EBOOK

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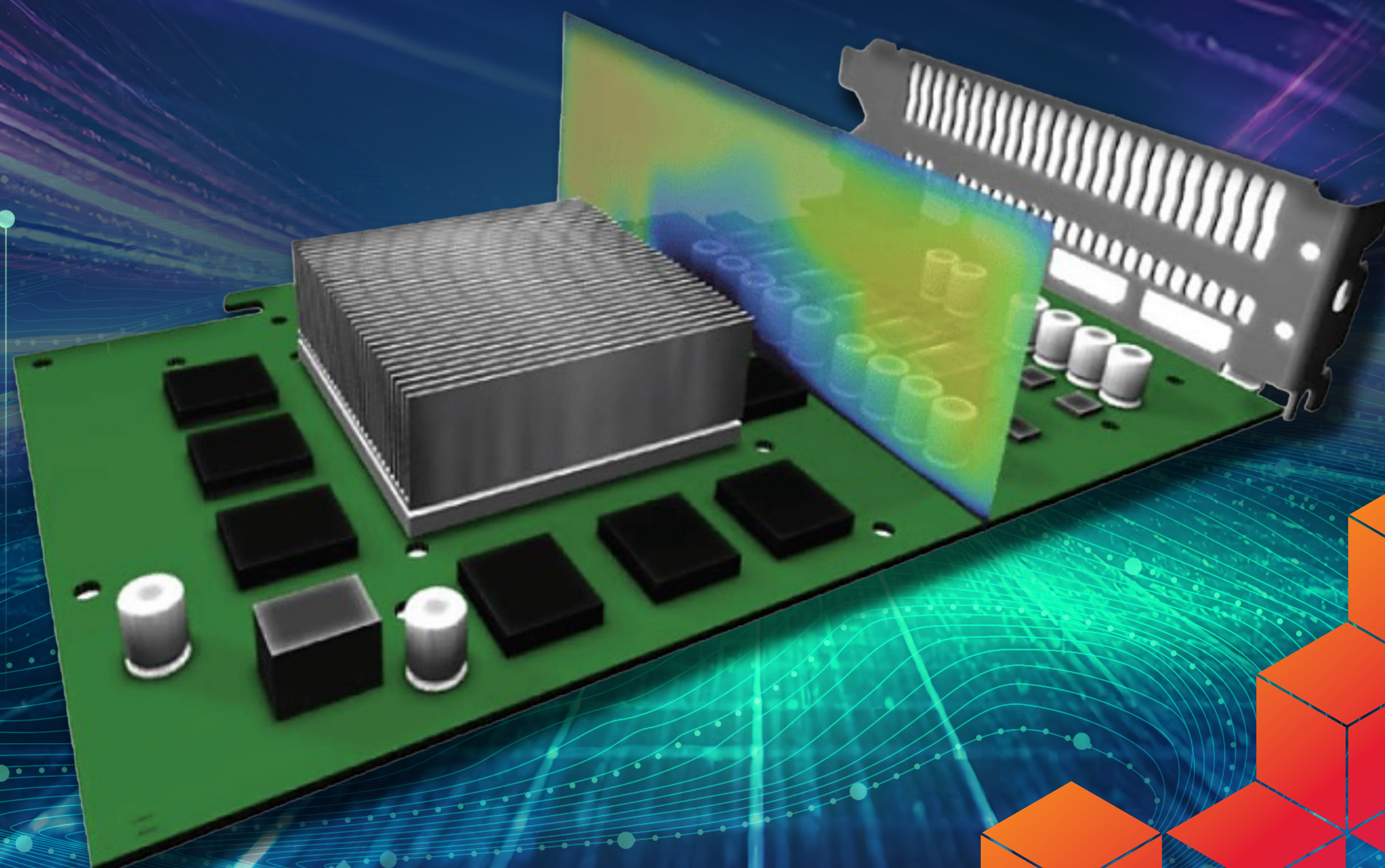
ENGINEER'S GUIDE TO SIMULATING ELECTRONICS COOLING

Intelligent thermal simulation of electronics systems

By Cadence



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Introduction

As electronic systems become smaller, faster, and more power-dense, managing heat is no longer just a reliability concern—it's a core design requirement. From consumer electronics and medical wearables to data center infrastructure and electric vehicles, excess heat can compromise performance, shorten component lifespan, and even lead to catastrophic failure.

Elevated operating temperatures don't just degrade performance—they accelerate failure mechanisms. According to the Arrhenius equation, many thermally induced failure modes follow an exponential trend, with failure rates doubling for every 10°C rise in temperature. Therefore, even modest improvements in thermal performance can significantly increase system longevity.

Thermal simulation is now an integral part of electronics design, applied early in development instead of left for late-stage checks. Yet, major challenges persist; preprocessing remains time-consuming, long solution turnaround times slow iteration, lack of scalability limits full-system modeling, and insufficient fidelity undermines confidence in the results.

To be effective, modern solvers must deliver both speed and accuracy while handling complex assemblies. The Celsius EC Solver enables the efficient and accurate modeling of heat flow across components, boards, and enclosures under realistic conditions, making this possible. As a result, engineers can ensure thermal margins are met, avoid expensive redesigns, and improve overall system reliability.

This guide introduces the core concepts, modeling techniques, and best practices needed to simulate and solve electronics cooling challenges. Real-world examples address specific workflows and design challenges in practice. This guide is intended for electrical, mechanical, and thermal engineers, whether you're new to simulation or looking to refine your design process. This guide will equip you with a structured, simulation-driven approach to identifying, analyzing, and solving electronics cooling issues before they become costly.

ENHANCING ELECTRONICS COOLING WITH THE CELSIUS EC SOLVER

The **Celsius EC solver** is one of several specialized tools within **Cadence's Celsius Studio Platform**, a suite built to tackle the full spectrum of thermal and power integrity challenges in electronics design.

Engineered specifically for electronics cooling, Celsius EC enables designers to model airflow, temperature, and heat transfer across PCBs, enclosures, and complex assemblies.
It supports all major modes of heat transfer—including natural and forced convection as well as radiation—making it ideal for a wide range of thermal scenarios.

With its intuitive interface, automated object-based meshing, and direct ECAD/MCAD integration, Celsius EC simplifies model setup while maintaining high accuracy. Engineers can easily run "what if" analyses, identify thermal bottlenecks early, and iterate cooling strategies without relying on external tools or late-stage prototyping.

FUNDAMENTALS OF HEAT TRANSFER IN ELECTRONICS

Thermal behavior in electronic systems is governed by the same physical principles that apply to all systems, but with distinct constraints in size, material composition, and power density. Understanding the modes of heat transfer and how they interact within a typical electronics assembly is critical for building accurate thermal models and designing effective cooling strategies.

Modes of Heat Transfer

As Figure 1 illustrates, electronics cooling typically involves three modes of heat transfer, often occurring simultaneously.

- Conduction: The transfer of heat through a solid material due to molecular vibration and direct contact. In electronics, conduction is the dominant mechanism for transferring heat through integrated circuit (IC) packages, thermal interface materials (TIMs), printed circuit board (PCB) copper planes, and heatsinks. High-conductivity materials such as aluminum and copper are commonly used to spread and conduct heat away from critical components.

- Convection: Heat transfer between a surface and a surrounding fluid, usually air. In natural convection, airflow is driven by buoyancy as heated air rises. This is common in passive enclosures or sealed systems. In forced convection, fans or blowers drive airflow across components and heatsinks to increase heat transfer rates. Forced convection is essential in systems with high power densities or restricted airflow paths.

- Radiation: The transfer of heat through electromagnetic waves, without the need for a physical medium. All objects emit thermal radiation based on their temperature and surface properties. Radiation becomes significant in systems with high surface temperatures and unobstructed surfaces exposed to open surroundings, where heat can freely radiate toward cooler regions. However, in most electronic systems, convection heat transfer dominates, making radiation a secondary effect, except in sealed enclosures or vacuum environments such as space, where airflow is limited or absent.

Thermal Resistance Network

To quantify heat transfer, thermal resistance networks are used to model the temperature rise (ΔT) from a heat source (i.e., junction) to the surrounding environment. The junction is the active region of a semiconductor device, such as a transistor or processor core, where electrical power is consumed and dissipated as heat. This is the primary

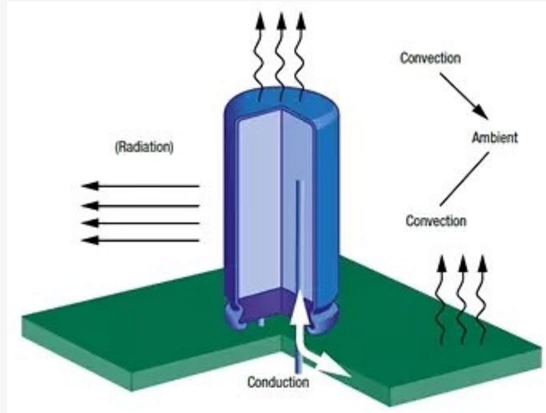

Figure 1: A PCB-mounted capacitor, where heat conducts from the component into the PCB, convective currents transport heat to the ambient air, and thermal radiation is emitted from exposed hot surfaces

source of heat generation, resulting from mechanisms such as switching losses, resistive heat, and leakage currents. In thermal modeling, the junction is treated as the origin of the heat flow, just like a current source in an electrical circuit. Thermal networks are analogous to electrical circuits, as defined in Table 1, which lists electrical concepts and their corresponding thermal analogies.

ELECTRICAL CONCEPT	THERMAL ANALOGY
Voltage (V)	Temperature (T)
Current (I), in amps	Heat flow (Q), in watts
Electrical resistance (R), in Ohms	Thermal resistance (Ɵ),, in °C/W
Ohm's Law or Voltage drop (ΔV=I*R)	Temperature rise (ΔT=Q*Ɵ)
Current source	Heat source/power dissipation (Q or Pd)
Voltage source	Fixed temperature boundary(e.g., isothermal surface)
Electrical ground (0 V)	Ambient or environment temperature (TA)

Table 1: Analogy between electrical and thermal systems

This analogy forms the basis of the thermal version of Ohm’s Law given by $\Delta T=Q*\theta$, or more specifically, in junction calculations: $T_J=P_d*\theta_{JC}+T_C$, where T_J and T_C denote the junction and case temperatures, respectively. Figure 2 illustrates the thermal network of a silicon die in an IC package, where heat flows through resistive elements, which are defined in Table 2. Each resistance contributes to the total temperature rise. The sum of these resistances, multiplied by the heat generated, gives the expected temperature rise under steady-state conditions.

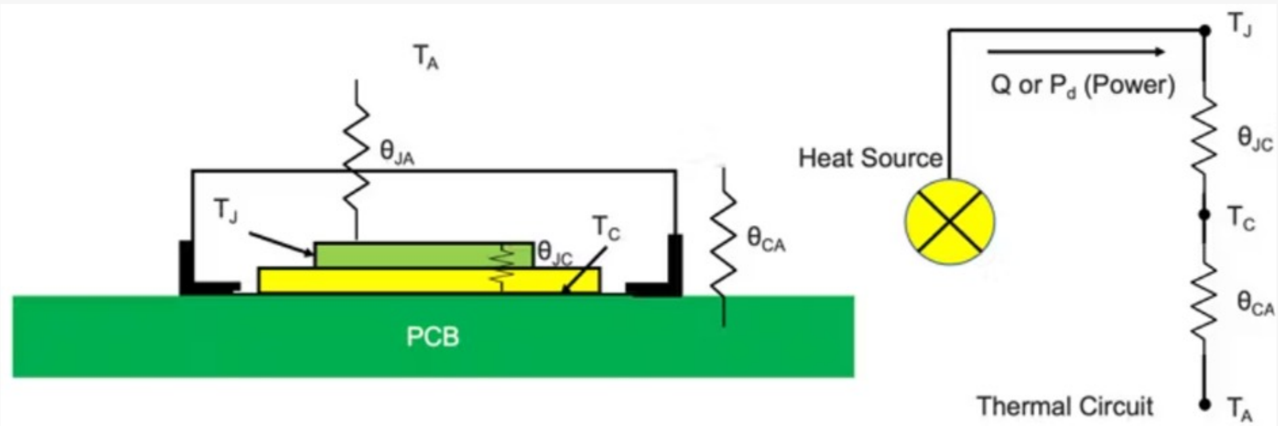

Figure 2: Thermal resistance network of the die in an IC package

TERM	DEFINITION
Junction-to-case resistance (θ_{JC})	Resistance from the die to the case
Case-to-ambient resistance (θ_{CA})	Resistance from case to ambient (includes TIMs, heatsinks, and convection)
Junction-to-ambient resistance (θ_{JA})	Total resistance from die to air (often used in datasheets)

Table 2: Common thermal resistance terms

Surface Area, Airflow, And Packaging

Effective thermal design hinges on managing how heat is removed from components and distributed through the system. Increasing the surface area of a heatsink (Figure 3) or enclosure allows more heat to be transferred through conduction at contact interfaces and via radiation and convection to the surrounding environment. Directional airflow, whether natural or forced, improves heat removal through convection. However, it is ineffective when the airflow bypasses main heat-generating components (i.e., thermal bypassing), becomes irregular or chaotic, resulting in turbulence, or when warm air recirculates back towards components instead of exiting the system, creating a recirculation zone. Furthermore, densely packed layouts or shielded enclosures designed to block electromagnetic interference can trap heat and restrict airflow. Thermal interactions and flow paths should be carefully considered when designing component placement and board orientation.

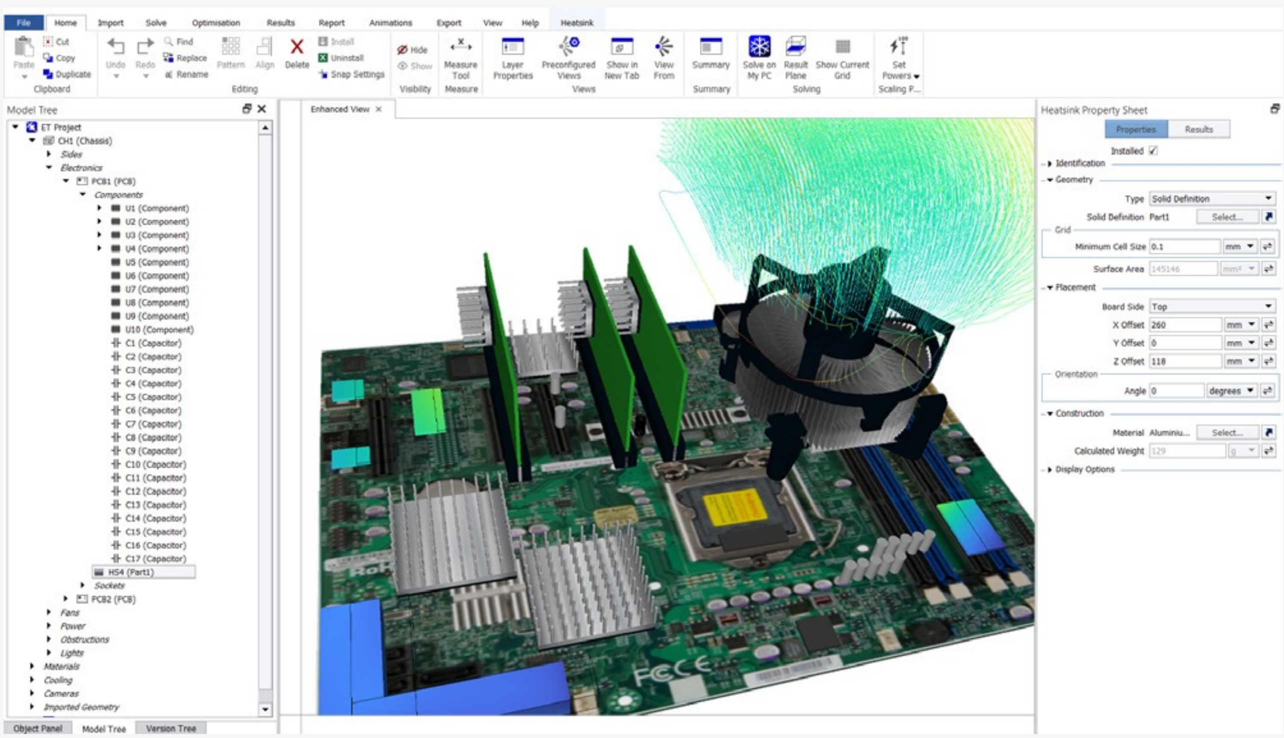

Figure 3: Celsius EC Solver interface showing PCB assembly, with fan-driven cooling and heatsinks positioned near high-power components

COMMON ELECTRONICS COOLING METHODS

Thermal management strategies in electronic systems can be broadly classified into passive, active, and system-level methods. Each addresses the movement and dissipation of heat in a different way, and most real-world designs require a combination of these approaches. This section discusses the basics of each method and the trade-offs they involve, as listed in Table 1.

METHOD		COST	COMPLEXITY	NOISE	RELIABILITY
Passive		Low	Low	Silent	High (no moving parts)
Active	Air	Low-moderate	Moderate	Moderate	Moderate (fan wear)
	Liquid	High	High	Low-moderate	Low (pump failure, leaks)
	Vapor Chamber	Moderate	Low-moderate	Silent	High (sealed system)

Table 3: Comparison of passive and active electronics cooling methods

Passive Cooling

Passive cooling refers to heat dissipation techniques that require no moving parts or external power. These methods rely on conduction, natural convection, and radiation and are favored for their simplicity, silence, and reliability. Key passive methods include:

- Heatsinks: Finned metal structures (typically aluminum or copper) that increase surface area to improve convective and radiative heat loss.
- Thermal vias: Copper-plated through-holes in a PCB (Figure 4) that conduct heat vertically from surface-mounted devices into internal or backside copper planes.
- Copper planes: Large conductive layers in the PCB that distribute heat laterally to reduce hotspots and improve thermal uniformity.
- Heat spreaders: Flat metal or graphite components that transfer concentrated heat loads over a broader area.

While passive methods are cost-effective and maintenance-free, they may not provide sufficient cooling for high-power devices or compact, sealed enclosures where natural convection is limited.

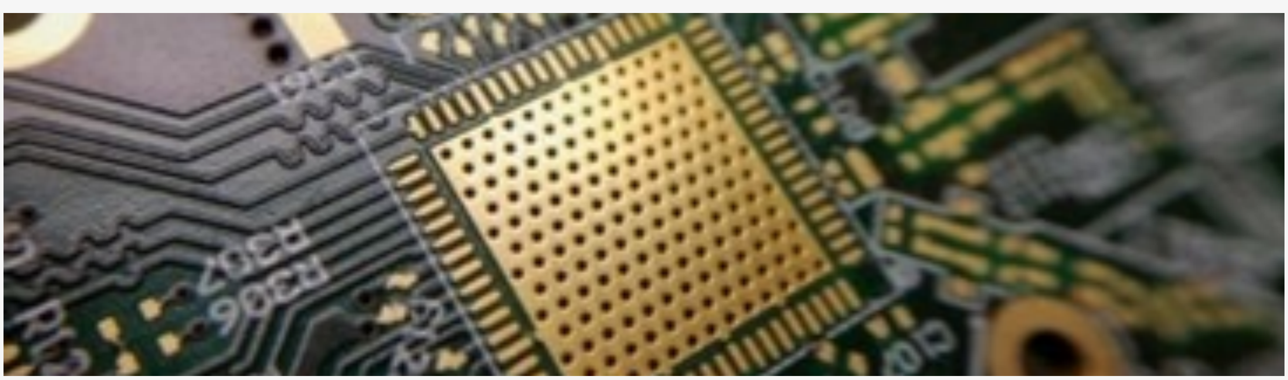

Figure 4: Thermal vias in PCB

Active Cooling

When passive methods fall short, active cooling is introduced to accelerate heat removal using mechanical or fluidic systems. These methods offer superior performance but introduce complexity, noise, and potential reliability concerns due to the presence of moving parts. Examples include:

- Fans and blowers: Rotating devices (Figure 5) that drive airflow over heatsinks and components, considerably increasing convective heat transfer. They reduce the thermal boundary layer thickness (i.e., the thin region of fluid near a heated surface), which decreases resistance to heat flow between solid surfaces and adjacent fluid.

- Cold plates: Metal blocks with embedded liquid channels, mounted in direct contact with hot components. Coolant circulates through the channels, extracting heat and transporting it to an external heat exchanger or radiator.

- Vapor chambers: Flat, sealed devices that spread heat via phase change processes, rapidly transferring thermal energy from hotspots to cooler regions through evaporation and condensation.

Active methods are indispensable in high-power systems, but they are relatively expensive, require careful mechanical integration, and sometimes need ongoing maintenance.

System-Level Thermal Design

Beyond individual components, the overall enclosure layout and airflow strategy play a major role in thermal behavior. System-level design decisions can enhance or undermine the effectiveness of passive and active cooling methods. Key strategies include:

- Ducting: The use of internal flow channels or baffles to guide cool air directly to high-power areas and separate intake from exhaust paths. Proper duct design can reduce thermal bypassing and improve flow efficiency.

- Vent placement: Optimal vent placement in enclosures promotes natural or forced convection by influencing the internal pressure distribution, thereby minimizing the risk of hot air recirculating through the system.

- Ambient conditioning: The process of adjusting environmental factors such as temperature, airflow, and humidity to maintain stable conditions. Additionally, it involves thermal management strategies, such as isolating hot zones and thermal derating in hot climates, to prevent overheating.

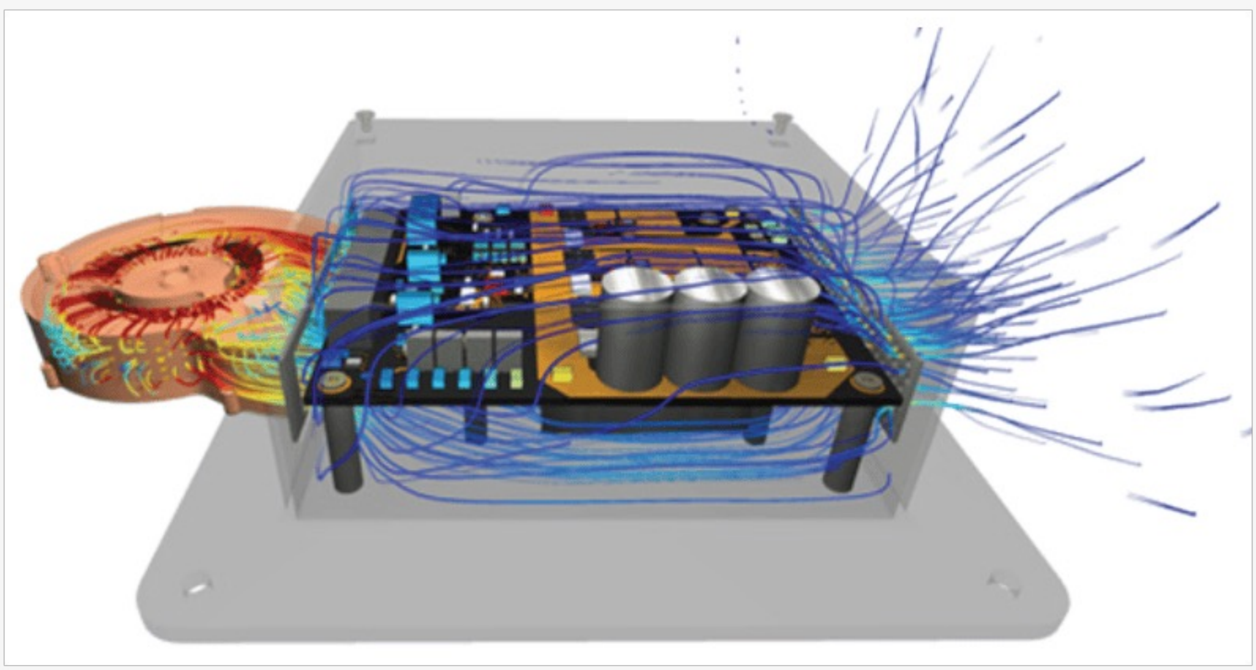

Figure 5: Airflow from rotating fan over PCB components, illustrating enhanced convective heat transfer

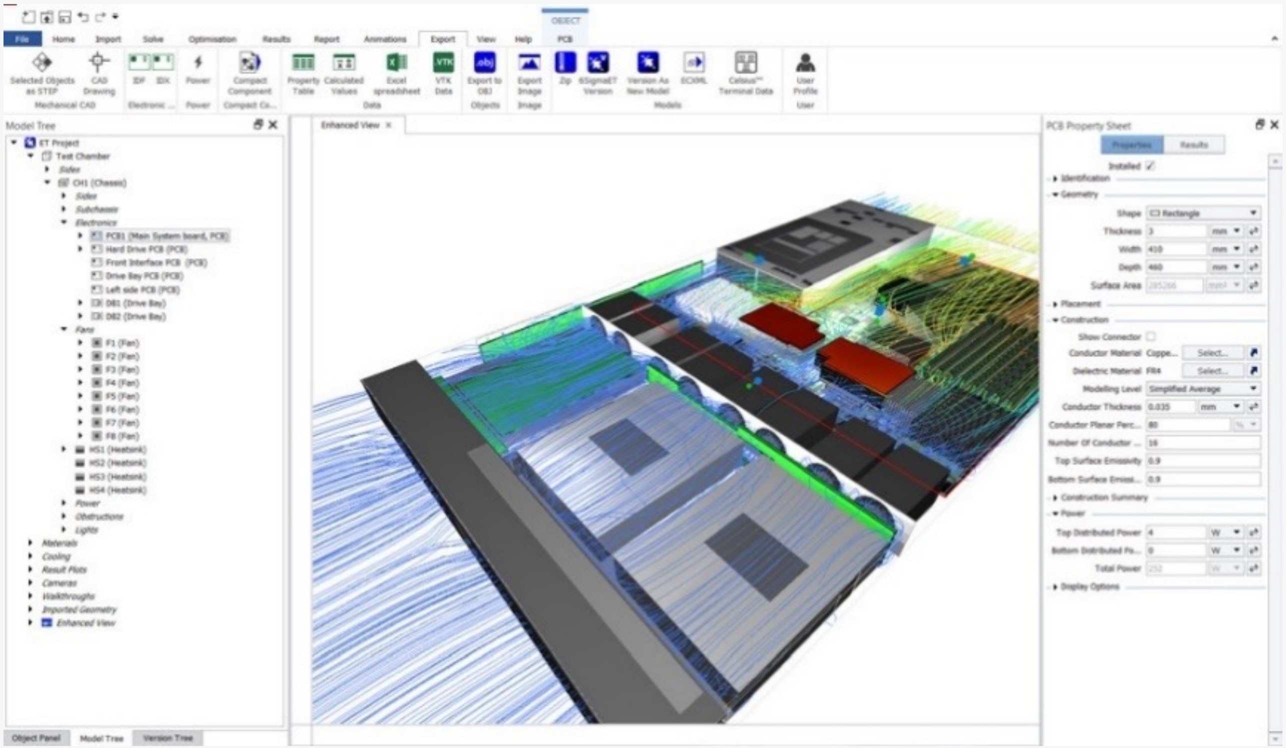

Figure 6: Streamlines around components in a rack-mounted server, where improper vent placement can short-circuit airflow, creating recirculation zones and localized hotspots

These system-level choices are often most effective when made early in the design process, when board layout, enclosure structure, and airflow paths are still flexible. For example, in a rack-mounted server (Figure 6), placing exhaust vents at the rear and intake vents at the front establishes a front-to-back airflow pattern. If vents are placed inconsistently (i.e., exhaust vents on both sides), the air might short-circuit, leading to localized overheating.

The optimal cooling solution rarely involves a single method. Instead, engineers must tailor a hybrid strategy based on power density, packaging constraints, environmental exposure, and long-term product reliability. The following sections demonstrate how simulation can be utilized to evaluate these strategies early in the design cycle.

SIMULATION GOALS AND PLANNING

Simulation-based design guides important engineering decisions such as cooling strategy, component placement, and enclosure design, long before hardware is built. However, before conducting simulations, it is crucial to clearly define the problem at hand. This process begins with identifying limits or constraints, anticipating risk areas, and selecting the appropriate model resolution.

Defining Temperature Limits or Thermal Constraints

Every simulation should begin with a well-defined set of thermal requirements. This includes manufacturer-specified maximum junction temperature for critical components, as well as any application-specific limits such as user-touch surface thresholds or ambient thermal safety margins. In many systems, components must be derated when temperatures exceed a threshold, making it important to simulate both typical and worst-case thermal conditions. Temperature limits can also vary by area within a system. For example, a processor may be able to tolerate higher temperatures than a memory module or display surface. These constraints form the reference points against which simulation results will be evaluated.

Identifying Hotspot Prone Areas and Airflow Challenges

Early in the design, engineers should identify where heat is most likely to accumulate. Hotspots often develop near high-power components, especially those that are stacked or shielded from airflow. Other common risk areas include tightly packed zones, corners of an enclosure (Figure 7), and regions without nearby heat-spreading paths. Moreover, material selection and interface quality greatly affect thermal resistance. Materials with high thermal conductivity are excellent heat conductors, whereas materials with low values are insulators.

Thermal contact resistance at mechanical or electrical interfaces can lead to localized resistive heating, which may go unnoticed until it causes overheating or field failure. These effects are often intensified in sealed or low-airflow environments. In air-cooled systems, it's equally important to assess airflow limitations. Structural obstructions, poor vent placement, or recirculation zones can reduce convective cooling efficiency and prevent hot air from exiting the system. Identifying these challenges early helps focus the simulation on the zones where cooling is most critical.

Accounting for Environmental and Operational Conditions

The physical environment in which a product operates has a direct impact on thermal performance. Simulations should reflect expected ambient temperatures, system orientation (e.g., horizontal or vertical mounting), altitude, and solar radiation exposure for outdoor or window-facing applications. For example, convection effectiveness decreases at high altitudes due to lower air density, and natural convection is orientation-sensitive. In sealed enclosures or hot climates, external ambient conditions may cause the system to approach its thermal limits. Taking these factors into consideration helps avoid setbacks during testing or field deployment.

Figure 7: Corners of an enclosure can be prone to thermal hotspots when airflow is restricted or fails to reach confined regions

Choosing the Right Level of Model Fidelity

Thermal simulations can be performed at multiple levels of abstraction. Selecting the right fidelity is crucial to obtaining useful results without unnecessary complexity. In early concept phases, device-level models, with simplified geometries and estimated power loads, are often sufficient to size heatsinks or select general cooling methods. As the design progresses, board-level models (Figure 8) that include copper planes, thermal vias, and detailed power mapping become essential to predict lateral heat spreading and component interactions. For enclosure-level thermal behavior, especially airflow, venting, and external conditions, system-level models are necessary. These can capture ducting effects, fan performance, and interactions between natural and forced convection across the entire assembly. The ideal simulation fidelity should strike a balance between accuracy and efficiency.

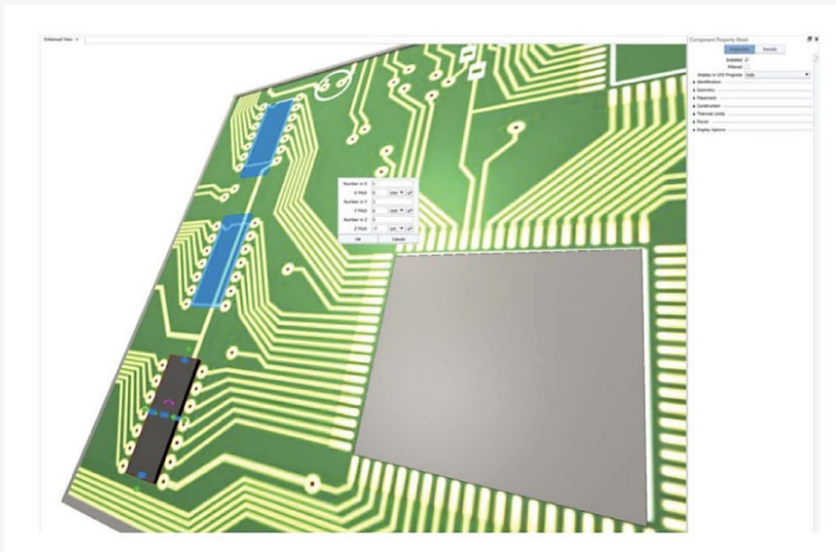

Figure 8: Board-level thermal model of PCB showing detailed copper routing

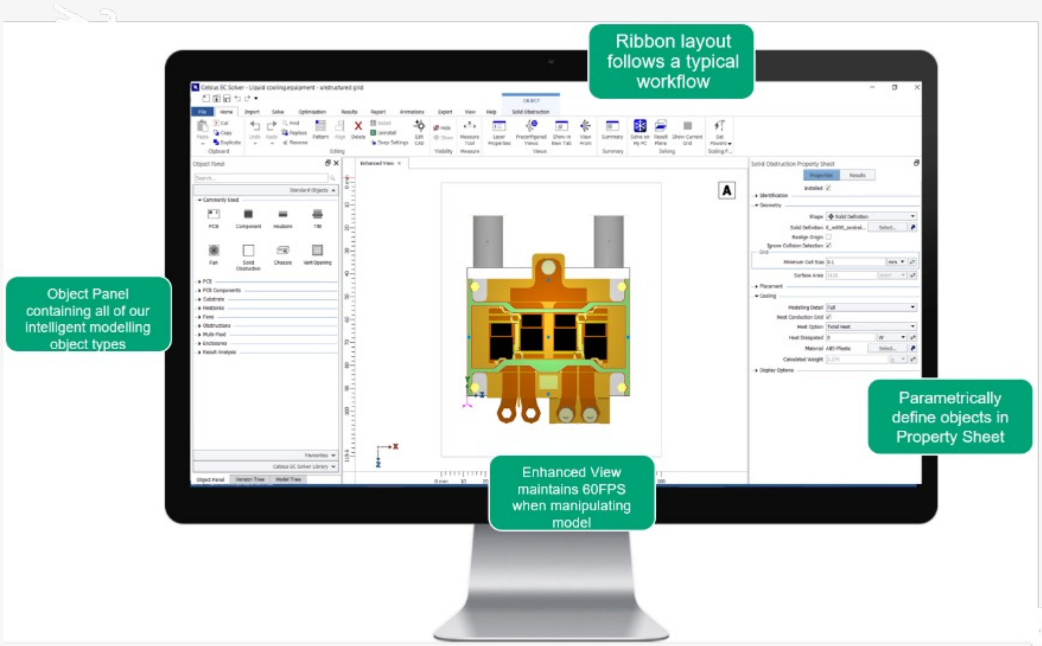

Figure 9: Intelligent and intuitive user interface of Celsius EC Solver showing object panel, ribbon layout, and parametric property sheet for defining and manipulating model geometry

Importing Geometry

Most electronics systems involve both PCBs and enclosures, requiring integration of both electronic computer-aided design (ECAD) and mechanical computer-aided design (MCAD) models, as depicted in Figure 10. Standard ECAD file formats include ODB++ and IPC2581, which capture board stackups, component outlines, and power maps. On the mechanical side, MCAD files in STEP, SolidWorks, or CATIA formats allow import of detailed housing geometry, such as venting, standoffs, or heatsink structures. Thermal models require alignment of these geometries at the system level. Ensuring clean, connected interfaces between electrical and mechanical parts is critical to prevent artificial gaps or unrealistic thermal boundaries.

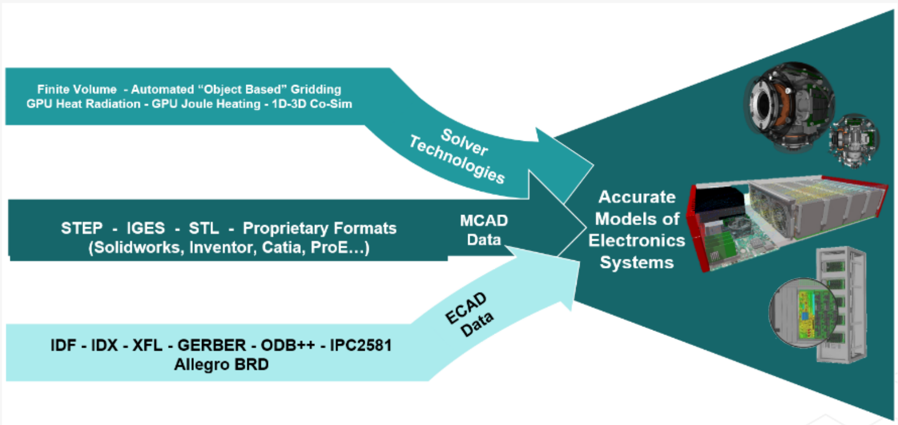

Figure 10: Celsius EC enables integration of ECAD and MCAD data with advanced solver technologies to generate accurate electronic system models for comprehensive thermal analysis

Simplifying Geometry for Thermal Relevance

While mechanical models often contain fine details, such as fillets, chamfers, or screw threads, these are usually thermally insignificant and can be safely removed to reduce mesh complexity. The goal is to preserve geometry that affects heat conduction, convection, or obstruction of airflow, while eliminating features that only add computational overhead. In conventional solvers, simplification must be balanced carefully to avoid overlooking important bottlenecks or thermal interfaces, especially in dense layouts or narrow air channels. However, the Celsius EC Solver can handle full assemblies and system-level models with high fidelity, allowing engineers to capture the complete thermal behavior of intricate designs without oversimplification.

Assigning Physical Properties

After importing and simplifying the geometry as needed, a critical step in preparing a thermal model is assigning accurate physical properties to all regions of the geometry, whether solid or fluid. This typically starts by assigning materials to components based on their real-world equivalents. The Celsius EC Solver offers a library of common materials, including copper, aluminum, FR-4, and various polymers, each with predefined thermal properties. These materials are used for conductors, heatsinks, enclosures, substrates, and other solid parts of the assembly.

In addition to solids, any fluid regions present in the model, such as air spaces for convection or liquid coolants for active cooling, must also be defined with appropriate physical properties. For air, this includes density, viscosity, thermal conductivity, and specific heat, which may vary with temperature. Liquid coolants, such as water or glycol mixtures, require similar definitions for simulating forced circulation in cold plates or liquid loops. Even enclosed air pockets in passive systems must be modeled as fluid volumes to capture buoyancy-driven natural convection.

Mesh Generation

With material properties defined, the model is then discretized into a computational mesh of finite cells, providing the framework for numerically solving the coupled fluid flow and energy equations that govern heat transfer within the system. The resolution and quality of the mesh have a significant impact on both accuracy and simulation runtime. A fine mesh improves accuracy in regions with high thermal gradients (e.g., near hotspots, fins, or vents), while a coarser mesh may suffice in thermally uniform areas. Local refinement (Figure 11) can also be applied selectively to balance fidelity and solve time.

EFFICIENT PREPROCESSING WITH CELSIUS EC

Celsius EC provides a CAD-agnostic, edit-in-place workflow that lets users modify imported ECAD and MCAD geometry, such as resizing holes, adding vents, or removing features, directly within the simulation environment.

Once the geometry is prepared, Celsius EC’s multi-level unstructured meshing (MLUS) feature detects and fixes geometry defects like silvers or overlaps. Then the object-aware meshing feature automatically refines the mesh in critical areas based on component type.

These object-level rules are executed by the underlying MLUS engine, which adaptively controls global and local mesh resolution, enabling robust convergence and efficient simulation.

Defining Heat Sources

Once the mesh is generated, the next step is to assign heat sources that represent power dissipation from electronic components. Engineers can specify these in different ways: a single total power value for simplified blocks, per-component power dissipation imported from ECAD data, power maps for fine-grained distribution across chips or boards, or multiple junctions in systems with several active ICs. Defining the magnitude and location of heat sources is crucial, particularly for capturing hotspot interactions and assessing thermal margins.

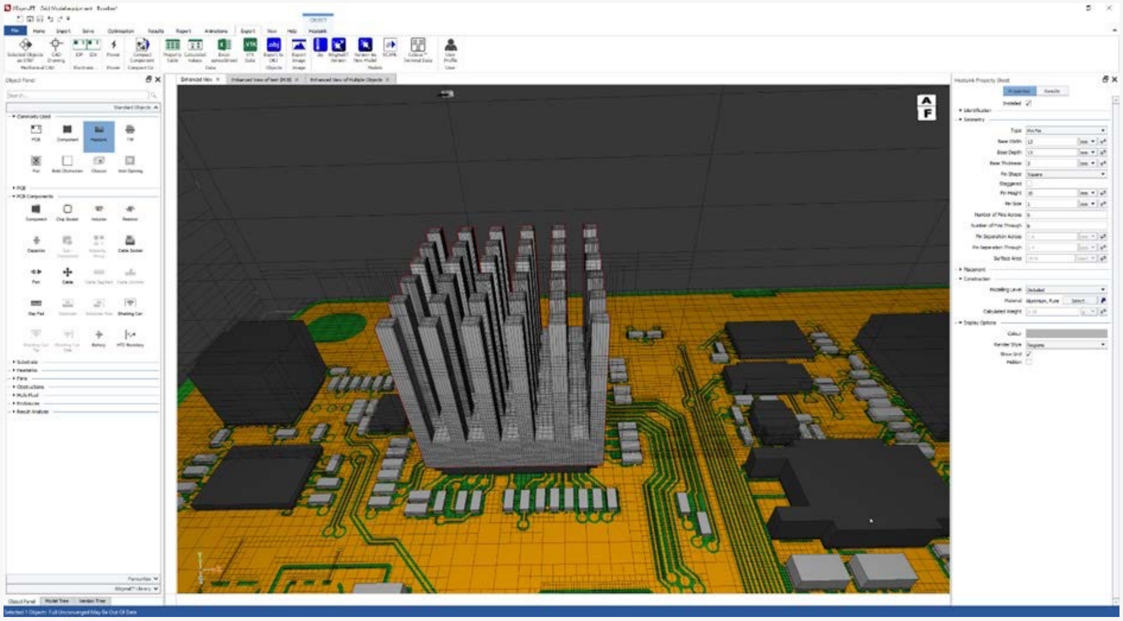

Figure 11: Celsius EC applies component-specific mesh rules, such as fine resolution between heatsink fins, to accurately capture airflow

Applying Boundary Conditions

With heat sources defined, the surrounding environment must be specified through thermal boundary conditions. These describe how heat leaves or enters the system and set the stage for simulating realistic heat transfer. Errors in boundary setup can lead to results that considerably deviate from real-world performance. Table 4 presents typical boundary conditions and their application.

BOUNDARY CONDITION	DESCRIPTION	SETUP METHOD
Ambient Temperature	- Fixed reference temperature of the surrounding environment where a device or system operates. - Sets the baseline for convection and radiation calculations.	- Apply ambient temperature as a global condition in the fluid domain.
Convection	Heat transfer between a solid surface and a surrounding fluid.	- Natural convection: Specify ambient temperature; solver calculates buoyancy. - Forced convection: Define inlet velocity, flow rate, or pressure; fan curves may be applied. - Simplified case: Assign film coefficient (h-value) together with ambient temperature.

BOUNDARY CONDITION	DESCRIPTION	SETUP METHOD
Radiation and Solar Loading	Heat exchange via surface emissivity or external flux.	- Enable radiation with emissivity values. - Specify surface-to-surface or surface-to-ambient radiation. - Apply solar flux for outdoor exposure.
Inlets and Outlets	Entry/exit paths for fluid flow.	- Inlets: Define velocity, mass flow rate, or volumetric flow rate. - Outlets: Manually set static pressure or let solver balance mass/volumetric flow, leaving the outlet with whatever enters the system. - Placement of inlets and outlets should match real vent/duct geometry.
Surface Conditions	Idealized boundaries for simplifying models while preserving physics.	- Apply isothermal surfaces for fixed temperatures (e.g., cold plates and heatsinks). - Use adiabatic surfaces for insulation or symmetry planes.

Table 4: Common boundary conditions in electronics cooling simulations

Boundary conditions should always reflect the actual operating scenario. A sealed enclosure with limited convection requires a different setup than an open chassis or actively ventilated rack server. For rugged outdoor equipment, environmental extremes like wind, altitude, or solar load should be accounted for. For consumer electronics, transient usage patterns and intermittent fan operation may be more important. By tailoring boundary conditions to the physical context, engineers can ensure simulations predict not only maximum component temperatures but also system-level interactions such as hotspots, airflow bypass, and thermal coupling between subsystems. Properly applied, boundary conditions bridge the gap between abstract models and real-world electronics performance.

TYPES OF ANALYSIS

With the geometry, materials, mesh, heat sources, and boundary conditions established, the model is ready to be solved under different analysis modes. As discussed below, the choice between steady-state, transient, convection, radiation, or other modeling approaches depends on the simulation objectives and the level of fidelity required.

- Steady-State and Transient Analysis: Thermal simulations can be run in steady-state, where temperatures and heat flows are assumed to have stabilized, or transient, where the solver captures time-dependent variations. Steady-state analysis is faster and ideal for identifying hot spots under peak or average power loads. Transient analysis, though more computationally intensive, is essential for capturing thermal cycling, warm-up periods, power pulses, and other dynamic behaviors, especially in systems where reliability is tied to time-varying temperature profiles.

- Natural and Forced Convection: Convection in electronics cooling can be driven passively (natural) or actively (forced). Natural convection arises from buoyancy effects resulting from temperature differences and requires careful modeling of the enclosure geometry and vent placement. Forced convection uses fans or blowers to enhance airflow (Figure 12). The simulation should correctly represent fan curves, airflow boundaries, and turbulence regions. Modeling forced convection correctly is vital for systems with constrained airflow paths, high component densities, or directional ducting.

- Radiation Modeling: Thermal radiation becomes important in systems with high surface temperatures, large exposed areas, or environments with limited airflow, such as sealed enclosures, outdoor controllers, or spacecraft. Radiative heat transfer equations are solved using surface emissivity and view factors. In space applications, radiation is often the dominant heat transfer mechanism that is dependent on material properties and orientation-dependent exposure.

- Joule Heating and Electrothermal Effects: Joule heating, or resistive self-heating, occurs when electrical current flows through conductive paths. In high-current applications, such as power delivery networks, relays, or connectors, Joule heating can cause a significant temperature rise. Electrothermal co-simulation couples electrical and thermal solvers to model how temperature affects current paths, and vice versa, enabling better prediction of localized heating and thermal-induced failure modes.

ADVANCED SOLVER CAPABILITIES IN CELSIUS EC

Celsius EC supports steady-state and transient analysis with both natural and forced convection, plus radiation modeling. The solver engine includes support for CFD-based and conjugate heat transfer simulations. It handles temperature-dependent properties, power maps, and electrothermal coupling via Joule heating. With built-in models for cold plates and liquid-cooled assemblies, as well as 1D-3D co-simulation options, Celsius EC scales from quick "what-if" studies to high-fidelity system modeling.

Celsius EC has a highly parallelized architecture that has been tested on up to 352 cores. Its GPU solving technology for auxiliary calculations has removed previous bottlenecks in the simulation process, making same-day results possible. Additionally, Joule heating and radiation view factor calculations are up to 125X and 140X faster, respectively. Simulations can be solved locally on a dedicated server or on the cloud.

- Liquid Cooling and Cold Plate Simulation: Liquid-cooled systems use cold plates, heat exchangers, or pumped coolant loops to handle high thermal loads in dense or rugged applications. Simulating these systems involves modeling fluid bodies, pressure drop, and heat transfer through interfaces. Accurate modeling of coolant properties, flow rates, and contact resistances is key. CFD-based solvers can capture flow distribution across manifolds and between channels in cold plates.

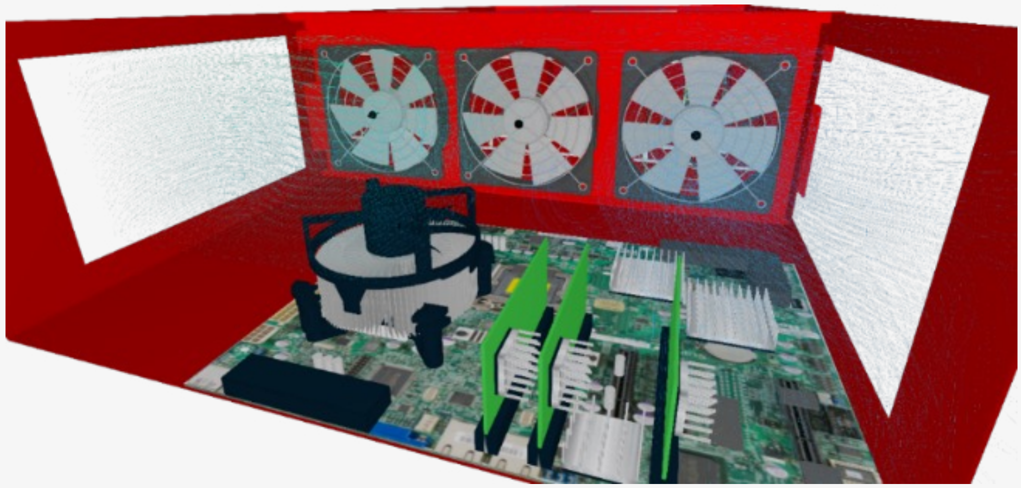

Figure 12: Forced convection in an electronics enclosure, where multiple fans drive airflow across a populated circuit board to enhance cooling efficiency

- **1D-3D Co-Simulation for Systems-Level Efficiency:** For complex systems like servers or EV inverters, combining 1D system-level models (e.g., flow networks) with 3D thermal domains allows engineers to more efficiently simulate full platforms. 1D-3D co-simulation passes flow, temperature, and pressure information between domains, optimizing runtime while preserving essential local physics. This is particularly useful in early design stages or iterative architecture evaluations.
- **Temperature-Dependent Properties and Power Dissipation:** In many electronics systems, material properties, such as thermal conductivity, specific heat, and electrical resistivity, change with temperature. Power dissipation from chips and other active devices may also vary based on temperature, voltage, or workload. To simulate these dependencies, solvers must dynamically update material and power parameters during runtime. Including these effects improves accuracy in high-power and thermally sensitive designs, where fixed-property assumptions may underestimate the severity of hot spots or thermal gradients.

Each simulation requires careful setup of numerical parameters to ensure convergence and stability. The convergence criteria (e.g., residual thresholds) define when a solution is considered accurate. Solver steps and iteration tuning control how aggressively the simulation proceeds through time or convergence cycles. Additional controls include under-relaxation factors (i.e., numerical damping factors that update variables gradually to stabilize convergence), thermal timestep size for transients, and error-checking flags. An appropriately tuned solver leads to faster convergence (Figure 13) without sacrificing accuracy.

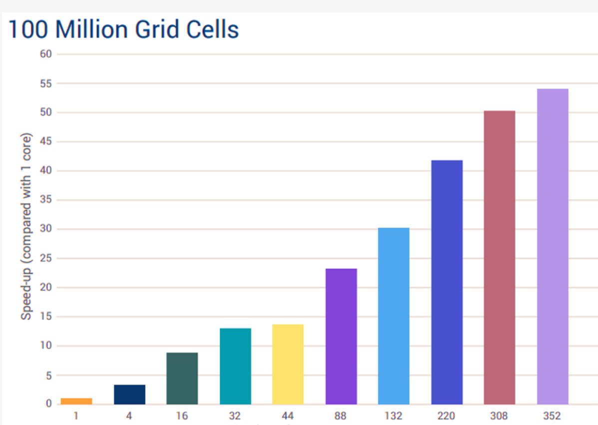

Figure 13: The Celsius EC Solver handles up to 750 million grid cells, solves 100 million cells per hour, and manages tens of thousands of objects for complex CAD and PCB designs

POST PROCESSING AND INTERPRETATION OF RESULTS

Once a simulation is complete, the next step is to translate raw data into engineering insights. Post-processing allows for the visualization and analysis of key thermal behaviors, communication of results, and informed design decisions. Visualization typically starts with contour plots of airflow, temperature, and heat flux across the system. These graphical results help identify hot zones, stagnation regions, and inefficient airflow paths. By overlaying stream-lines on velocity or temperature maps, engineers can assess whether cooling air is reaching critical components or bypassing them entirely.

For more in-depth analysis, cut planes, section slices, and point probes can be utilized. These tools allow focused inspection along specific directions or surfaces, which is vital for pinpointing thermal gradients, tracking airflow obstructions, or comparing component performance. Probes can extract numerical values like local temperature, heat flux, or airspeed, enabling a direct comparison against design specifications. A common evaluation metric is temperature rise, the temperature difference between a component and its environment, such as junction-to-ambient. Engineers can also assess whether junction temperatures stay below component limits and whether sufficient thermal margin exists under worst-case loading or ambient conditions. These checks are important for validating reliability, especially in mission-critical or safety-certified designs.

Results can be exported in various formats to facilitate communication and documentation. As shown in Figure 14, high-resolution images, annotated screenshots, tabulated probe data, and even animations showing transient temperature evolution are commonly used. Celsius EC also supports automatic report generation, bundling plots, metrics, and setup information into a shareable summary. Through these post-processing tools, engineers can ensure that results are not only accurate but also presentation-ready. As a result, findings can be clearly communicated to design teams, project managers, and stakeholders, reducing review cycles and enabling faster design decisions.

COMMUNICATING SIMULATION FINDINGS EFFECTIVELY WITH CELSIUS EC

The Celsius EC Solver takes much of the manual effort out of post-processing by combining automated reporting tools with flexible visualization options. Users can generate detailed, structured reports in just a few clicks, complete with preformatted plots, annotated images, and key numerical results.

Customizable legends allow precise control over how data is displayed, including the number of color bins, range boundaries, and color mapping. This flexibility helps highlight subtle temperature gradients, airflow patterns, or heat flux variations that might otherwise be missed.

Dynamic max/min markers automatically identify the hottest and coolest points in the model, updating instantly as the user adjusts result planes, component selections, or view angles. Thus, it’s easy to focus attention on critical thermal limits and validate whether design targets are being met.

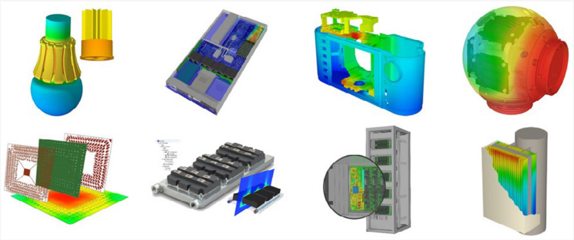

Figure 14: Examples of post-processing outputs across electronics cooling applications using the Celsius EC Solver

DESIGN OPTIMIZATION

Thermal simulation is not just about verifying that a design works; it's about finding ways to improve it. Once the initial analysis highlights problem areas (Figure 15), simulation tools allow engineers to explore modifications, test alternatives, and validate improvements quickly and cost-effectively.

One of the most direct optimization strategies is rearranging component layout to minimize thermal interference. Spacing heat-generating components apart, relocating sensitive devices away from hot zones, and aligning components with airflow paths can significantly lower peak temperatures. Simulation makes it possible to test these changes without costly hardware rework.

Another key area is improving airflow management. This can involve refining ducting, repositioning vents, or adjusting fan placement to ensure cooling air is delivered efficiently to the most critical components. In forced-air systems, optimizing fan selection, considering airflow rate, ability to handle system pressure, and acoustic performance can yield both thermal and operational benefits.

Material and cooling hardware choices also play a major role in performance. Evaluating different heatsinks, TIMs, or higher-conductivity substrates can help achieve target temperatures without resorting to larger or noisier cooling solutions. The Celsius EC Solver makes it easy to compare these options side by side.

INTELLIGENT MODELING FOR RAPID DESIGN ITERATIONS

The Celsius EC Solver includes a library of over 100 intelligent thermal components, such as PCBs, cold plates, heatsinks, and fans, that can be inserted, resized, and reconfigured directly in the simulation model. These prebuilt objects preserve thermal realism while making it easy to test multiple design variations quickly, enabling structured iteration without redrawing geometry from scratch.

For more systematic exploration, engineers can use parametric sweeps to evaluate how design variables, such as component spacing, power distribution, or vent geometry, affect thermal performance. This approach identifies not only optimal configurations but also tolerance ranges, helping ensure the design remains robust under manufacturing variation or environmental changes.

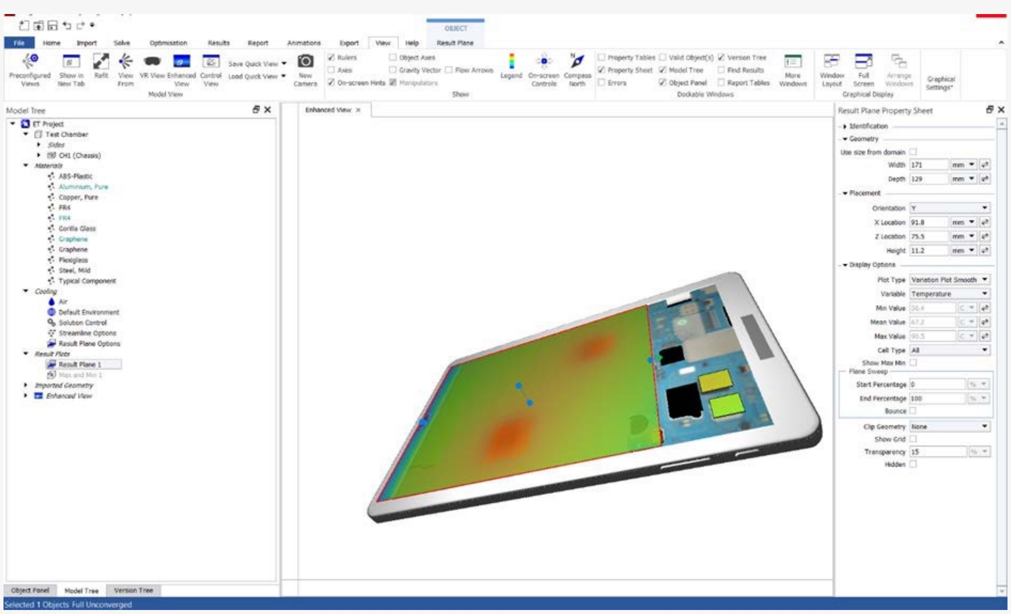

Figure 15: Screen surface and internal component temperatures of a tablet computer

BEST PRACTICES AND COMMON PITFALLS

Even the most advanced thermal simulation software can produce misleading results if models are built on inaccurate assumptions or incomplete data. Following best practices helps ensure results are both credible and actionable.

One of the most common mistakes is assuming uniform convection across a system without verifying airflow behavior. In reality, airflow is rarely evenly distributed; fans have characteristic flow curves, ducts and obstructions create pressure drops, and components can block or redirect cooling air. To achieve realistic results, it is important to explicitly model airflow paths or use accurate convection coefficients whenever possible.

Equally important is using appropriate material data and sufficiently dense meshes. Overly coarse meshes can blur temperature gradients and hide hotspots, while incorrect or generic material properties can distort conduction paths. Engineers should pay particular attention to the thermal conductivity of TIMs and anisotropic PCB properties, as these have a major influence on heat spreading.

Furthermore, validate simulation results against measured data from prototypes or past designs. By comparing predicted and measured temperatures, material properties, boundary conditions, and solver settings can be refined to bridge the gap between simulation and real-world performance.

Finally, recognize the limitations of steady-state analysis in systems with considerable time-dependent behavior. Failures commonly occur during power cycling, warm-up, or fluctuating load spikes. Consequently, transient simulations are required to effectively capture these dynamic conditions.

COMMON THERMAL FAILURE MODES

Thermal overstress doesn't just raise temperatures, it accelerates specific failure mechanisms that can reduce product life and reliability:

- Solder fatigue: Caused by repeated thermal cycling and coefficient of thermal expansion mismatch between components and PCB.

- Dielectric breakdown: Degradation of insulating materials in capacitors, PCB substrates, or coatings due to high temperature and voltage stress.

- Diffusion-related failures: Material migration within semiconductor devices, often temperature-driven, affecting contact resistance and device thresholds.

- Electromigration: Movement of metal atoms in conductors under high current density. It is accelerated by elevated temperatures and leads to open circuits.

Keeping thermal margins within safe limits is critical to long-term reliability and prevention of these failures.

Rhode & Schwarz Boosts Simulation Productivity

Rhode & Schwarz (R&S), a global leader in test and measurement (T&M), broadcasting, secure communications, and network monitoring equipment, encountered growing challenges in managing the thermal performance of their increasingly compact, high-powered electronic systems. As shown in Figure 16, the company's portfolio spans from handheld devices to large chassis-based instruments, each with unique thermal demands. As the complexity and power density of their designs increased, so did the risk of thermal issues impacting performance and long-term reliability. The team's existing thermal analysis software proved inadequate, as it struggled with limited simulation capacity, lacked robust MCAD import functionality, and often resulted in long simulation runtimes or failed to converge altogether. These limitations forced R&S to seek a more scalable and reliable simulation platform that could handle detailed electronic assemblies without compromising accuracy or speed.

R&S engineers evaluated Cadence's Celsius EC Solver, formerly 6SigmaET, which offers fast and accurate electronics cooling simulations across device, board, and system levels. To benchmark its performance, the team conducted a side-by-side comparison of the Celsius EC Solver against their legacy tool for 12 thermal simulation cases of varying size and complexity. The evaluation covered every stage of the workflow, including preprocessing, geometry import, meshing, solving, and post-processing. The results were decisive: the legacy tool failed to complete seven out of twelve cases, even after significant model simplification, and could only handle the remaining five in low detail. In contrast, the Celsius EC Solver successfully ran all twelve simulations using full-detail CAD models, including detailed PCB and component geometries, without requiring simplification. In four out of the five comparable cases, Celsius EC also delivered faster simulation runtimes while maintaining high fidelity. One case showed equal performance. Overall, the total time for importing, meshing, and solving a complex PCB or blade design dropped from 45 hours to just 15 hours (Figure 17)—a threefold improvement.

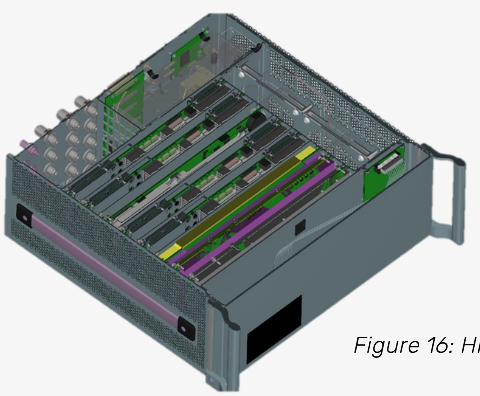

Figure 16: High-frequency T&M equipment (courtesy of R&S)

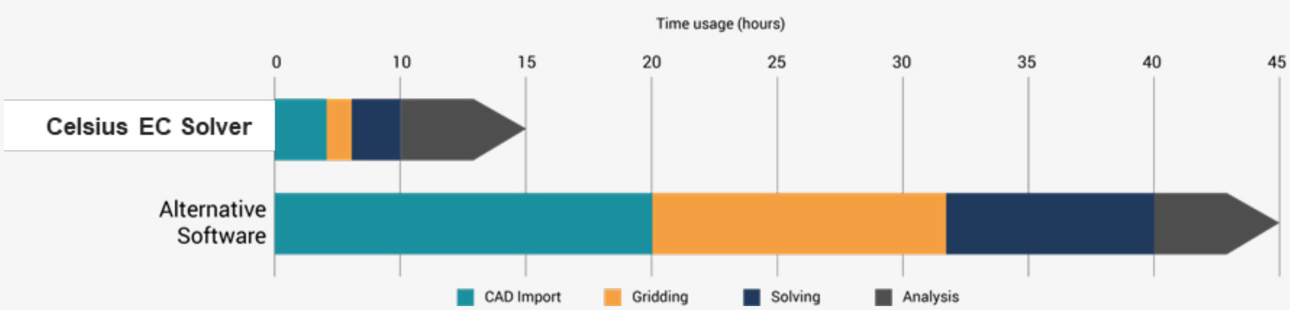

Figure 17: The Celsius EC Solver achieved a 3X performance gain in terms of turnaround time for the highly complex PCB/blade design versus the simplified legacy model

The adoption of the Celsius EC Solver transformed R&S’s thermal simulation workflow, enabling a shift from reactive bottlenecks to proactive exploration and optimization. Engineers could now simulate full model assemblies without compromise, thereby gaining deeper insight into airflow behavior, heat spreading, and component-level hotspots. With faster runtimes and improved convergence stability, the thermal team could iterate more rapidly and evaluate multiple alternatives under realistic operating conditions.

The improved MCAD integration also eliminated manual geometry cleanup steps, considerably reducing preprocessing time. This facilitated closer collaboration between mechanical and thermal design teams and supported faster turnarounds for new product development. In high-complexity systems, such as rack-mounted equipment or densely packed multi-board enclosures, Celsius EC enabled simulations that were previously infeasible, allowing R&S to verify thermal compliance early in the design cycle and avoid costly late-stage redesigns.

Ultimately, the ability to run all 12 benchmark cases without simplification, while decreasing simulation time by 66%, validated Celsius EC as a robust and scalable solution for modern electronics cooling. The platform now plays a central role in R&S’s thermal design process, helping ensure that even the most compact and power-dense systems meet performance and reliability goals.

> “We wanted to have a tool that could directly use our CAD model in order to increase our productivity. It was a big surprise for us to see the functionality of Celsius EC Solver. Due to our comparison, it is definitely the best tool for R&S in the field of thermal simulation.”
>
> Raimund Blankenburg, Rohde & Schwarz

ACCELERATING IC PACKAGE DESIGN

Thermal analysis of modern electronics often requires simulating an entire package-on-PCB assembly. In this case study, the thermal model included a multi-chip substrate, a detailed evaluation PCB with numerous components and copper layers, as well as localized Joule heating from current flow. The complexity of the geometry and physics made the model (Figure 18) extremely demanding to simulate. Traditional thermal solvers struggled with the scale of the problem, forcing simplifications that reduced accuracy and failed to capture critical hotspots. Long runtimes and preprocessing bottlenecks further limited design exploration, slowing iteration and increasing the risk of performance and reliability issues going undetected.

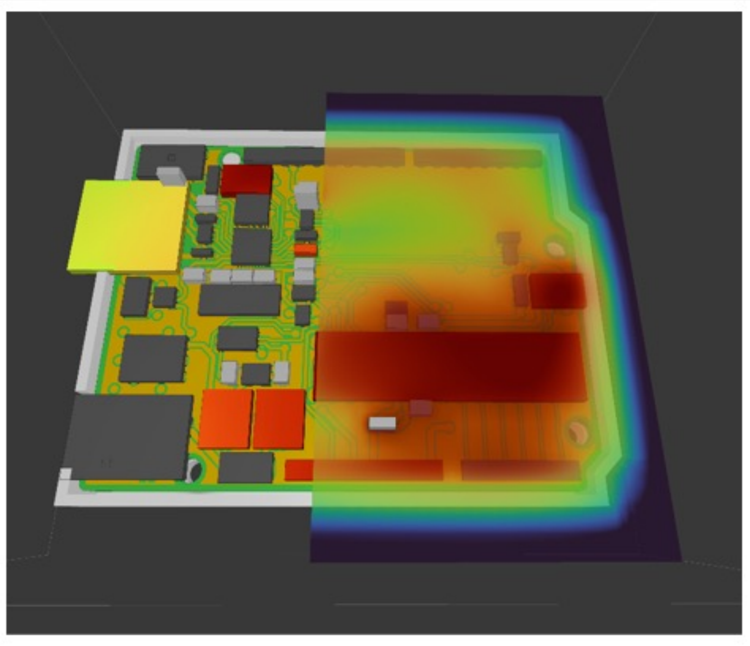

Figure 18: Thermal simulation of a detailed package-on-PCB assembly, showing localized hotspots

The Celsius EC Solver overcame these challenges by enabling full-scale simulation of the package-on-PCB assembly without simplification. Its object-based meshing technology and memory-efficient solver architecture handled the detailed substrate, PCB, and Joule heating effects directly. In benchmarking, the simulation that previously required about three hours with a legacy solver was completed in only eighteen minutes using Celsius EC—a tenfold improvement in performance. This speed gain allowed more scenarios to be explored in less time, facilitating earlier detection of thermal bottlenecks and improved validation of cooling strategies. With its exceptional detail and rapid turnaround times, Celsius EC made it practical to analyze highly intricate package and board assemblies, improving both design productivity and reliability assurance.

CONCLUSION

Thermal simulation is no longer a specialized task reserved for late-stage verification—it is a foundational pillar of electronics design. As power densities increase, form factors contract, and thermal budgets narrow, cooling performance becomes inextricably linked to functionality, reliability, and regulatory compliance. While simulation is now a standard component of product development workflows, barriers to effective deployment persist. Chief among them are preprocessing inefficiencies, prolonged simulation turnaround times, and limited solution fidelity—challenges that continue to constrain design agility and undermine predictive confidence.

This guide has outlined the full lifecycle of electronics cooling simulation, from the physics of heat transfer to geometry import, material assignment, defining boundary conditions, solver selection, and post-processing. Each stage introduces its own trade-offs—between accuracy and speed, fidelity and simplicity, automation and control. In practice, many engineers find their productivity limited not only by simulation capability itself, but by workflow constraints: lengthy CAD cleanup, ambiguous boundary condition setup, trial-and-error meshing, and slow solver convergence. These bottlenecks restrict design exploration, delay thermal signoff, and lead to an over-reliance on approximations or excessive safety margins.

The Celsius EC Solver is designed to directly address these pain points. By integrating intelligent thermal components, automated preprocessing, GPU acceleration, and dynamic visualization tools, this solver transforms formerly time-intensive steps into fast, scalable operations. Rather than waiting days to analyze layout changes, engineers can now iterate within hours—enabling earlier intervention and tighter coupling between electrical and thermal design decisions.

However, effective electronics cooling simulation requires more than access to software—it demands well-informed modeling strategies, attention to boundary conditions, and a willingness to move thermal analysis upstream in the design process. When implemented correctly, simulation does more than verify—it enables optimization. It empowers engineers to avoid overdesign, reduce development risk, and validate performance under real-world operating conditions. In this way, thermal simulation becomes not just a safeguard but a strategic advantage in the race to build denser, faster, and more reliable electronic systems.

Want to Learn More?

If you're interested in taking the next step in electronics cooling simulation, the Celsius EC Solver is designed to help engineers overcome the traditional challenges of thermal design. By combining automated meshing, MCAD/ECAD data integration, and advanced solver technologies, Celsius EC delivers high-fidelity results without the bottlenecks of conventional tools. Whether you are working at the device, board, or system level, Celsius EC provides the efficiency, accuracy, and scalability needed to evaluate thermal performance early and often, reducing costly redesigns and accelerating time to market.

To learn more about how the Celsius EC Solver can streamline your thermal design workflow and improve reliability across your projects, visit **Cadence's official product page** to **request a demo** or speak with an expert from the Cadence team.

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