Design for **Six Sigma in Electronics Cooling**

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Temperature problems are well known in the high-tech industry. Everyone knows of cases where overheated products stopping working and in the best case scenario, resume their function, but only after an extensive period of cooling down.

In past years, electronics cooling was very much about cooling consumer electronics, mainly TVs, computers and networking devices. Nowadays we see the focus shifting towards smartphones, tablets, smart watches and other wearable electronics but also towards all other transitional fields in our society. Energy savings? Cooling of LED lighting is a hot item. Energy transition? Cooling of power electronics, for example in automotive electronics, for solar cells and inverters, or in fast chargers for electric cars and electric buses. Also, the trend towards more and more data communication is enabled by cooling of electronics. One can think about cooling of datacenters, servers and telecom equipment for 5G, and the Internet-of-Things

Everywhere energy is stored or transformed, part of it is released as heat. Higher operating temperatures impact reliability, lifetime and safety, hence embedded control algorithms are increasingly used, dialing back performance or switching off once a measured temperature exceeds a threshold value. A good thermal design will keep your product cool and its performance up.
For many product developers, the temperature of their product is something that just happens, and they discover only at the stage that the total product has been realized in hardware and software and is tested for the first time. At that point it is far too late for a cost-effective solution. In addition, problems are difficult to solve, solutions often comprise multiple parts, and are difficult to realize, requiring multiple prototypes and may also involve further fixes when production starts (Figure 1). In the worst case scenario, problems are found in the field with product reliability being impaired due to thermal reasons.

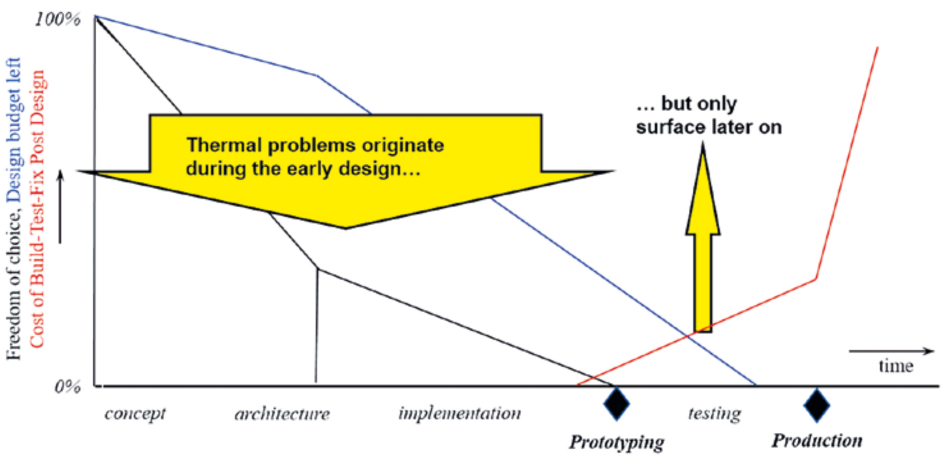

Figure 1. Typical development trajectory

Why are thermal problems so difficult to solve? Simply put, it is because heat flows are so elusive. A typical product has multiple, often interconnected heat flow paths each consisting of multiple steps, and each step represents a thermal resistance. A high source temperature is the result of a high heat dissipation, a high thermal resistance or a combination of both. The heat dissipation is a direct consequence of the functional performance, and usually this cannot be lowered without a performance penalty. This leaves low thermal resistances and short paths as the preferred option to control temperature.

In the ideal case, each heat path from each source to the environment is formed through a chain consisting of a low number of low thermal resistances. But this is not easy to realize. Part of the thermal resistances is either air-related or infra-red radiation related, which makes them invisible to the human eye. While air might be the primary cooling medium, it does not appear on the Bill-Of-Materials (BOM) for the product, and so far not tracked through the normal change request procedures. Changes that affect the air flow are unseen, and so also likely to recur in the next design iteration, and indeed in the next product development.

Design for Six Sigma (DfSS) is a design philosophy aimed at improving the success of innovation processes. The method is very well suited to the thermal field. Thermal design starts with identification of the product requirements (Define Phase), and flows down to how this translates to the thermal requirements, usage conditions, magnitude and location of heat sources, environment, and the location of temperature critical components (Identify Phase). A good thermal design then provides a robust solution to heat removal, in close collaboration with the mechanical design and electrical design flows (Design Phase) Identification of input parameters, exploration of the solution space and making a conscious design choice are key concepts.

In the very early design phases thermal concept design can be done analytically, using hand calculations and estimations. This has the advantage of additionally identifying the key input parameters that influence the thermal behavior of the total product, but requires experience and engineering judgement. For more complex cases computer simulations are increasingly used, both in the architecture phase and in the implementation phase. For air-cooled products, use of CFD is the highly preferred option, as in this approach both the heat transfer coefficient and the temperature of the cooling air are calculated as a function of the air flow, rather than assumed to be a generic value to a constant air temperature.

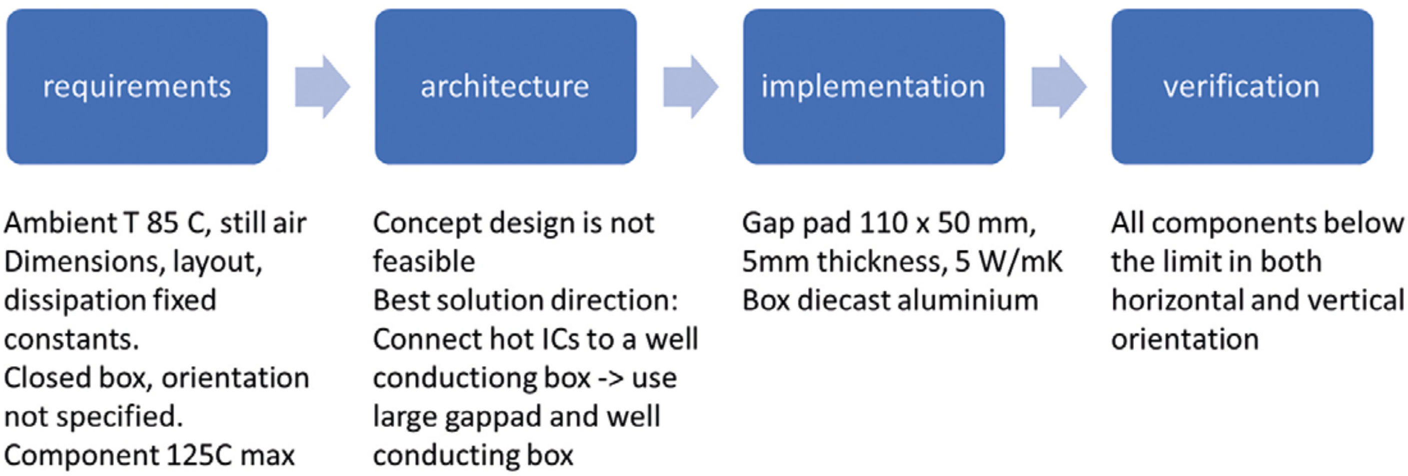

Figure 2. Example of the thermal design process of an automotive electronic box

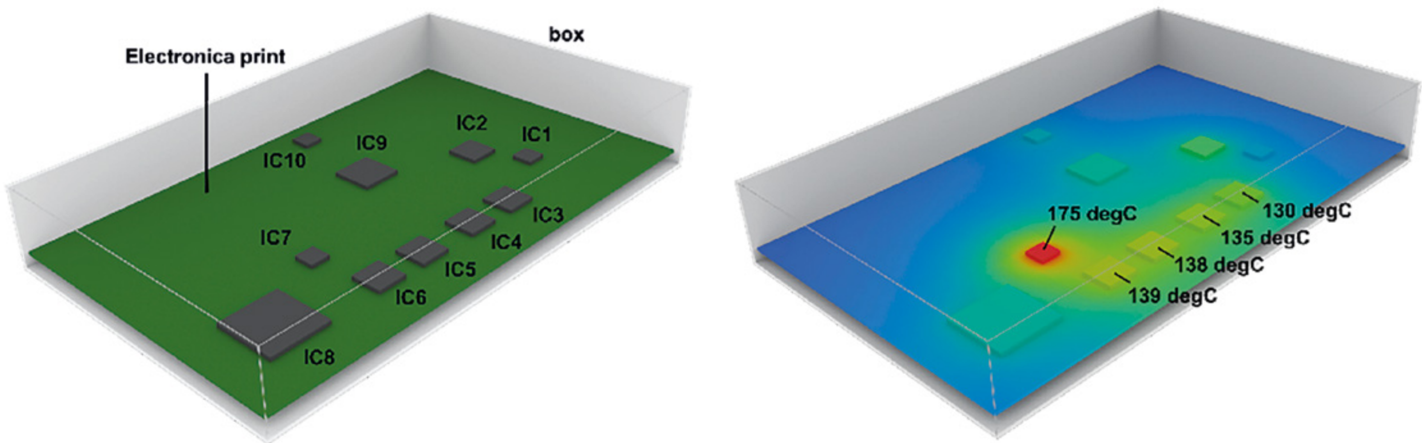

Figure 3. Left: Geometry, Right: Simulated temperature field with the first concept

	0	1	2	3	4	5	6	7	8	9	10	11
Gravity Direction	**Negative Z**	Negative X	Negative Z	Negative Z	Negative Z	Negative Z	Negative Z	Negative Z	Negative Z	Negative Z	Negative Z	Negative X
box material : Conductivity (W/(m K))	**0.2**	0.2	0.2	0.2	2	8	15	15	15	130	130	130
gappad for IC7 : Activated	**No**	No	No	Yes	Yes	Yes	Yes	Yes	No	Yes	No	No
large gappad for hot area : Activated	**No**	No	No	No	No	No	No	No	Yes	No	Yes	Yes
board : Conductivity (W/(m K))	**10**	10	10	10	10	10	10	20	10	10	10	10
Heat Sink for IC7 : Activated	**No**	No	Yes	No	No	No	No	No	No	No	No	No
IC7 : Temperature (degC)	**175.6**	174.6	148.2	163	154.7	144.2	138.2	129.4	137.1	122.1	121.3	121
IC3 : Temperature (degC)	**130.8**	128.2	130.6	130.8	130.2	129.8	129.6	122.5	112.6	128.8	103.4	103
IC4 : Temperature (degC)	**135.7**	133.1	135	135.6	134.7	134.2	133.8	126	115.2	132.4	104.3	103.9
IC5 : Temperature (degC)	**138.7**	136.4	136.7	138.2	136.7	135.4	134.4	126.9	117.3	131.5	104.9	104.6
IC6 : Temperature (degC)	**139.8**	138.7	135.9	138.8	136.4	133.9	132.3	125	117.8	127.5	105	104.7

Figure 4. Scenario table with all virtual experiments

In fan-less products the magnitude and the topology of the air flow field and the heating of the cooling air flow are non-trivial and can have very significant impact on the temperature behavior of a product.

In many cases the true power of computer simulation is not in number crunching the detailed mechanical and electrical CAD design as a final check just before production. Rather the true added value is in the use of a series of numerical experiments in the early architecture phase. Choosing the right architecture from the start can free up design space to pursue the most desirable product from the earliest stage. Using computer simulations one can virtually explore the solution space and choose the most appropriate solution direction without incurring the large cost in time and financial resources that would be needed to pursue a similar goal through testing hardware. In the author's experience it would be very common to perform between 10 and 40 computer simulations to finally get to the most optimal architecture for the design. After choosing the most appropriate architecture – tailored to the specific product requirements and usage conditions – detailed design can then follow, often helped by additional computer simulations on the CAD data.

Figure 2 shows the thermal design process of an automotive electronics box as an example. The concept design starts from a closed plastic box containing a Printed Circuit Board (PCB). The thermal requirements are that the box is placed inside a non-ventilated environment of 85ºC with a maximum allowed component temperature of 125ºC. In the architecture phase, CFD simulations start from this concept design, and an aggressive estimate for the powers to ensure that design is robust enough to deal with the anticipated worst case power consumption.

Figure 3 shows the geometry (left). Note that this concept simulation is performed with only a very rough mechanical/electrical model, and without using mechanical or electronic CAD files or data. Rather, these architecture-stage simulations precede the detailed mechanical and layout CAD design which take place after the architecture is chosen. The results of the simulations are shown in the calculated temperature field in Figure 3 (right) show that the proposed concept design is not thermally feasible. Multiple ICs are above the 125°C temperature limit, and the hottest component being 50ºC higher.

In this product, the key parameters for the thermal resistances consist of the dimensions and material properties of the box, the layout and heat dissipation of the PCB, and the mounting of the PCB inside the box. The size of the box, the fact that the box needs to be closed, the layout of the PCB and the heat dissipation are fixed. Parameters that can be changed can all be investigated in the architecture phase of the thermal design. These are:

- The material of the box, especially the thermal conductivity (normal plastic k=0.2 W/mK, thermal plastic – low budget k=2 W/mK, electrically insulating k=8 W/mK or electrically non-insulating k=15 W/mK, or die-cast aluminum k=130 W/mK) are all discrete options
- Thermal management products: using a heatsink and/or a gap pad – a thermally conductive solid material bridging the air gap between the PCB and the box can be investigated, with
    - **a)** Location limited to the hottest component, IC7
    - **b)** Distributed over the entire hot zone
- Thermal conductivity in the printed circuit board itself (layout and construction related, e.g. number of layers, buried power and ground planes).

Another aspect of DfSS is de-risking the potential influences of causes of variation. As the orientation of the box is not prescribed in the product requirements, the box must be simulated both in horizontal and in vertical orientation, since its mounting is under the control of the end user company.

"I find FloTHERM's Command Centre indispensable for running the many scenarios that I need to make sure that I do not just have a working design, but the best working design possible for my circumstances."

Figure 4 shows FloTHERM's scenario table with all the calculated cases and corresponding results. In the scenario table, each column represents a virtual experiment. In total, the table shows 12 different virtual experiments. In the top blue part of the table the chosen key design parameters are shown. The bottom, orange, part shows the corresponding calculated temperatures for the key ICs on the PCB.

Scenario 0 is the original concept design. In this design IC7 is 50°C above spec and IC3 to IC6 are also above spec. Scenario 1 shows the results for the vertical orientation. It shows that the horizontal orientation can be considered worst case, and we continue subsequent scenarios with horizontal orientation. In scenario 2, a heatsink is used on IC7, and this is not a viable solution. Scenario 3 – 6 virtually explore the use of a gap pad in conjunction with a closed box of increasing thermal conductivity. The results show that a small gap pad to a plastic box does not work, also not if the box is made of thermal plastic and also not if the PCB itself is better conducting (scenario 7). Scenario 8 shows that also a large gap pad to a thermal plastic box does not solve the thermal problem – clearly a metal box is needed.

Scenario 9 shows that a local gap pad on IC7 to an aluminum die cast box solves the problem for IC7, but IC3 is still above specification. Finally, scenario 10 shows that to apply a gap pad over the hot zone in conjunction with a die-cast aluminum box is a feasible solution, and scenario 11 shows that this solution is also robust with respect to different orientations: in vertical orientation, this solution also fills all requirements.

Figure 5 shows the calculated temperature and flow fields for scenario 10, the final solution, in horizontal orientation. The layout of the board is unchanged, and applying a gap pad of sufficient size bridging the air gap between PCB and box in conjunction with an aluminum die-cast box, a thermal design is realized that will keep all temperatures within the specified boundaries irrespective of the orientation of the final product.

The automotive box example illustrates the importance of a good thermal design and a methodical exploration of the solution space.

Using a heatsink on IC7 was not a solution because the heatsink lowered a resistance in a path that contains a very large second and third thermal resistance: the heat transfer of the air inside the box to the wall of the box, and the heat transfer of the box to the environment. In the chosen solution, multiple resistances in the same heat path are lowered through a strategic choice of thermal input parameters.

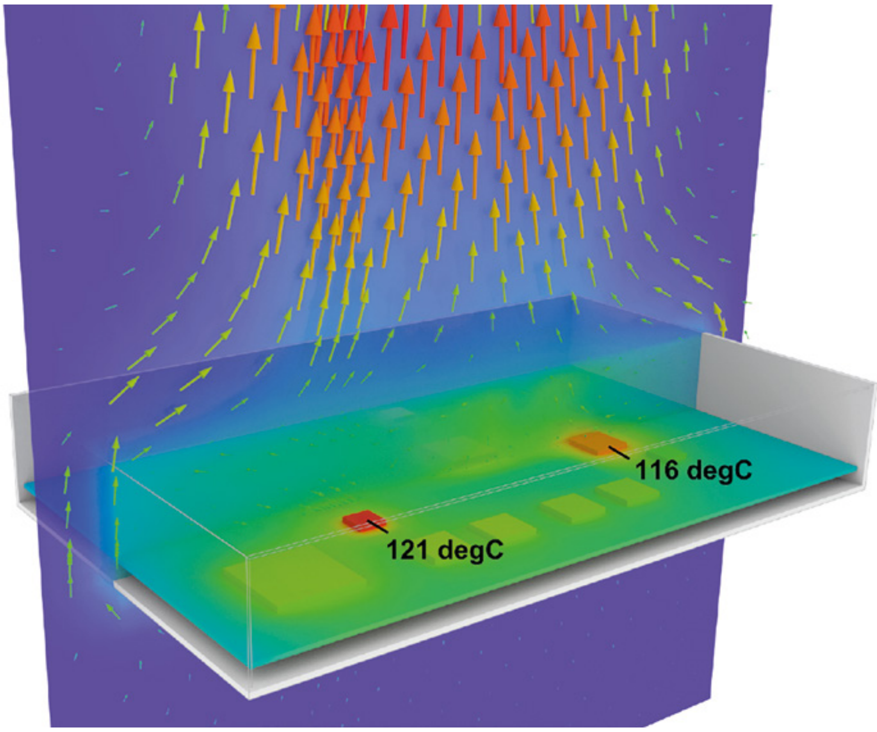

Figure 5. Surface temperature, air temperature and flow field for the final chosen architecture

In the case of the simple automotive box example, purchasing can now proceed to source a supplier for a die-cast box and the gap pad, while in parallel the mechanical developer can proceed to implement the detailed CAD design for a die-cast box. Thermal design in the pre-CAD phases was sufficient to make informed thermal design choices and lower the risk of wasted time and project resources by detailing an unfeasible design to a significant degree. Rather, having de-risked the project from the outset, as more becomes known about the component placement, board layout, component powers etc. the detailed design can explore ways in which the cost can be reduced. In this example, a smaller gap pad may be possible, or a cheaper material with a lower thermal conductivity might perform adequately. Exploration of the solution space is one of the pillars of Thermal Design for Six Sigma as it allows thermal solutions to be found that potentially free up design space to increase product desirability as well. As an example, avoiding the use of the heatsink potentially enables the box to be flatter and reduce its volume claim. It is not limited to the architectural design phase and can be used to very good effect from both engineering and financial standpoints throughout the development.