Implementing Embedded Component from Concept-To-Manufacturing

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Introduction

If we go back and study the evolution of computer engineering, we will see that many of the products we have adopted as part of our everyday lives have changed significantly over time. Thinking back to the days of the Apollo workstations, the first PCs and mainframes that could occupy complete building floors, it is evident that miniaturization is the common denominator on how technology has progressed over time. Recent innovations in tablets, smartphones, ultrabooks and many other applications have created a greater challenge for engineering and design teams to balance the act of implementing the optimal form, fit, and function during product development. They also have to carefully take into account materials, components, and signal/power quality requirement to ensure that all specifications are realized to deliver their products to the market. One of the key factors enabling design teams to meet these requirements is the cost-effectiveness and advancement in the application of embedded components in PCB design.

Use of embedded components has grown significantly in the defense, aerospace, telecommunications, medical and consumer markets. We may not have experienced the impact of the embedded components in most of these industries, but we have all experienced first-hand the birth of compact cameras and camcorders in the late 80s into the early 90s. With the decreasing cost of manufacturing boards containing embedded components, other industries are adopting this technology as part of their product designs, and we are sure to see a new wave of innovative products on the market in the future.

To support this innovation, there has been a parallel evolution on the design and manufacturing of PCBs. Companies are working closely with their manufacturers to refine the process of producing "multi-functional" boards and packages to support the requirements for new product development using cutting-edge technologies. Some of these boards include electro-optical components with flexible interconnections, embedded optical connectors and polymer-based optical waveguide Embedding passive and active components within the substrate with laser cavities, and now placing high pin-count ICs within the substrate with microvias connecting both sides of the chip to adjacent conduct layers is a commodity these days for advanced PCB manufacturers.

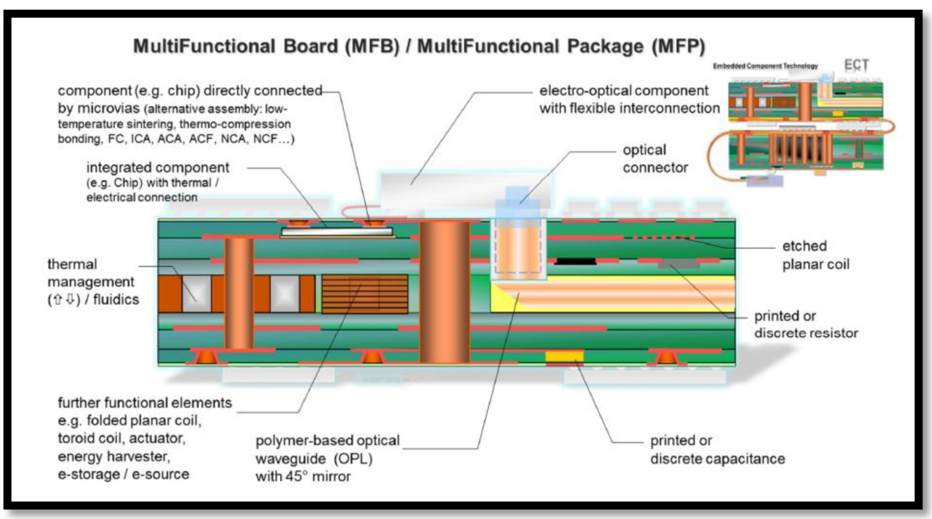

Figure 1: Evolution of PCB design and manufacturing (Image courtesy of Würth Elektronik)

Advantages and disadvantages of embedded components

Sharon Starr, Director of Market Research at IPC, reported in 2010 that, "Embedded components, some believe, could move board manufacturers into the role of chip integrators. The board will become one large component. Resulting developments will be new technologies that can manage electrostatic discharge and shock. In addition, some components will move from

PCBs to being embedded in ball-grid-array (BGA) semiconductor packages. This trend could continue to drive the merging of PCB and semiconductor technologies. It is believed that the major developments will occur on the package/substrate side than on the PCB side." Embedded components have been typically used to form or place passive components on inner layers of PCBs. With the continuous push of miniaturization of electronics, the industry is further pursuing new ways to expand the implementation and manufacturing, we are already seeing companies exploring the mass production of boards with embedded processors, including the use of complex system-in-package (SiP) devices on boards to push the envelope on product form factors.

Before using embedded components on your designs, it is important to understand their impact before implementing them in your next project:

Advantages of embedded components:

- Reduction in outer layer surface area
- Increased functionality for same surface area (greater density)
    - For example, the number of components in mobile phones is increasing, however the general form factor limitations remain the same
- Performance improvement
    - Shorter trace lengths with reduced trace inductance - allows for increased circuit speed
    - Traces closer to reference planes to improve SI characteristics or even components formed within a Faraday cage to reduce susceptibility.
- Potential decrease in total assembled costs
    - PCB cost will be higher, but some cost can be offset by fewer total components for final assembly
- Solving thermal issues
    - Using the structure of the board to dissipate heat
- Eliminating reliability issues
    - Components within a board are less susceptible to failure if the board suffers flexing in its environment
- High pin-count active devices can be embedded directly within the substrate
    - This can be used to project the IP of your design

Disadvantages of embedded components:

- Too many workarounds to implement within legacy 2D design tools
- Meeting tolerance requirements can be more difficult for formed components
    - Trimming can be slow and expensive
- Achieving required value from formed (passive) components is difficult
- Prototype cost is higher
- Embedded components can be damaged during assembly
    - Rework is not possible
- Multiple dies will increase number of power-rails
- Impact on thermal behavior of the system
- Added cost of getting bare-dies from IC vendors or development of ASIC devices for inner layer placement

Common design issues with embedded components

From a design perspective, we have been planning and designing boards as if they are two-dimensional objects, but with advancements in embedded component technology, electronic design needs to be treated as a three-dimensional problem. Design teams need to work closely and intelligently from the conceptual phase of the design process, all the way down to manufacturing, and they cannot continue working only on one board or package at a time – they need to design their products as a complete system. Some of common issues found when working with embedded components include the high-speed packaging and characteristic issues, understanding the required design rules and implementing embedded components within the design, and considering the requirements for fabrication and assembly with upfront rules to design for manufacturing.

This trend in IC design continues to result in high performing, miniaturized, low power consuming, and lower cost devices that require finer design rules, higher clock frequency, and lower core and I/O voltages. Design teams are then faced with newer challenges, such as more heat dissipation, greater electrical noise, and higher risk of issues with signal quality, so taking into account proper thermal and electrical noise management in advance when considering embedded components becomes even more vital to the design process.

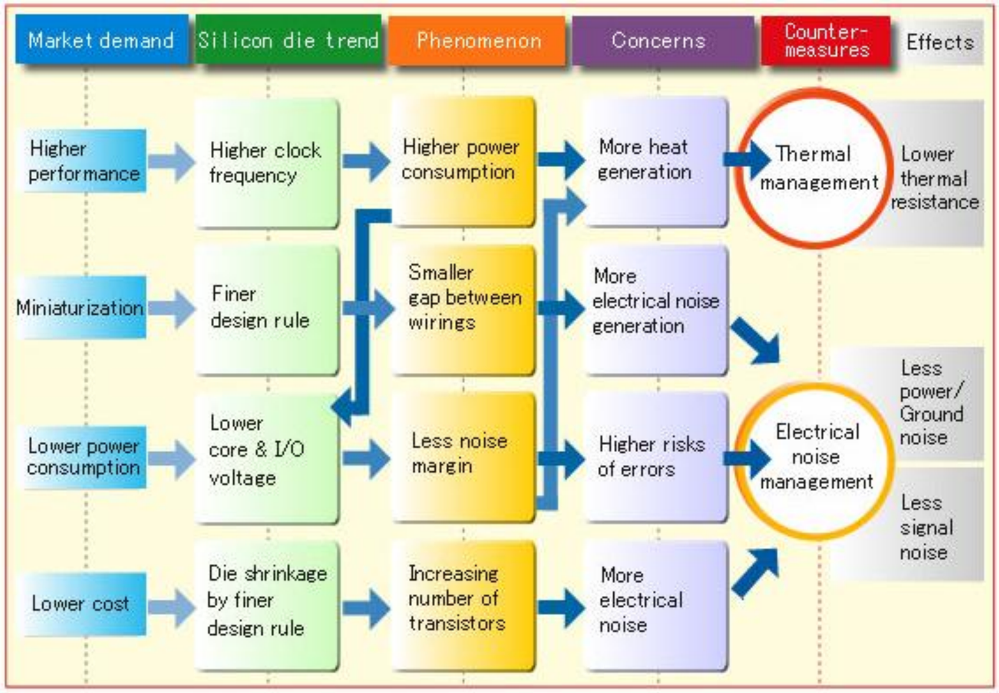

Figure 2: Impact of market demands vs. thermal and electrical integrity (Image courtesy of Renesas)

When considering components to embed within your design, the first things to be considered are the packaging and the high-speed requirements of the device. Whether the IC is designed internally, outsourced, or purchased off the shelf, engineers have to take into account the overall size, including the total pin count and die size. Also, the spacing or pitch between the pins within the geometry, along with the package material (for embedded passive devices) has an impact on the process used to embed the component and the required stack-up for the PCB. Engineers must also consider the material of the package due to impact on hermeticity, thermal effects, cost, and other factors that determine the selection of the component that will be embedded.

Package-less devices

One solution to dealing with high-speed devices is to consider a package-less approach and embed the bare die directly within the PCB. Applying a bare die for PCB design is more commonly used for multi-chip modules (MCMs) or chip-on-board (COB) assembly technology. The benefits of this approach lead to reduced cost and savings in board area space with reduced size and volume. It also addresses some of the challenges associated with high-speed packages, such as the growing number of I/Os and increasing power dissipation.

Utilizing package-less devices enables die stacking, where bare die of comparable sizes are bonded together and now connected together using through-silicon vias (TSVs), more commonly found in dense system-in-package (SiP) devices. This process also offers etching and metallization steps that provide optimal interconnection between chips to help improve the overall electrical and thermal performance, along with minimized signal trace lengths that improve the rising edge of the signal and reduce trace inductance to provide better electromagnetic compatibility (EMC) on the design. With consumer demands continuing to push for smaller, faster and smarter digital devices, directly embedding the die can help achieve the current and future market demands.

Placing active components

As more functions are required for the same surface area on current product designs, design teams are often faced with difficult obstacles in floorplanning the design. Even the use of SiP or package-on-package (PoP) devices can relieve the congestion on a board. Considering the next generation smartphone designs or wearable computer products such as a smart watch or smart glasses, you have to wonder how we will continue to satisfy all the functional, electrical, and mechanical requirements with so little space. This is where we are experiencing breakthrough approaches on the use and placement of embedded components in both rigid and flexible PCBs. Some component suppliers are producing specialized low-profile components more suited for embedding into a PCB for the latest applications.

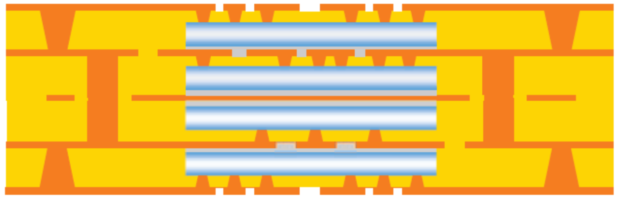

Figure 3: Embedded SiP with four stacked ICs (Image courtesy of FhG-IZM Berlin)

Some of the breakthroughs in placement of embedded components include inserting a stacked SiP within the substrate (Figure 3) and placing active components with cavities on core layers within the stack-up (Figure 4). The ability to place components on the core layers is made possible by stacking multiple prepreg layers with cavities cut out for the components. The prepreg layers are stacked until all components are covered with the proper spacing requirements. Pressure and heat are then applied to cure the prepreg layers surrounding the components to create a new core. The core with embedded components can then be used as building blocks for the rest of the PCB.

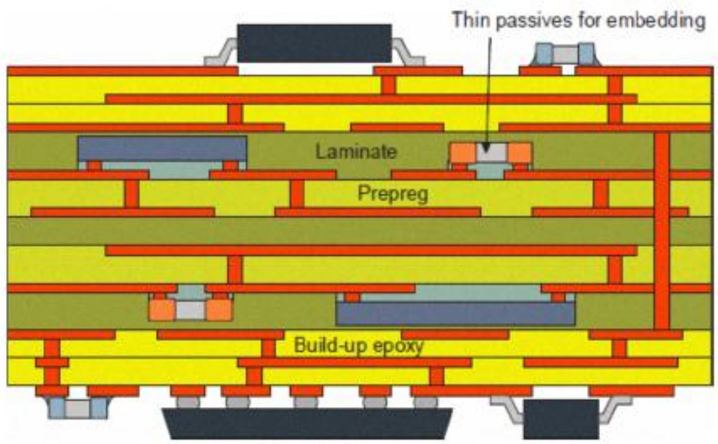

Figure 4: PCB stack-up with two cores dedicated for embedded components

There are two primary methods of connecting active components within the inner layers of a PCB. One method is to solder the component directly to a conductive layer. This approach is a more proven and manufacturable method, but the risk you take is that the solder could melt during subsequent steps within the manufacturing process. The second method is to place the active component between conductive layers, directly within the laminate and connect to the conduct layers using a laser-inserted microvia. The benefit of this approach is that it allows the connection on both sides of the IC, resulting in minimized footprint of the geometry of the IC and maximized pin-outs for the device. This allows improved fan-out and routability from the device and can help reduce overall trace lengths to improve signal performance. The issue you may incur is that the embedded component could be damaged during blind via laser drilling or during via plating. By understanding these limitations and risks, it should be clear that manufacturability is a key limiting factor in the approach considered in placing active components. Many companies are working closely with their suppliers and manufacturers to help mature this process and ongoing improvements are being pursued to address these concerns. With these breakthroughs, design teams can apply new solutions to the floorplanning issues found in PCB design today and continue to innovate to create the next wave of cutting-edge products.

Design rules for embedded component design

Before designing your next PCB with embedded components, it is important to ensure that your ECAD tools are suitable for implementing this technology. In the past, using manufacturers' knowledge and experience, boards were designed with embedded components using software intended to solve two-dimensional design issues. With the complexity introduced by the latest technology in printed circuit board design, ECAD systems now need to see this as a three-dimensional problem--and that requires a native 3D ECAD system to tackle it. We should also consider the design rules that need to be applied to satisfy electrical, fabrication, and assembly requirements across the PCB design flow, starting from conceptual design and product planning, all the way down to design and manufacturing. The design rules would encompass definitions satisfying the requirements with respects to a 3D-based design.

As shown in Figure 5 below, you will see an example of design rules for embedded component technology for flip chip devices and the connecting microvias. This type of requirement set includes standard information we would see in high-density interconnect (HDI) applications with build-up microvias, such as pin pitch requirements, pad-to-pad spacing and pad width. This typically coordinates with rules implied for layers assigned for build-up structures or core layers. However, in this specification you will notice spacing for components on inner layers, recommended thicknesses for the components, minimum dielectric thickness and spacing to consider between the adhesive sidewall to the edge of the component body. If we study these additional rules, we can see that many of the rules are take into account the required specifications for both the inner layers and in the Z-axis direction. We have been designing with these technologies far too often with manual and error-prone work-around, so it is important that we setup our design tools with the correct set of rules upfront to take advantage of 3D systems to design technologies within our products intelligently and accurately.

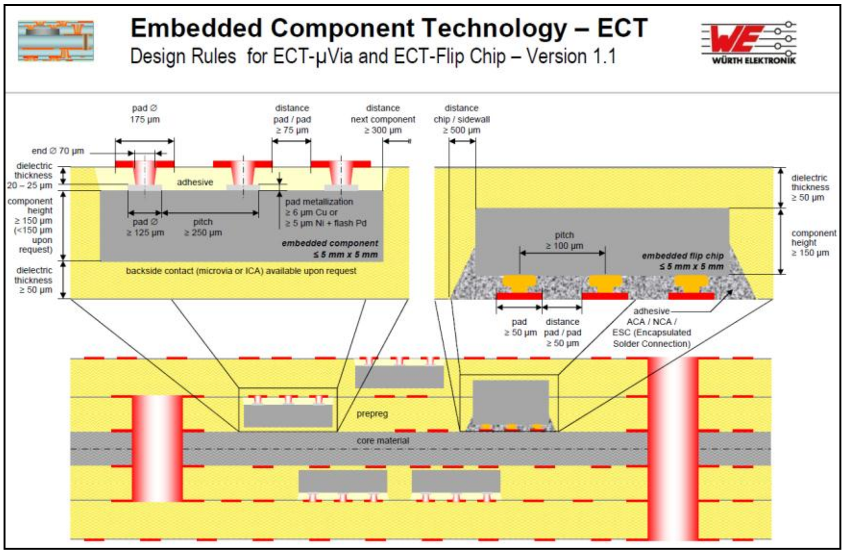

Figure 5: Example design rule specification to support embedded component design (Reference: Würth Elektronik)

During the setup of the design rules, designers should also take into consideration the actual layers that are allowed for embedded components and what is the mounting side, also the connection strategy used for each layer. Depending on the manufacturer or stack-up materials, engineers may have the freedom to place components on any layer or mount them on any side. If you are working with boards that require embedded components with cavities, then there might be restrictions on what layers can be used for embedded components or what side they are mounted on. It is important to collaborate closely with your manufacturing vendors to understand the process, and define these types of placement rules in your design rule library to avoid problems during the detail design phase.

The ECAD parts library must also be considered for defining the correct set of rules when designing with embedded components. In traditional EDA tools, users have to define a unique footprint for each layer on which the component will be used. Some systems will require you to even define a separate part number to use for each footprint. That can create a nightmare when linking the information to your corporate PLM/PDM system. If you are using modern ECAD system, then you will have the flexibility to just simply flag that component to be used both as a surface mount component and to be embedded on any layer. In most cases you will want to create a separate footprint for each because the manufacturing specification will be different, so you may need to associate two footprints to a part number. Ideally, you can simply flag that component to be embedded and it will be independent from the actual number of layers that will be on a design. If the component will reside within a cavity, you will want to also define the correct outline and rule so that it will be realized automatically during layout. Once you have all the required rules in the library and the footprints created to meet the manufacturing requirements, this will significantly simplify the process of designing your next printed circuit board with embedded components.

Implementing embedded components

One of the major challenges of using embedded components is the actual implementation in your design tools. Since most CAD tools are in 2D, accurately designing with embedded components and modeling the correct connection type can be difficult and requires many intensive manual steps to ensure the outputs generated for manufacturing can be accepted.

Often, a great deal of documentation must be prepared for manufacturing vendors so that errors do not occur and the boards are built as intended. Intelligent and effective implementation of embedded components starts during the product planning phase.

Most design teams have a system or hardware architect that starts the product concept or planning by gathering the various requirements from many sources, such as the CEO/CTO of the company, marketing, or industrial engineers. The system or hardware architect will then use a variety of different standard tools found on their desktop to start outlining the high-level details of the new product. These tools include spreadsheets, presentation slides, text documents, block diagrams, and drawing tools. Unfortunately, most of these tools were never intended for electronic design. When tackling the issue of embedded components, many of the real detail impact study cannot take place until you have an actual design file generated in the ECAD system.

To optimize the placement and partitioning of electronic systems, the best approach is to start the design planning process with a system-level product planning tool integrated with the detail design process and intended for electronic design. The system architect can accurately floorplan the designs and understand the impact of the actual real estate of the various boards to see how much space can be saved or new functions added when using embedded components to help the architect conduct trade-off studies. This approach enables designers to leverage design reuse and maintain a link with changes to determine which version of the design is best to send to production, and also helps start early planning of the next design iteration. Since the architect will have 2D and 3D views of the design along with functional block diagram and bill-of-materials (BOM), he can create outputs to start early thermal, electromagnetic, and RF analysis. He can also share information with 3D MCAD systems to collaborate on the mechanical aspects of the design such as the enclosure of the product to conduct interference checks.

During the logical circuit design phase, the hardware or electrical engineer can take the design data from the planning phase to begin work on the remaining part of the design. The hardware engineer will have more information about the details of the stack-up to be used on the project, and then communicate to the PCB designer and the manufacturer on the materials and thicknesses. This approach will help realize requirements related to impedance-controlled signals and other high-speed constraints. Depending on the process used by a given design team, it is important that the engineer can also define constraints for the embedded components during this phase to specify, for instance, the required layer and the footprint to be used during layout. The PCB designer can also determine this, but if the hardware engineer has this option, it can save time during the design process. Also the engineer should be able to attach notes with specific instructions or associate images to the schematic design to share with the PCB designer during layout.

Once you get to the physical circuit design phase, it is time to start the detail floorplanning or placement process for the embedded components. If you are using a traditional 2D system, there may be enough functionality to place standard discrete components directly formed or mounted on inner layers. Check that there are proper design rule checks in place to ensure errors do not occur. If you are working with discrete or active components that will be placed on inner layers potentially including cavities or needing connections with microvias, then a native 3D system is more suitable. Designers have access to the necessary design rule checks to support the real-time placement tasks and it will simply model the actual connections on inner layers and manage the cavity structures. The cavity shapes may also require unique shapes per layer. It is important to define these details accurately with input from the manufacturer. Make sure to also define the design rules for cavities. Example of design rules can be seen in Figure 7. The important thing to remember when working with cavities and embedding high pin-count devices is that it does take up routing space on the inner layer, so plan for this in advance.

During placement, you will also need to correctly define the connection type for the embedded components. As it is possible to connect the devices by either pads or using microvias on one or both sides, you want to define and model this during layout. The impact to consider here is that the location of the pads and microvias will need to be shared with the manufacturer for fabrication and assembly. If you are using a 3D system, then this can be done easily; if you are using a 2D system, then you will need to manually extract the centroid coordinates of each pin or via and submit that to your board vendor.

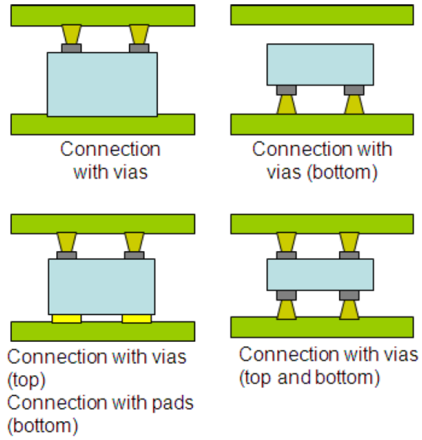

Figure 6: Example of via and pad connections for embedded components

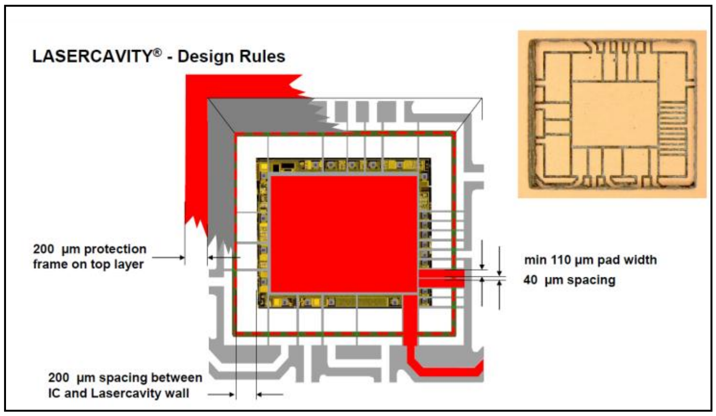

Figure 7: Example design rules (Reference: Würth Elektronik)

Upfront manufacturing checks and results collaboration

Along with design rules for embedded components, board vendors also conduct their checks to make sure that designs can be manufactured. This can add extra time and costly rework, and this process only gets more complex with embedded components. To save time in both the design and manufacturing process, designers should define the manufacturing rules within the rules database of your ECAD system and conduct checks against these rules as you design your printed circuit boards. Your board vendor may be able to supply you with standard fabrication and assembly rules, along with technology-specific requirements. In most cases, there are unique rules when working with embedded components, flexible printed circuit board, advanced packaging or hybrid design. If you work with several board vendors, then make sure you define the unique rules for each board, as this will allow you to concurrently check your designs to each board vendor's specification.

The manufacturing checks conducted during layout can be used as part of sign-off process before releasing the design to manufacturing. Find out from your board vendors what formats they support beyond the standard Gerber and NC drill files. Manufacturers may offer support for IPC-2581 or ODB++, so using an intelligent file format can also save time for you and for the manufacturers. You can also automatically generate spreadsheets with sign-off results and graphical snapshots of any issues on the board to ease communication with manufacturers if your tool supports these capabilities.

Summary

There are many benefits of using embedded components today. When working with embedded components, it is important to understand the current and new approaches for implementation and the necessary steps and challenges within the design process. As manufacturing processes continue to mature, you can easily realize your new products with more functions within the same or less space and still achieve of the right margins for profitability. Technology has advanced, so too have the methodologies that are currently being used or explored with embedded components, including the increased use of cavities and connection options for high pin-count devices.

To gain the greatest value and result of using embedded components, start the floorplanning of your electronic system during the planning phase and take a rules-driven approach across the logical and physical circuit design phase and into manufacturing. If you can utilize a 3D platform to plan and design your printed circuit boards with embedded components, it will help you model your design and generate the outputs to manufacturing with accuracy, and can help save time across the product development cycle.

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