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ECO-DESIGN OF HEAT SINKS BASED ON CAD/CAE TECHNIQUES

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Abstract: *In the context of industry 4.0, the overall performance of manufacturing systems largely depends on the performance of embedded electronics. Such devices are responsible for conditioning information between machines and equipment such that desired input / output actions can be achieved. To be competitive, manufacturers are harnessing their products by performing several design decision loops based on the product's overall performance during their lifecycle. Even so, due to new developing technologies such products become soon obsolete. Thus, high demands for new products cause large streams of electronic waste. To overcome this issue new design principles have emerged. Eco design together with the development of sustainable technologies help manufacturers to conceive their products in order to meet both environmental and customer requirements. Such interdisciplinary approaches maintain a balance between environmental costs and material necessities having a major impact on all lifecycle stages of a product. As a consequence, landfill is lowered and more value is added to the final product. Valuable knowledge is also achieved and transferred to new products by means of guidelines, check list and software extensions. Power electronics embedded in manufacturing systems requires proper thermal design to withstand high temperatures and perform according to the design specifications. Heat sinks are one of the most common devices used for cooling electronics. This paper deals with the lifecycle stages of heat sinks, discussing about the traditional CAD/CAE design tools extended to meet eco-design criteria. A case study illustrates the given concepts for the design of a variable speed drive passive cooler.*

Key words: *heat sinks, design tools, eco-design, variable speed drives.*

1. INTRODUCTION

Nowadays, industrial applications are characterized by a high degree of automation. Such complex systems generate desired physical outputs (i.e. indexing the position of a part) by processing signals from machines or sensors. Control loops, decisions and actions are a result of the continuous information exchange between mechanical and informational subsystems. Basically, a numerically controlled axis comprises mechanical components (i.e. servo drive, gearbox) and electrical components (i.e. PLC, variable speed drive) responsible for generating specific signals that change according to the information acquired from transducers and sensors [1].

The relationship between control signal and physical response is satisfied by means of embedded electronics. Such devices are widely available in industrial applications.

With the introduction to Industry 4.0, more physical devices are now connected together. The performances of the resulting cyber-physical systems [2] are governed in equal balance by hardware and software potential. To gain advantage of these technologies companies demand integration of more intelligent machines and embedded electronics in their applications. Due to the increase of ecological awareness, such manufacturing systems will have the priority of manufacturing products that are environmentally sound, thanks to the complex energy monitoring and data processing decision capabilities of this next generation smart factories [3]. To fulfill the ecological awareness, next generation manufacturing systems are also required to integrate sustainable electronics [4].

Being one of the main waste streams, electronics represent a growing concern for the environment due to the hazardous, complex and expensive to treat nature of such parts and assemblies [5]. With less than 10% of the electronic products that end in the waste stream being recycled [6], creating design and technological innovations has moved forward towards a future electronic industry that is environmentally sound.

Dimensions of industrial electronics have decreased and many devices were removed (i.e. math co-processors, Multi I/O boards and others) and replaced with solutions that embed several functions on the same electronics assembly. While such replacements minimized sizes, cooling remained a central design issue. This makes thermal design indispensable and a growing need to develop sustainable thermal design has emerged in the given industrialization context.

Approaches regarding sustainability of heat sinks have been studied in [7]. The work seeks a "least energy" design approach for optimizing natural and forced-convection cooled heat sinks. The aim is to maximize heat transfer with the least material requirements without

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the necessity of excessive pumping power. Another approach is presented in [8]. In this case the sustainability index is used to quantify the subtle balance between the achieved thermal performance and the investment of material of various cooling designs, allowing an environmentally optimal configuration to be chosen.

This paper presents a sustainable approach regarding the design of heat sinks used for cooling electronic components in industrial engineering. The first part of the work describes the basics of the design, simulation and manufacturing of heat sinks. In the second part, Life Cycle Assessment (LCA) is discussed as an important environmental cost evaluation tool and how LCA is used to create ECO-Design specific knowledge. The third part of the work describes the traditional thermal design approach for heat sinks. Adding an ECO-Design loop to this approach requires not just the least material thermal design, but a deep understanding of multiphysics problems (i.e. thermal, mechanical, dynamical aspects) combined with manufacturing possibilities and overall environmental costs. To illustrate the given concepts, the final part of the work presents a CAD/CAE approach for designing a heat sink for a variable speed drive that satisfies all requirements while being sustainable.

2. DESIGN, SIMULATION AND MANUFACTURING OF HEAT SINKS

Thermal management plays a decisive role in the proper performance and optimal life span of industrial electronics. The proper selection of components that comprise a cooling solution for a specific application is the aim of thermal design, a new branch of industrial engineering design.

Most of the industrial electronics use a thermal management solution that comprises a heat sink which efficiently absorbs or dissipates the heat to the surrounding environment and a cooling fan, as a forced convection flow device used for expanding the total heat transfer rate of the heat sink. While fans are an optional requirement, heat sinks represent the most important component of a thermal management solution employed in industrial electronics. Due to the complexity of heat generation of electronic components used in industrial engineering, the necessity to create custom tailored heat sinks for a specific product range arises several design constraints. These can be geometrical constraints (i.e. allowable width and length), heat constraints (i.e. total heat transfer rate, allowable junction temperature) or economic constraints (i.e. choice of materials that satisfy both thermal and price requirements). From the initial design constraints until the manufacturing of the final solution, three stages can be depicted on Figure 1:

1. *Design stage*

This step is characterized by a continuous interaction between the design teams that use an extended range of software. Several design scenarios are proposed for the same initial input.

2. *Simulation stage*

The simulation stage is characterized by an interaction between designers and simulation engineers. The aim is to validate proposed design scenarios in order to predict the behavior of the product during its life cycle. For this purpose, Computer Aided Engineering (CAE) software is used. Because some design scenarios may be hard to manufacture or may require complex manufacturing processes, design scenarios completed by CAE simulations are further subjected to Computer Aided Manufacturing (CAM) procedures.

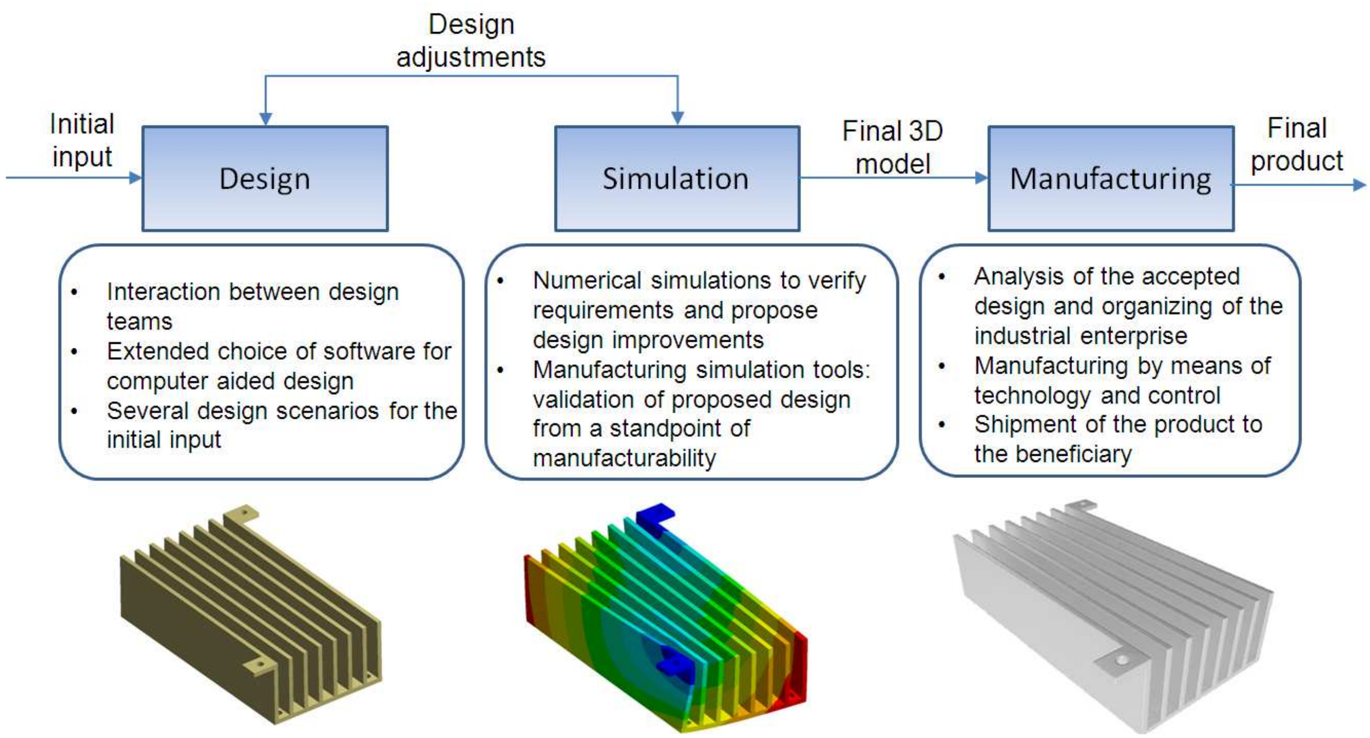


Fig. 1. Stages of Heat Sinks design, simulation and manufacturing.

3. *Manufacturing stage*

The complete 3D model that was analyzed by both CAE and CAM is used by manufacturing engineers who investigate the given design for organizing the work in industrial enterprises. Specific technologies are accessed to transform raw material in final products. Quality control stages ensure the conformity of the physical product in accordance to the design requirements. The final product (the heat sink) is shipped to the beneficiary to be mounted as part of a thermal management solution of an industrial electronic assembly [9].

3. LIFE CYLE ASSESMENT

Life cycle assessment (LCA) can be defined as a methodological framework that provides complementary insight related to the environmental impact of a product. Such tools are used by experts to support pollution prevention by means of process improvement [10].

Figure 2 depicts the main environmental impact sources associated to a heat sink's life cycle:

1. *Manufacturing*

   To manufacture a heat sink, raw material under different forms (ingots, sheets, billets etc.) is used as work piece for cold forming (i.e. extrusion, machining) or for hot forming (i.e. casting). Due to the energy required from both work piece and final product manufacturing, CO_2 is released into the environment. In the case of heat sinks, the manufacturing stage represents the major source of emissions during the product's life cycle.

2. *Use*

   Only a small amount of emissions are generated during the use of a heat sink. This may include emissions resulting from the use of cleaning chemicals or from the replacement of the thermal interface material during scheduled maintenances.

3. *End of life*

   At the end of the heat sink's life, emissions are expected due to the product reuse (disassembly processes, light machining of surfaces scratched / damaged and assembly of the heat sink on new products). If the product can't be reused, furnace melting is used to recover materials for recycling.

The design of heat sinks is largely responsible with the level of emissions generated during the product's lifecycle. The role of LCA is to create a balance between the impact sources such that the environmental costs are minimized, while the product performs at its requirements.

LCA can be considered a main source of knowledge building for developing software and common framework solutions for specific applications. This allows for sustainable product development. It can assist to the following tasks [11]:

- environmental improvement opportunities at different points of life cycle stages;
- effective strategies for designing or redesigning a process ;
- quantification of environmental outcome by means of benchmarking and measurement.

4. ECO-DESIGN

Eco Design can be defined as a new design principle involved in the design process of a product at early design stages [12]. The aim of Eco Design (Fig. 3) is to lower the environmental problems associated with the reference product, while meeting the requirements of the customer in a more sustainable manner.

Eco Design approach plays an important role in the design and manufacturing cycle of sustainable products. Nevertheless, such design approaches haven't completely developed into a standard, being rather a designer-manufacturer dependent solution [13].

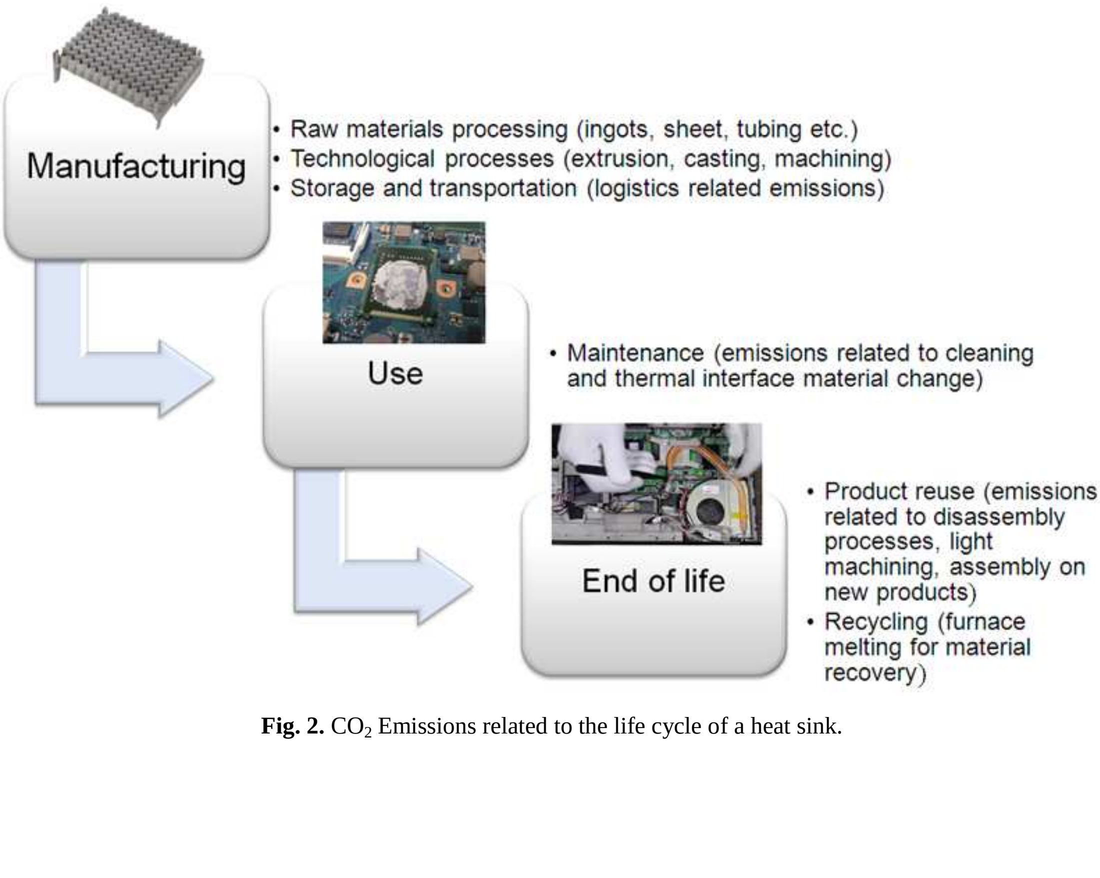


Fig. 2. CO_2 Emissions related to the life cycle of a heat sink.

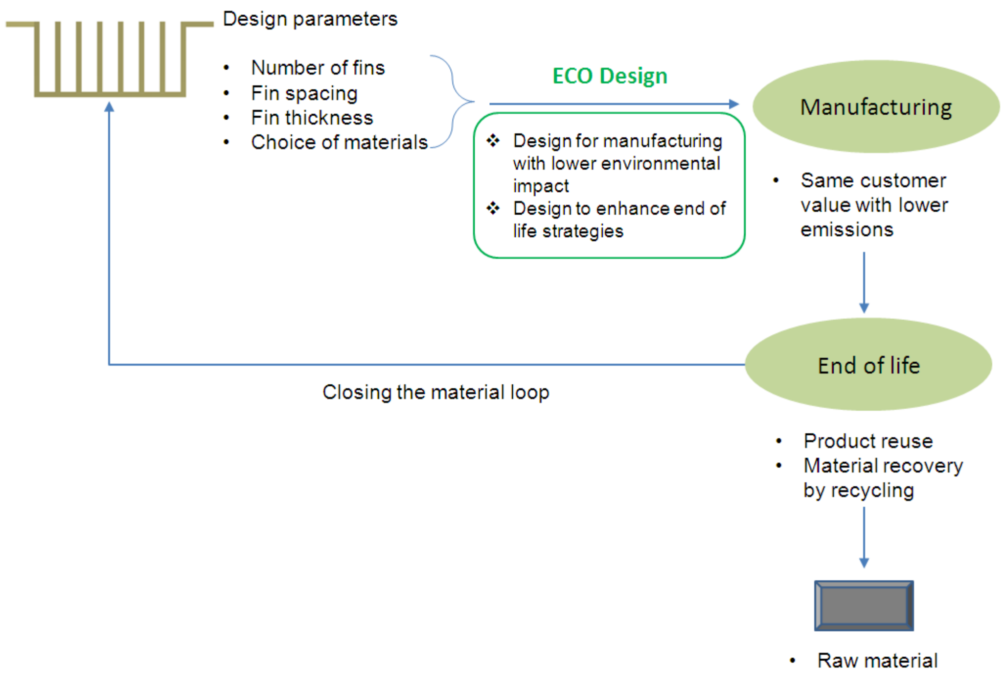


Fig. 3. ECO-Design principles.

Eco design is the result of knowledge achieved by LCA in the form of guidelines, check lists and know-hows.

Because in the design stage the geometrical shape of the product has to be defined, material and structural aspects must also be evaluated, to determine an optimal balance between the environmental costs and the manufacturability can be considered the most significant step for the sustainability assessment.

5. EXTENSION OF TRADITIONAL DESIGN TOOLS TO SATISFY ECO-DESIGN PRINCIPLES

Choosing a heat sink as part of an optimal thermal design requires the completion of three stages, consisting of: analytical solutions, 3D CAD modeling and CAE simulations. Including ECO-Design concepts to traditional design tools involves the addition of a decision loop to asses a design scenario by its environmental costs. Figure 4 depicts both traditional design and an ECO-Design extension for conceiving sustainable heat sinks:

5.1. Analytical solutions

Several guidelines regarding the heat sinks design are available.

One of the most significant work [14] describes the steps required to perform the sizing of the heat sinks for various applications, under different air flow conditions and design constraints.

Designing optimal heat sinks with given design constraints (i.e. heat dissipation, fin mass, profile length and others) requires at first the definition of the fluid properties. In the case of natural convection cooling, the following fluid properties are required:

- Thermal conductivity k (W/m°K);
- Kinematic viscosity υ (m^2/s);
- Thermal diffusivity α (m^2/s);
- Expansion coefficient of air β

For forced convection cooling the thermal diffusivity is not required, but the Prandtl number Pr is defined, together with the expansion coefficient of the air β, determined as a constant for the optimum heat transfer rate dissipated from the fin, for a constant profile area.

The Nusselt number N_u is used to determine the heat transfer coefficient h and the optimal fin spacing z_{opt} for natural convection cooling:

$$N_u = \frac{h \cdot L}{k} \tag{1}$$

The Reynolds number R_e is used in the case of forced convection to predict the flow pattern, laminar or turbulent, according to the air velocity U, the kinematic viscosity υ and the fin length L:

$$R_e = \frac{U \cdot L}{\upsilon} \tag{2}$$

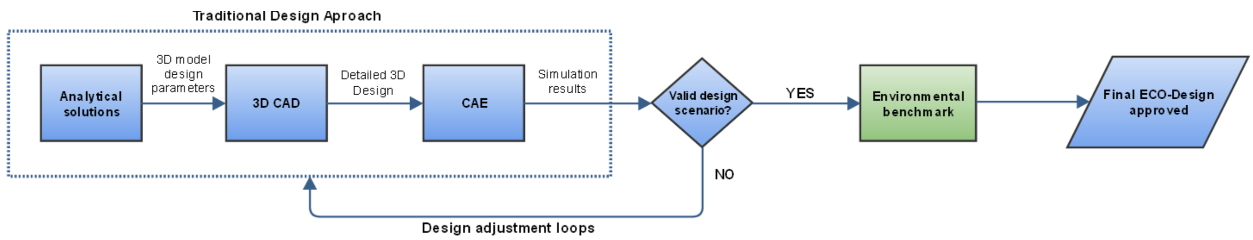


Fig. 4. The extension of traditional to Eco Design.

The next step consists of determining the optimum fin spacing z_{opt} for natural convection cooled heat sinks:

$$\frac{z_{opt}}{L} = 2.714 \cdot Ra_L^{\frac{-1}{4}}, \quad (3)$$

where Ra_L is the Rayleigh number for a flow over a plate of length L.

For forced convection cooling the optimum fin spacing is:

$$\frac{z_{opt}}{L} = 23.24 \cdot \mathrm{Re}_L^{\frac{-1}{2}} \cdot \mathrm{Pr}^{\frac{-1}{4}}. \quad (4)$$

The total number of fins n_f can be described as:

$$n_f = \frac{W}{z_{opt+t}} \quad (5)$$

where W represents the width and t - the fin thickness.

To determine the optimum fin thickness t and the overall thermal resistance R_t, the total heat transfer rate Q requires evaluation. In the case of natural convection, the total heat transfer rate Q is defined as:

$$Q = A_t \cdot \eta_0 \cdot h_z \cdot \theta_b, \quad (6)$$

where A_t represents the total area, η_0 – the overall fin efficiency and h_z – the heat transfer coefficient and θ_b – the average of the maximum allowable temperature and the ambient temperature.

Elenbaas [14] provided the experimental data where the Elenbaas number based on the Rayleigh number was used. In respect to these considerations for a vertical plate the average Nusselt number from the Elenbaas equation is:

$$\overline{Nu} = \frac{h \cdot z_{opt}}{k} = \left[\frac{576}{El^2} + \frac{2.873}{\sqrt{El}}\right]^{\frac{-1}{2}}. \quad (7)$$

where El represents the Elenbaas number.

The optimum fin thickness is obtained by choosing a thickness range and creating a plot of the optimal fin thickness vs the heat transfer rate. For natural convection the total profile length b is defined as a design value, while in the case of forced convection cooling, the profile length b can be written as:

$$b = \beta \cdot \left(\frac{k \cdot t}{2h}\right)^{1/2}. \quad (8)$$

The peak values for the total heat transfer rate represent the optimal fin thickness.

Figure 5 depicts an optimal fin thickness to satisfy a forced convection cooling design for a given heat transfer rate of 20W.

5.2. 3D CAD model

The 3D representation of solid bodies represents an essential step for different design activities that is done preliminary to manufacturing a physical product. By using a 3D CAD software, engineers concept the virtual

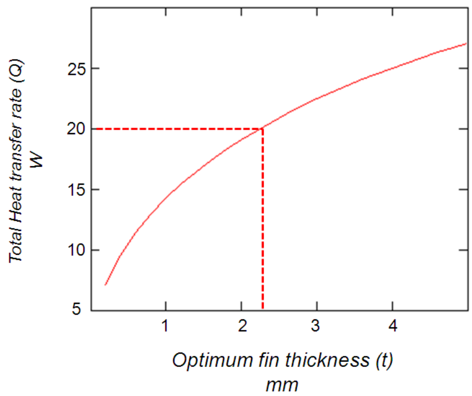


Fig. 5. Optimum fin thickness vs heat transfer rate for a 20W forced-convection cooled heat sink design.

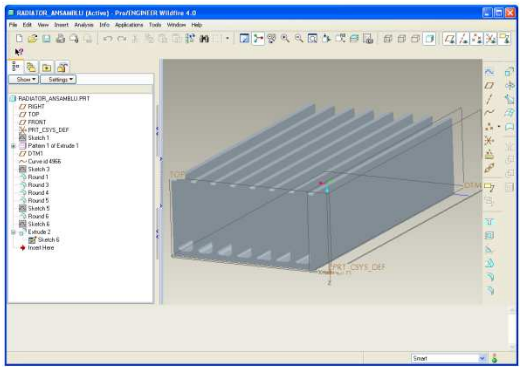


Fig. 6. 3D CAD model using PTC ProEngineer.

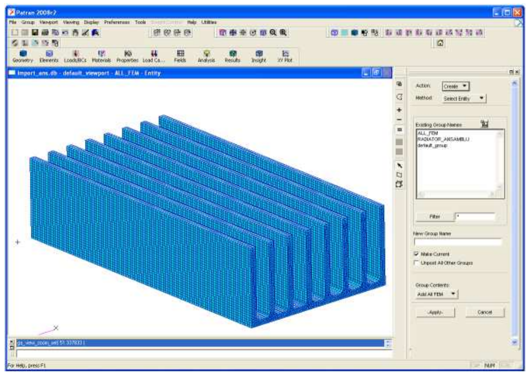


Fig. 7. CAE Model Pre-processing using MSC Patran.

prototype of a product by designing its real shape (Fig. 6). The importance of the 3D CAD model is also that of creating a link between design, simulation and manufacturing due to its universal file transaction possibilities between design environments [15].

Having all the preliminary design parameters from the analytical solutions, design engineers can create the virtual prototype of a heat sink. In most of the cases the preliminary design requires additional adjustments (i.e. holes for mounting, additional surfaces for locating and fixing the heat sink to the supporting wall).

5.3. CAE

Computer aided engineering (CAE) simulations have been since long one of the most used numerical simulation tools to analyse, confirm or optimize a design study. The initial input for a CAE analysis is the geometry file imported from a 3D CAD environment.

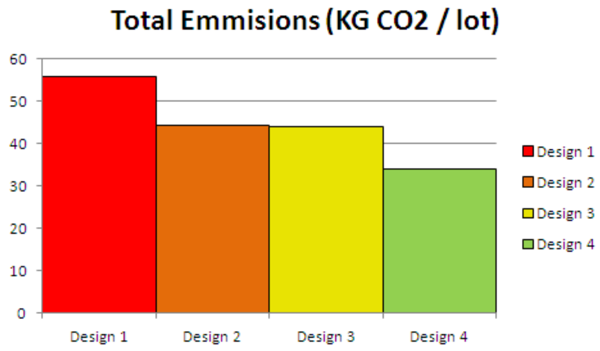


Fig. 8. Environmental benchmark of multiple design scenarios.

The resulting CAD - CAE transaction is used to create a simplified simulation model according to the objective of the study [16].

In the case of heat sinks, thermal analysis is first done for a cross verification purpose between analytical and simulation results. The operating environment and secondary functions of the heat sink defines its multi physics analysis strategy. For example, a heat sink that is attached to the active electronics of the machine tools, that has both a structural and thermal role, is subject to thermo-mechanical analysis or pre-stressed modal analysis taking in to the account the material properties of the heat sink found at the operating steady-state temperature.

5.4. Environmental benchmark

With a design that is valid from both perspectives of CAD and CAE, the next step towards an Eco-Design is to benchmark the resulting geometry in terms of environmental costs. This extension allows the analysis of a design study from the point of view of raw material requirements, manufacturing necessities, storage and transportation strategies and the end of life environmental sound disposal methods.

Evaluation of a design can be done in the following steps:

- choosing the required work piece material;
- cnalysis of the surfaces for determining the proper manufacturing technologies;
- cssessment of emissions required for both work piece and manufacturing methods of the final product
- cnalysis of end-of-life strategies and how can they be applied for optimal material recovery or product re-use;
- creating an index of overall emissions and selecting a proper design scenario to satisfy the performance, manufacturability and the lowest emission levels.

Currently there is no software or application procedures dedicated for ECO-Thermal design. Even tough, each designer can tailor its software suite to meet the Eco-Design requirements. For example, addingcalculation tools for manufacturing parameters, together with spreadsheet calculation for emission evaluation can be considered a sustainable extension.

6. CASE STUDY

The following design constraints (Table 1) were chosen to size a thermal design solution for a variable speed driver.

Table 1

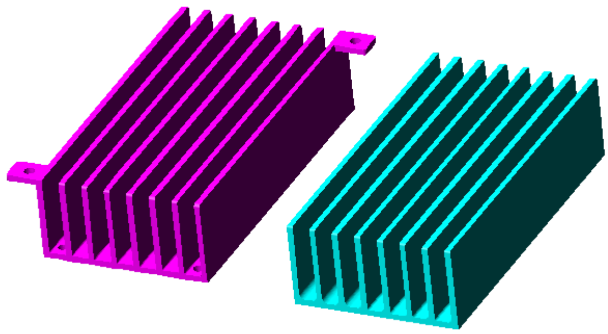
Design parameters for thermal design sizing

Design parameter	Specifications
Material	Aluminum A360.0-F
Type of thermal design solution	Natural convection cooling type
Width (W)	Up to 67 mm
Length (L)	125 mm
Heat dissipation	30 W
Lowest junction temperature of active components	100°C

Table 2

Design parameters for thermal design sizing

Results	Specifications
Optimum fin spacing (z_{opt})	6.62 mm
Total number of fins (n_f)	8
Chosen profile length (b)	300 mm
Optimum fin thickness (t)	2.3 mm
Overall thermal resistance (R_t)	2.494 W/°C
Total heat transfer rate (Q)	30.071 W



a b

Fig. 9. Heat sink: *a* – baseline design; *b* –final design.

Based on the analytical approach presented in chapter 5, the following results are derived for a natural convection vertical plate heat sink design.

Having all the necessary geometrical data, the virtual model of the baseline heat sink can be designed using 3D CAD software AutoCAD (Fig. 9).

The initial geometry is the input for a steady-state thermal analysis in ANSYS Workbench environment. The results of the simulation are further used for cross-verification purposes between analytical and numerical results. Figure 10 and Table 3 depict the results of the analysis.

With a valid FEM model, CAD adjustments can be made to the baseline design to accommodate the heat sink mounting. To check if the new design can withstand the structural load imposed by the variable speed drive's mass of 10 N, a static analysis will be performed using the same mesh settings. For this analysis, the heat sink will be fixed at the mounting flanges and the mass of the speed drive will be equally distributed to the mounting holes. A uniform body temperature of 100°C will be considered to take in to account thermo-mechanical effects.

Results of the analysis indicate an equivalent stresses level that does not affect the structural integrity of the heat sink (Fig. 11).

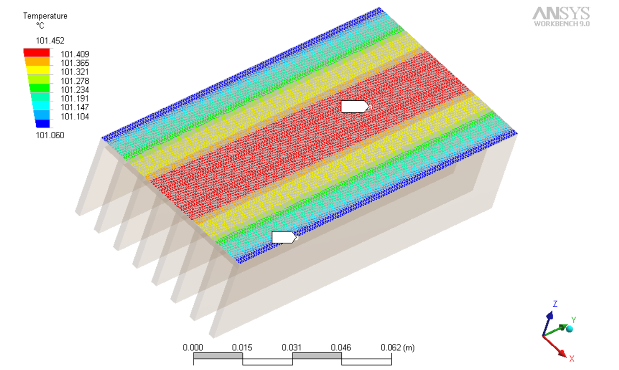


Fig. 10. Steady-state temperature at the bottom of the heat-sink.

Table 3

Steady-state thermal analysis

<table>
<tr><td rowspan="3">Mesh</td><td colspan="2">Element topology</td><td>3D 4 node Tetrahedral</td></tr>
<tr><td colspan="2">Number of elements</td><td>470371</td></tr>
<tr><td colspan="2">Number of nodes</td><td>748746</td></tr>
<tr><td rowspan="3">Boundary conditions</td><td colspan="2">Environmental temperature</td><td>20°C</td></tr>
<tr><td colspan="2">Heat flow at the base of the heat sink</td><td>30 W</td></tr>
<tr><td colspan="2">Convection coefficient for vertical planes</td><td>6.62 W/m²°C</td></tr>
<tr><td>Results</td><td colspan="2">Steady-state temperature at heat sink base</td><td>101.45°C</td></tr>
<tr><td colspan="4">Results verification</td></tr>
<tr><td rowspan="2">Thermal resistance</td><td>Analytical</td><td>FEM</td><td>Margin of error</td></tr>
<tr><td>2.494 W/°C</td><td>2.542 W/°C</td><td>1.84 %</td></tr>
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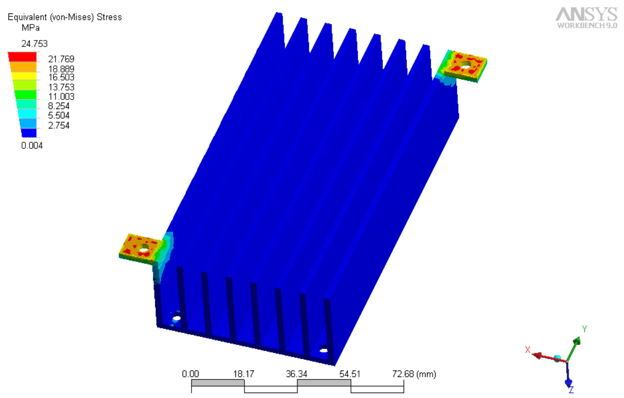

Fig. 11. Equivalent Von-Misses stress of the heat sink.

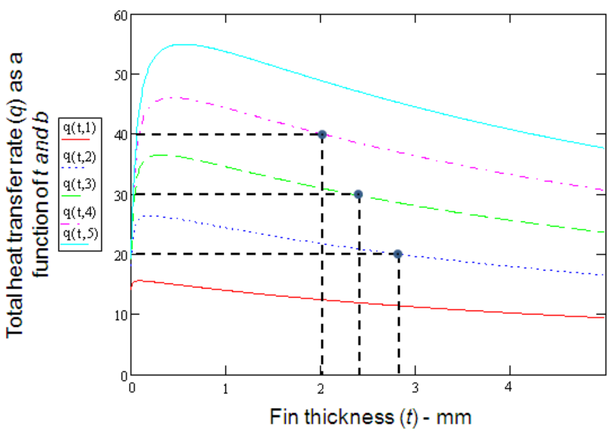

Fig. 12. Multiple design scenarios for varying the total profile length.

The final step is to perform an environmental benchmark of the purposed design and to check it against other design scenarios. In this case, varying the profile lengths leads to several design solutions that are available o Figure 12.

The purposed environmental benchmark requires a three stage simplified design investigation:

- analysis of the 3D model to identify manufacturing methods;
- identification of the initial material requirements for all manufacturing stages;
- identification of technological parameters required to evaluate CO_2 emissions for all technological processes.

For this case study the heat sink's final design can be manufactured by means of high pressure die casting, milling and drilling technologies.

Considering that the average amount of material that remains usable in high pressure casting processes (yield) is around 70% [17], the initial material requirement T_r can be calculated as:

$$T_r = \frac{70 \cdot m}{100}, \tag{9}$$

where m represents the mass of the heat sink in kg.

Under the form of billets, bars or ingots, aluminum work piece are manufactured with a carbon footprint of 9.11 t CO_2/t [18]. Knowing that high pressure casting requires a tacit energy of $1.192 \cdot 10^{-10}$ kWh / t, and that the standard emission factor for electrical energy is around 0.7 t CO_2/kWh [19], emissions can be calculated for work piece and high pressure casting requirements.

The next step is to perform the emission estimation for milling and drilling processes. Milling operations are completed for finishing the base of the heat sink while drilling operations are done for mounting purposes. For this example, Sandvik CoroGuide is used for determining both tool and process parameters. Results are presented in Table 4.

Finally, the same approach is applied for other design scenarios until one design that satisfies both customer needs and minimum total emission is found.

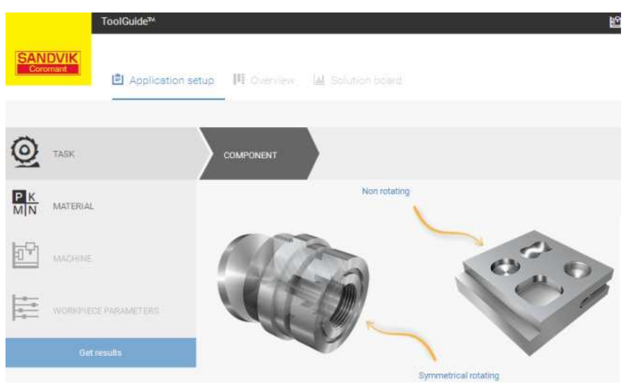

Fig. 13. Sandvik CoroGuide tool and process parameter calculator.

Table 4

Total emission estimation

Operation		**Power requirements**	**Total emissions**
Workpiece material		-	2.2 kg CO_2
High pressure die casting		1.52 kWh	1.52 kg CO_2
Machining	Finishing	0.075 kWh	0.03 kg CO_2
	Drilling	0.00271 kWh	0.001 kg CO_2
Total emissions			3.75 kg CO_2 per heat sink

7. CONCLUSIONS

Sustainable thermal design has emerged in the context of new manufacturing systems that include more and more electronic components, but also have to meet high ecological demands. In this context the traditional design of the heat sinks has to be reconsidered.

The study presents an innovative CAD/CAE perspective regarding the heat sink design used in industrial engineering applications taking into account Eco-Design principles. All the new concepts were explained and the decision loop included in the design chain to asses the environmental scenario by its costs has been justified. The novelty of the research consists in introducing manufacturing criteria combined with emissions estimation. The case study regarding the heat sink for a variable speed drive proved the efficiency of the new CAD-CAE scenario, satisfying all the design requirements while being sustainable.

Future work will be focused on new multicriteria optimization techniques that can help the designer to further decrease the manufacturing costs.

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