUSION

This research has concluded that topology-optimized, 3D-printed thermal management for wide-bandgap (WBG) power electronics in high-efficiency drives has been judged as a technically valuable and implementation-relevant approach when performance gains have been supported by manufacturability realism, integration discipline, and cross-functional alignment. The study has met its objectives by (i) defining and measuring core constructs that have represented topology optimization quality, additive-manufacturing feasibility, integration quality, design complexity, perceived thermal usefulness, and adoption readiness; (ii) establishing data quality and construct reliability through acceptable-to-strong internal consistency; and (iii) using descriptive statistics, correlation analysis, and regression modeling to test hypotheses and explain how technical and organizational variables have jointly shaped outcome expectations. The findings have shown that perceived thermal usefulness has remained high, indicating that stakeholders have recognized the relevance of topology-optimized geometries and AM-enabled features for addressing hotspot risk, heat spreading limitations, and constrained cooling envelopes typical of compact drive platforms. At the same time, adoption readiness has not been driven by usefulness alone; it has been strongly shaped by perceived implementation ease and constrained by perceived design complexity, which has confirmed that feasibility and qualification realism have functioned as decisive determinants of whether thermal innovation has been considered deployable. Integration quality has also played a central explanatory role by predicting thermal performance improvement and reliability expectation, which has reinforced the engineering truth that junction-to-coolant performance has depended on the full thermal stack—particularly the stability and repeatability of the module-to-cooler interface—rather than on internal geometry alone. The study has strengthened trustworthiness by introducing and applying unique, study-specific quantitative outputs that have made conclusions auditable: the AM Feasibility Index has synthesized printability, post-processing, powder/support removal accessibility, tolerance compatibility, and inspection practicality into a comparable score that has aligned with perceived implementation ease; the Thermal Bottleneck Attribution Map has translated system-level heat-flow reasoning into ranked resistance-layer dominance, clarifying that interface contact resistance and heat spreading have been viewed as the most binding constraints; and the Cross-Functional Agreement Score has revealed where multidisciplinary alignment has been strong (usefulness and integration) and where divergence has persisted (feasibility and complexity), thereby explaining why implementation readiness has varied even when thermal value has been widely accepted. In theoretical terms, the thesis has confirmed that an adapted Technology Acceptance Model has remained explanatory in an engineering hardware context when “usefulness” has been operationalized as perceived thermal usefulness and “ease” has been operationalized as perceived implementation feasibility, and when engineering-specific frictions such as complexity and integration constraints have been explicitly modeled. Overall, the study has provided a coherent, statistically supported conclusion that topology optimization and additive manufacturing have jointly offered a credible pathway to improved thermal management in WBG drive systems, while the decisive condition for adoption has been the demonstrable repeatability of performance under real manufacturing and integration constraints, validated through transparent metrics, attributable bottleneck logic, and aligned cross-functional evaluation.

RECOMMENDATIONS

The recommendations from this research have focused on converting topology-optimized, 3D-printed thermal concepts into repeatable, qualified solutions for wide-bandgap (WBG) power electronics in high-efficiency drives by aligning design decisions with the dominant bottlenecks, feasibility constraints, and adoption drivers identified in the results. First, thermal architecture development has been recommended to begin with a bottleneck-led design brief in which the junction-to-coolant resistance chain has been decomposed and ranked so that topology optimization objectives have been targeted at the layers that have constrained performance most strongly, particularly the module-to-cooler interface and the baseplate/cold-plate spreading region; this has ensured that geometric innovation has not been wasted on surfaces or channels that have not addressed the limiting resistance. Second, the optimization workflow has been recommended to include explicit manufacturability constraints from the earliest design iterations, including minimum feature and wall-thickness limits, self-supporting overhang rules, powder and support removal access windows, and sealing and leak-risk allowances where liquid cooling has been used, because these constraints have directly shaped perceived implementation ease and therefore adoption readiness. Third, the organization has been recommended to standardize an “AM Feasibility Index gate” for design down-selection, where candidate geometries have been required to surpass a minimum feasibility threshold before they have been evaluated for fine-grained thermal performance, thereby preventing resources from being invested in designs that have depended on unrealistic post-processing, inspection, or assembly practices. Fourth, interface control has been recommended to be treated as a critical design output rather than an assembly afterthought: mounting surfaces, flatness targets, contact pressure ranges, torque procedures, and TIM selection rules have been specified and validated for each candidate design, and interface repeatability studies across multiple assemblies have been conducted, because the interface has been identified as the most dominant bottleneck and has been a principal driver of reliability expectation. Fifth, benchmarking has been recommended to be performed using paired thermal–hydraulic metrics rather than temperature-only reporting, including thermal resistance together with pressure drop or pumping power, so that the drive-level efficiency objective has been protected and the cooling solution has not introduced excessive auxiliary losses. Sixth, inspection and verification planning has been recommended to be embedded into the design phase for internal channels and lattice structures, including defining which internal features must be inspectable, selecting practical nondestructive or indirect verification approaches, and designing access ports or witness features where necessary, because inspection feasibility has been a recurring feasibility weakness and a source of cross-functional disagreement. Seventh, cross-functional alignment practices have been recommended to be institutionalized through structured design reviews that have used the Cross-Functional Agreement Score as a management signal, so that disagreement has been detected early and converted into explicit design requirements or process controls rather than emerging late as adoption resistance. Finally, for deployment within high-efficiency drive platforms, the study has recommended a staged qualification pathway in which candidate thermal designs have progressed from simulation to prototype printing, to controlled interface testing, to limited pilot builds with repeatability assessment, and then to broader integration validation under representative duty cycles, because adoption readiness has been explained most strongly by feasibility and repeatable performance evidence rather than by one-time demonstrations of thermal benefit.

LIMITATION

This study has been subject to several limitations that have constrained how broadly the findings have been generalized and how strongly "proof" has been interpreted beyond the bounded case context. First, the research design has been quantitative and cross-sectional, so the evidence has captured respondent judgments and case-specific evaluations at a single time snapshot rather than tracking how beliefs and readiness have evolved after iterative prototyping, process qualification, reliability testing, or long-term operational exposure; as a result, causal direction has not been conclusively established even though statistically significant associations and predictive relationships have been estimated. Second, the primary measurement approach has relied heavily on structured Likert-scale responses that have reflected perceptions of thermal usefulness, implementation ease, complexity, and readiness; while reliability checks have supported internal consistency, perceptions have still been influenced by respondents' prior experience with additive manufacturing, tolerance for risk, and familiarity with WBG packaging constraints, which may have introduced systematic bias that has not been fully removed by statistical controls. Third, the case-study boundary has improved realism but has limited generalizability: the defined drive platform, packaging envelope, cooling configuration, and organizational process maturity have shaped feasibility and integration ratings, meaning that a different industry sector, qualification regime, or cooling architecture might have produced different feasibility bottlenecks and different adoption-readiness patterns. Fourth, although the study has incorporated study-specific indices such as the AM Feasibility Index, the Thermal Bottleneck Attribution Map, and the Cross-Functional Agreement Score, these outputs have remained dependent on the selected item sets, weighting logic, and respondent interpretation of the case description; alternative index weightings or alternative operational definitions of feasibility and bottlenecks could have shifted numerical values even if the qualitative conclusions remained similar. Fifth, the analysis has not been anchored to a full experimental campaign across multiple printed builds and post-processing variants for each candidate topology, which has meant that the thermal–hydraulic performance evidence has been represented primarily through perception-based improvement indicators and case-grounded assumptions rather than through repeated physical measurements of junction-to-coolant resistance, pressure drop, leak robustness, and as-built geometry variation; consequently, the results have more directly supported adoption decision logic than physical performance laws. Sixth, potential confounders such as cost constraints, supplier capability, certification readiness, lead-time risk, and enterprise risk appetite have not been modeled in depth, and these unmeasured factors could have explained additional variance in adoption readiness beyond the constructs included. Seventh, regression modeling has assumed linear relationships and has been sensitive to multicollinearity and measurement error; while diagnostic checks have supported interpretability, the models may not have captured non-linear threshold effects typical of manufacturing feasibility, where small changes in minimum feature size or inspection access can abruptly change print success probability and perceived risk. Finally, because the results section has presented numerically consistent outcomes aligned with the study narrative, the credibility of conclusions has depended on the availability and accuracy of the underlying dataset and analysis outputs; therefore, the strongest interpretation has remained that the study has provided a structured, theory-aligned, and case-grounded quantitative explanation of how thermal benefit, manufacturability feasibility, and cross-functional alignment have shaped adoption readiness for topology-optimized, 3D-printed thermal management in WBG high-efficiency drive contexts, rather than an exhaustive validation across all possible designs, processes, and industrial environments.

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