Heat Transfer Engineering, 24(4):39–48, 2003

ISSN: 0145-7632 print / 1521-0537 online
DOI: 10.1080/01457630390199733

Taylor & Francis
Taylor & Francis Group

Sustainability Assessment of Aluminum Heat Sink Design

NAIM AFGAN and MARIA DA GRAÇA CARVALHO
Instituto Superior Tecnico, Lisbon, Portugal

SUZANA PRSTIC
Intel Corporation, Chandler, Arizona, U.S.A.

AVRAM BAR-COHEN
University of Maryland, College Park, Maryland, U.S.A.

The present effort addresses the application of sustainability criteria to the design of "heat sinks" used to cool advanced microelectronic components. The sustainability assessment is based on several criteria, including the use of natural resources, the environment, social welfare, and economic impact. The development of forced convection heat sinks, which are compatible with sustainable development, involves a subtle balance between the achieved thermal performance and the investment of material and energy in the fabrication and operation of the heat sink. It is shown that sustainability criteria can be used to select the environmentally optimal configuration among the most promising heat sink designs, including the lowest pumping power, the least mass of material, and the lowest total (fabrication and operation) energy for a specified application. Of the options considered for cooling a 100 W microprocessor with an aluminum heat sink operating at an excess temperature of 25 K, the heat sink design with the lowest total energy consumption was found to display the highest Sustainability Index.

Continued rapid industrialization and unfettered technology advancement are threatening to deplete valuable resources and exact an unacceptable toll on the Earth's environment. As a result of the explosion in information technology, an incredible number of computers is in use all around the world, perhaps as many as 600 million units by year-end 2001 [1]. Approximately half of these are personal computers, using a heat sink and fan for cooling a microprocessor dissipating on average 30 W. In addition to the 300 million microprocessor-driven personal computers currently in use, sales of such units are expected to exceed 100 million in 2001. The requisite thermal management of such high-performance desktop computers is most often achieved via an aluminum heat sink (fin structure) and a small fan.

The substantial material stream and energy consumption rate associated with the cooling of these desktop computers, as well as other categories of computers and electronic equipment, lends urgency and importance to

Address correspondence to Professor Naim Afgan, Instituto Superior Tecnico, Ave. Rovisco Pais, 1049 Lisbon, Portugal. E-mail: nafgan@navier.ist.utl.pt

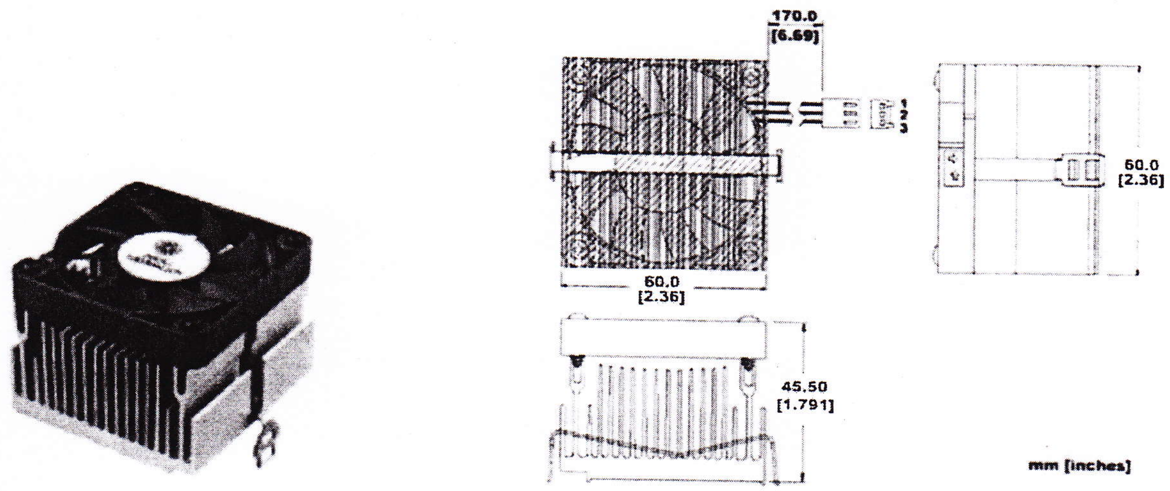


Figure 1 Fan/heat sink.

the "perfection" of these air-cooled heat sinks. The effort discussed herein deals with the development of a design and optimization methodology for "sustainable" forced convection-cooled, plate fin, electronic heat sinks. This methodology seeks to maximize the thermal energy that can be extracted from a specified space while minimizing the material and energy consumed in the fabrication and operation of the specified heat sink.

Two forced convection air cooling configurations are in common use. In the "fan-sink" configuration, a fan is used to directly impinge air on the fins of a heat sink attached to the microprocessor packages, as in Figure 1 [2]. In the second configuration, a fan is used to develop a pressure head, which pushes or pulls airflow through a heat sink, as in Figure 2, to reduce the chip junction-to-ambient thermal resistance to the commonly encountered value of 1.1 $\sim$ 1.7 K/W. For a microprocessor with a typical heat generation of 30 W, both of these configurations require between 1.0 W and 1.6 W of electricity to operate the fan [3]. While the power used for computing creates unique opportunities for the enhancement of human activity, use of power for these cooling systems is "parasitic" and has no inherent value.

Based on information available from the aluminum industry in Japan [4], approximately 85 kWh/kg are required to form, assemble, and transport aluminum heat sinks, including the use of 3% recycled material. Combining this energy investment with that consumed in the operation of the fans, the total energy required for the thermal management of a typical microprocessor can be expressed as:

$$E_T = 85\ \mathrm{M} + W_{\mathrm{PP}} t_1 \tag{1}$$

where E_T [kWh] is the energy used for cooling, M [kg] is the heat sink mass, W_{PP} [kW] is the pumping power of fan, and t_1 [h] is the lifetime operating hours of the fan/heat sink combination.

To determine the total energy consumption for the cooling of desktop microprocessors, it is convenient to examine a "best-practices" personal computer heat sink design [5]. In that study, the authors determined that an 80 g fan-cooled heat sink, operating with 0.18 W of

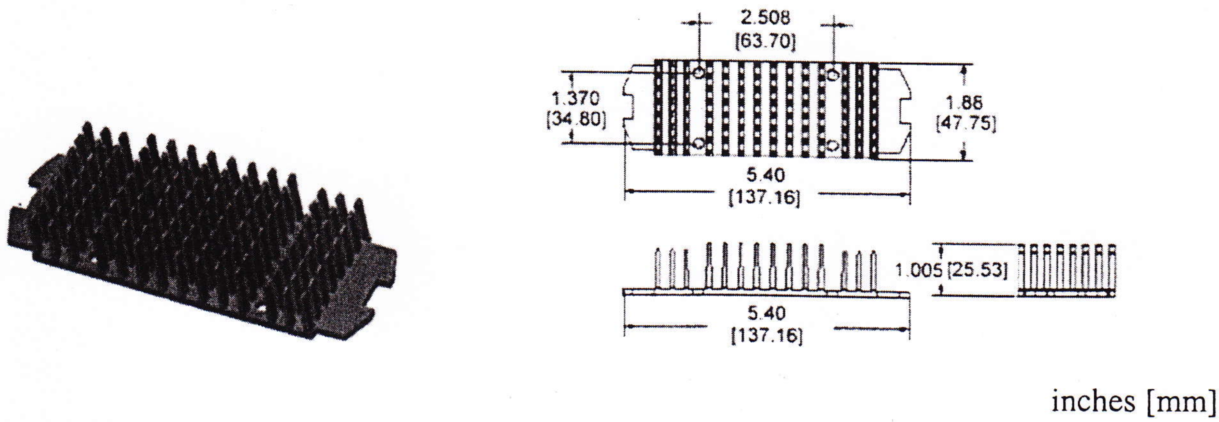


Figure 2 CPU heat sink.

pumping power in the flowing air, can adequately cool a 30 W microprocessor. The formation and fabrication of such a heat sink thus requires some 6.8 kWh. Assuming 2000 hours per year of fan operation, some 0.36 kWh in pumping power will be needed annually for this fan. Thus, assuming an average of 3 years of life for such a personal computer, the total energy consumed by the heat sink will reach some 7.9 kWhs, or—on average—approximately 2.6 kWh/yr. Extrapolating from this example, it may be expected that the energy used for the cooling of the approximately 400 million desktop computers anticipated to be in use by the end of 2001 could exceed 1 Terra (1×10^{12}) Wh per year.

ANALYTICAL MODEL FOR THERMAL CHARACTERIZATION OF PLATE FIN HEAT SINKS

The analytical model developed by Holahan et al. [6] for calculating the thermal performance and pressure drop in fully-shrouded, laminar, parallel plate heat sinks has been utilized to characterize the thermofluid performance of the present heat sinks. Results obtained with this approach, which evaluates fin conduction by successive superposition of a Kernel function determined from the method of images, was shown to give good agreement with experimental results, e.g., the data of Iwasaki et al. [7]. The simple side-inlet-side-exit (SISE) configuration considered in the current study is depicted in Figure 3, showing the nomenclature of the array geometry, including the fin height (H), fin thickness (t), inter-fin spacing (S), width of base (W), and length of the heat sink base (L).

In this approach, the local heat transfer coefficient needed to evaluate the heat transfer rate from individual segments of the fin surface area is obtained from the correlation for developing thermal and hydrodynamic laminar flow in parallel plate channels with uniform wall temperature, provided in Kakac et al. [8], and given by

$$h_{\text{fin,local}} = \frac{k_{\text{air}}}{2s}\left[7.55 + (0.024X^{-1.14}) \times \frac{0.0179\text{Pr}^{0.17}X^{-0.64} - 0.14}{(1 + 0.0358\text{Pr}^{0.17}X^{-0.64})^2}\right] \tag{2}$$

where k_{air} is the air thermal conductivity and $\text{Pr} = \nu/\alpha$ is the Prandtl number, with ν as the mean kinematic viscosity of air and α the thermal diffusivity. In Eq. (2), X is the dimensionless axial distance and is given by

$$X = \frac{[x\nu]}{4s^2 U_m \text{Pr}} \tag{3}$$

where x is the distance along the stream tube from the fin entrance to the patch and U_m is the mean air velocity.

The heat transfer rate from a single segment is then found using fin-to-air temperature difference for each segment (θ_B). This heat flow, divided by the local temperature difference, yields the fin temperature for the segment of interest. A simple heat balance on the fluid flowing in each inter-fin channel can then be used, in an iterative fashion, to determine the local air temperature [6]. The heat dissipation from the heat sink array, q, is then found by the summation of the heat transfer from all the segments ($q = \sum_n q_n$). A careful analysis of the resulting heat dissipation rates, throughout the parametric space of interest, can then be used to guide the designer to the most thermally advantageous combinations of air flow characteristics and fin geometries.

THERMO-ECONOMIC ASSESSMENT OF HEAT SINK DESIGNS

In succeeding sections of this paper, an advanced aluminum heat sink, occupying a volume of 500 cm^3 [$0.1 \text{ m} \times 0.1 \text{ m} \times 0.05 \text{ m}$] and operating with an excess

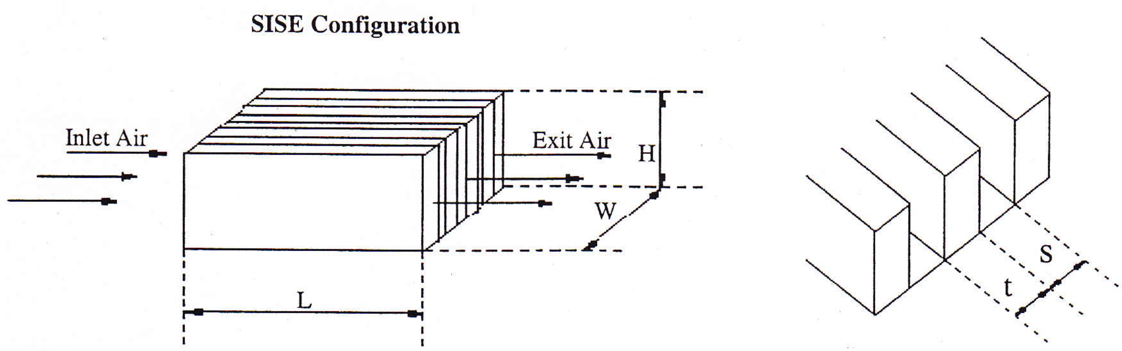


Figure 3 Side-inlet-side-exit (SISE) rectangular plate fin heat sink configuration.

Table 1 Candidate heat sink configurations

Options	Option definition	N	t [mm]	s [mm]	H [mm]	Mass [kg]	Pumping power [W]
D-1	Smallest pumping power	15	3.3	3.4	26.4	0.664	0.2
D-2	Least mass use	17	0.5	5.3	22.5	0.124	1.6
D-3	Lowest total energy	18	0.7	4.9	21.3	0.163	0.5

base temperature of 25 K, is used to illustrate the design methodology. Using the analytical model described in the earlier section [6], volumetric air flow rates and pressure drops across the heat sinks varied from 0.01 to 0.04 m^3/s and 20 to 80 Pa, respectively, yielding pumping powers ranging from 0.2 W to 3.2 W. This methodology has been described in detail by Bar-Cohen et al. [9]. Three heat sink designs, each dissipating 100 W (within $\pm$ 5 W), were chosen for comparison and evaluation by sustainability criteria: a design requiring the lowest pumping power (D1), a design consuming the least mass (D2), and a design that utilizes the lowest total energy (D3). The geometric dimensions of these three heat sinks are shown in Table 1. The calculated energy and economic parameters for these three heat sink designs are shown in Table 2.

As may be seen in Table 2, the three candidate designs offer significant differences in the required operating energy and formation energy, spanning a range of 1.2 kWh to 9.6 kWh in operating energy (for the assumed 6000 h of operation) and 10.2 kWh to 54.9 kWh in formation energy. Somewhat surprisingly, the lowest pumping power design (D1) requires more than five times the mass and formation energy of the "least mass" design (D2) and thus, despite its very frugal use of pumping power, is very high in total energy consumption. By contrast, the "least-mass" design consumes eight times more pumping power than D1. The lowest energy design (D3) requires just 30% of the total energy investment required by the smallest pumping power design (D1) and is 17% lower in total energy than the "least mass" configuration. The least mass design appears to be the second best choice, while due to its very high formation energy of 54.9 kWh, the lowest pumping power design (D1) is the worst design in terms of total energy consumption. These same trends are reflected in the economic indicators shown in Table 2, where the least energy design is seen to offer the lowest cost option; about three times cheaper than the lowest pumping power design and 30% lower than the least material design.

MULTICRITERIA SUSTAINABILITY ASSESSMENT METHODOLOGY

The multicriteria sustainability analysis of these high-performance heat sinks uses the following Sustainability Indicators:

- RI—Resource Indicator
- OEI—Operation Energy Indicator
- FEI—Formation Energy Indicator
- FCI—Formation Cost Indicator
- OCI—Operation Cost Indicators

The values of these Indicators were determined from the data shown in Table 3. The multicriteria sustainability assessment is based on the use of the Sustainability Index, which is defined as the additive aggregative function of the sustainability indicators and meets the condition of monotonicity [10]. The weighted arithmetic mean is the most popular type of synthesis function for

Table 2 Energy and economic indicators for candidate heat sink designs

Option	Resource indicators [kg/comp]	Energy indicators [kWh/comp]			Economic indicators [Cents/comp]		
		Operating energy*	Formation energy	Total energy	Formation cost†	Operating cost†	Total cost
D 1	0.664	1.2	54.9	56.1	284	12	296
D 2	0.124	9.6	10.2	19.8	48	96	144
D 3	0.163	3	13.5	16.5	70	30	100

*Based on 6000 h of operation.
†Based on a cost of $/kg for aluminum and $/kWh for electrical power.

Table 3 Sustainability indicators for heat sink design

Options	Definition	Resource indicators [kg/comp]	Operation energy indicators [kWh/comp]	Formation energy indicators [kWh/comp]	Formation cost indicators [Cents/comp]	Operation cost indicators [Cents/comp]
D 1	Lowest power	0.664	1.2	54.9	284	12
D 2	Least mass	0.124	9.6	10.2	48	96
D 3	Least energy	0.163	3	13.5	70	30

its simplicity and ease of interpretation. The Sustainability Index is defined as:

$$Q(q, w) = \sum_{i=1}^{m} w_i q_i \tag{4}$$

where w_i is the weight-coefficients and qi is the normalized specific indicators.

The normalization of the sustainability indicators is achieved by the use of their respective membership function. Assuming maximum and minimum values of each indicator will correspond to 0 and 1, respectively, and using a linear membership function, the set of indicators for all the heat sink options under consideration will be converted to a fuzzy set of the respective indicators.

The membership functions are defined as:

$$q_i(x_i) = \begin{cases} 1, & \text{if } x_i \leq \text{MIN}(i), \\ \left(\dfrac{\text{MAX}(i) - x_i}{\text{MAX}(i) - \text{MIN}(i)}\right), & \text{if MIN}(i) < x_i \leq \text{MAX}(i), \\ 0, & \text{if } x_i > \text{MAX}(i) \end{cases} \tag{5}$$

The membership function values corresponding to the actual values of the indicators leads us to the normalized specific indicators given in Table 4.

The weight coefficient, w_i, is a measure of the relative significance of the corresponding specific indicator, q_i, for aggregative estimation of $Q(q, w)$. The idea of randomization of uncertainty, which was developed by Bayes [11] and involves modelling the uncertain choice of a values w from the set of random objects uniformly distributed in the interval [0, 1], was used to define the weight coefficients. The application of this approach to the determination of the aggregative indices, in the presence of uncertainty (deficiency of information), is named ASPID (Analysis and Synthesis of Parameters under Information Deficiency) [12–15].

In order to use this method, we have to suppose that the value of the weight coefficients is accurate to within a step $h = 1/n$ with n a positive integer. With this assumption, the infinite set of all possible weight-vectors may be approximated by a finite set of all possible weight-vectors with discrete components. Under the assumption that the number of indicators $m = 5$ and $n = 40$, the number of elements of the set $W(m, n)$ may be determined by

$$N(m, n) = \frac{(n + m - 1)!}{n!(m - 1)!} = 135751 \tag{6}$$

Now, non-numerical information may be used for the reduction of the set $W\ (m, n)$ of all possible vectors $w^{(t)} = (w_1^{(t)}, w_2^{(t)}, w_3^{(t)}, w_4^{(t)}, w_5^{(t)})$ with discrete components to a $W(I; m, n)$ of all admissible weight-vectors that meet the requirements implied by additional information on mutual relations between criteria and the respective indicators.

The measure of reliability of the revealed preference relation between options is defined by

$$P(j, l, I) = \frac{|\{s : Q^s(q^{(j)}) < Q^s(q^{(l)})\}|}{N(I, m, n)} \tag{7}$$

where $|\{s : Q^s(q^{(j)}) > Q^s(q^{(l)})\}|$ is the number of elements in the finite set $\{s : ..\} \leq \{1 \ldots N(I, m, n)\}$. The non-numerical information in our analysis is defined as a constraint between the indicators. In our, analysis, we will take the cases as defined in Table 5.

Table 4 Normalized sustainability indicators for heat sink design

Options	Definition	RI	OEI	FEI	FCI	OCI
D-1	Lowest pumping power	0.000	0.971	0.000	0.000	0.971
D-2	Least mass	0.892	0.000	0.893	0.904	0.000
D-3	Least total energy	0.812	0.722	0.813	0.803	0.722

Table 5 Cases for non-numerical constraints

Cases	Non-numerical constraints
Case 1	RI = OEI = FEI = FCI = OCI
Case 2	RI > OEI = FEI = FCI = OCI
Case 3	OEI > RI = FEI = FCI = OCI
Case 4	FEI > RI = OEI = FCI = OCI
Case 5	FCI > RI = OEI = FEI = OCI
Case 6	OCI > RI = OEI = FEI = FCI
Case 7	FCI = OCI > RI = OEI = FEI

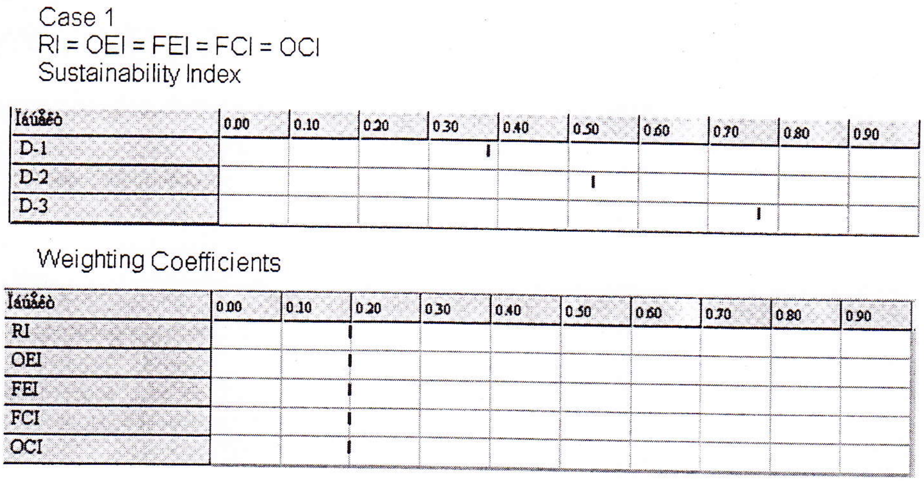


Figure 4 Sustainability index and weighting coefficients for Case 1.

The results of the multicriteria analysis are presented in the form of a diagram, displaying the value of the Sustainability Index on the abscissa between 0–1 and the heat sink options under consideration on the ordinate axis. The numerical value of the Sustainability Index is fundamental to the ranking of the options. For each value of the Sustainability Index, there is a respective dispersion that defines the accuracy of the obtained results. Every diagram also displays the numerical value of the probability dominancy among the options, with blue lines between two neighboring options, ranging in value between 0 and 1. A probability dominancy lower than 0.5 shows this combination to be improbable, and the respective case is not considered further.

Diagrams presenting the values of the weight coefficients are also given, along with the respective dispersion for each indicator. The values of the weight coefficients are obtained under the constraint given for each case and represent a random selection among the combinations generated by the randomization procedure.

CASE STUDIES

Case 1

Case 1 represents a situation in which it is assumed that all the weight coefficients have the same value. This is not a realistic situation because there is only one possible combination among the total number of the weight-coefficient vectors generated in this analysis. In all diagrams, the short vertical lines give the value of the Sustainability Index; the thick lines give the Standard Deviation of the Sustainability Index; and the thin lines give the Probability of Dominancy. Figure 4 presents the Sustainability Index and Weighting function values for this Case.

Case 2

Figure 5 presents Sustainability Index and Weighting function values for Case 2, in which maximum weight is given to the Resource Indicator (0.64) and all the other indicators are of equal weight, with weighting

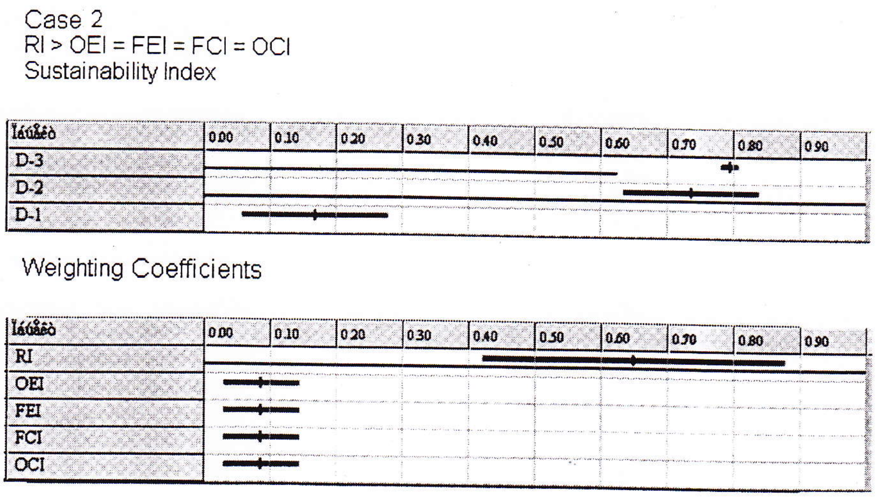


Figure 5 Sustainability index and weighting coefficients for Case 2.

coefficients of approximately 0.09. As is readily apparent in Figure 5, priority for this case is obtained by Option 3, the heat sink design requiring the lowest total energy, followed closely by Option 2, with Option 1 a distant third. It is thus apparent that in this case there is only a small difference between two of the options under consideration. The rather high value of the probability for mutual relations between Option 1 and Option 2 emphasizes the compatibility of these two options. The high value of the probability of dominancy as the measure of reliability of the results also indicates that this combination is a realistic case to examine among the many combinations under consideration.

In order to better understand the significance of the various Sustainability Indicators, subsequent Case Studies explore the impact of assigning a dominant weight coefficient to a single Indicator while maintaining the other weighting coefficients low in value and equal to each other.

Case 3

Case 3 is designed to investigate the situation in which primary weight is given to the Operating Energy Indicator. In this Case, Option 3—the option with the lowest total energy—yields the highest value of the Sustainability Index, with Option 1—the lowest pumping power—not far behind. Thus, despite Option 1's absolute advantage in operating energy, the inclusion of other criteria (albeit at low weights) recognizes the massive advantage enjoyed by Option 3 in formation energy and provides a slight advantage in the Sustainability Index to this least-energy design.

However, with the low reliability of the preferences between Options 1 and 3—reflected in the probability value of approximately 0.5 (shown in the upper part of Figure 6)—it can be concluded that this is an unrealistic case. Also, the high value of the standard deviation in the Sustainability Index for Options 1 and 2 casts considerable doubt on the accuracy of the prediction for this Case.

Case 4

In Case 4, primary weight is given to the Formation Energy Indicator (FEI), and the calculations are performed to assess this weighting on the Sustainability Index. The results (shown in Figure 7) lead to the conclusion that Option 3, offering the least total energy design, again has the highest priority in comparison with the other two options. Interestingly, despite the fact that Option 2 was specifically chosen to minimize the energy of formation, the need for substantial energy to operate this heat sink results in a lower Sustainability Index than Option 3, even with a very high weighting coefficient assigned to the Energy of Formation indicator.

Case 5

Figure 8 presents the Sustainability Index and Weighting Coefficient values for Case 5, representing the dominance of the Formation Cost Indicator relative to the other four indicators. The high value of probability among the Options leads to the conclusion that this is a realistic Case. On the other hand, it may be seen that imposition of the Formation Cost Indicator priority constraint results in only a small difference between Options 2 and 3.

Case 6

This Case is designed to investigate the impact of assigning priority to the Operation Cost Indicator. The results shown in Figure 9 reveal the Sustainability Index to

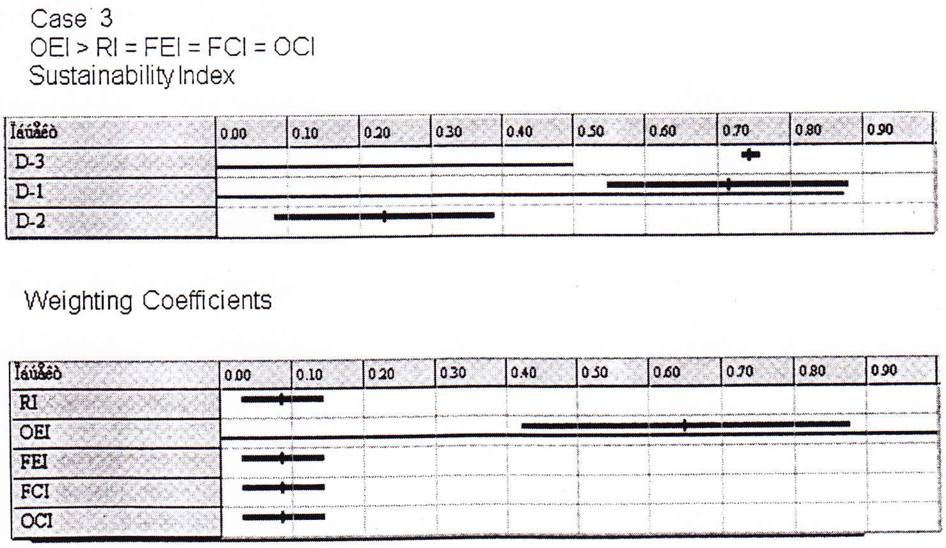


Figure 6 Sustainability index and weighting coefficients for Case 3.

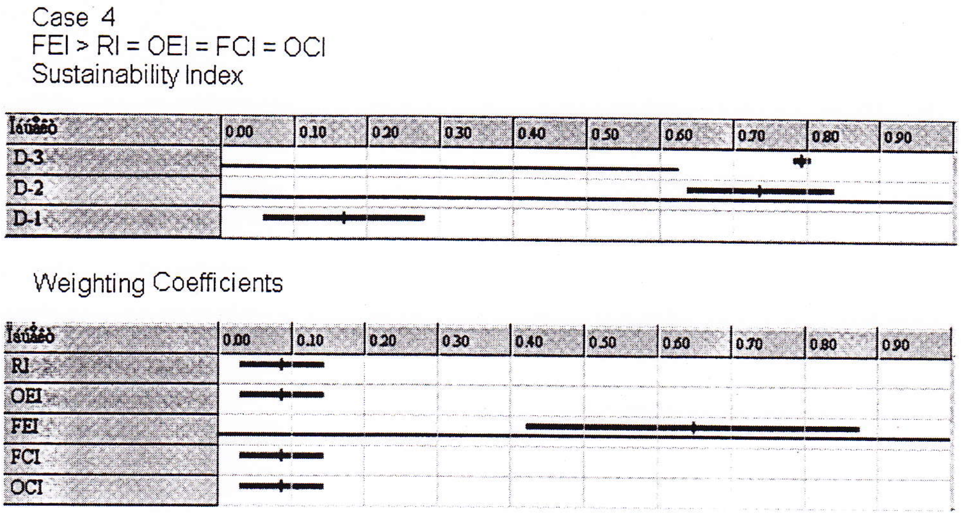


Figure 7 Sustainability index and weighting coefficients for Case 4.

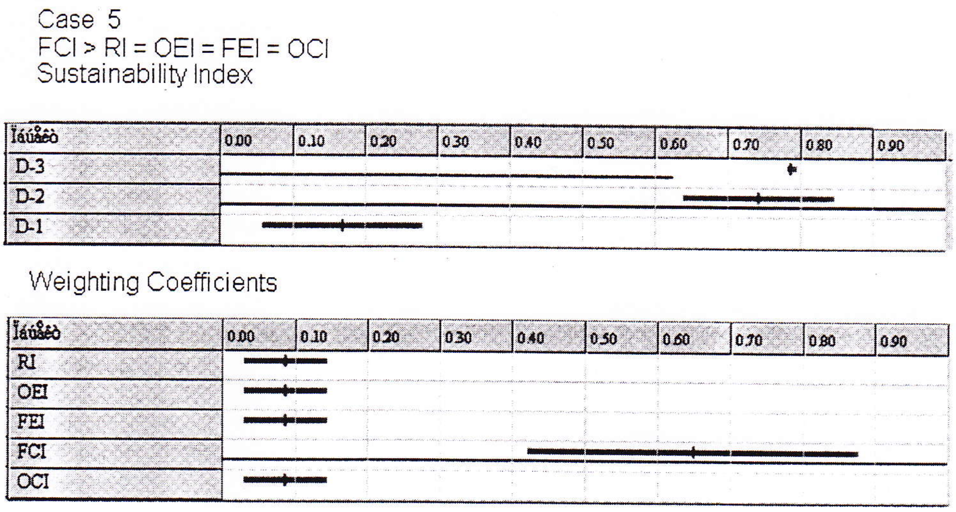


Figure 8 Sustainability index and weighting coefficients for Case 5.

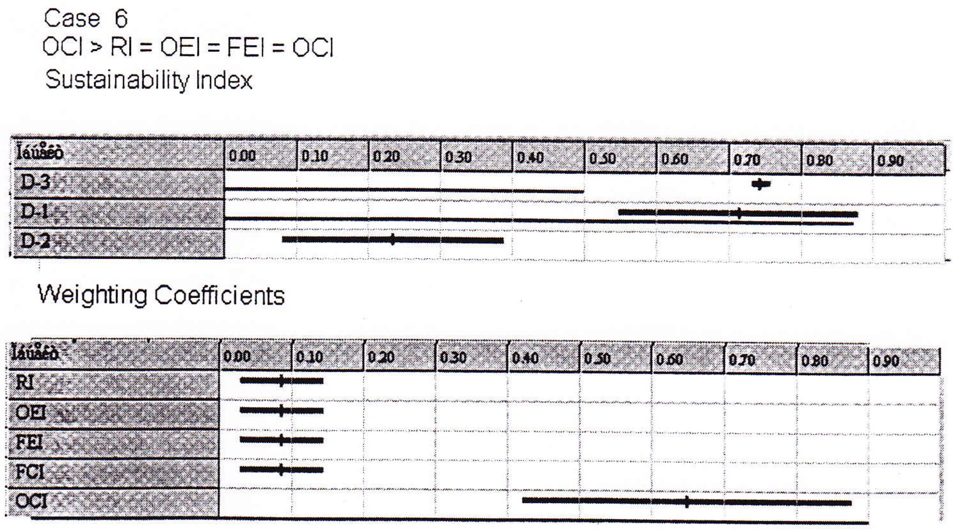


Figure 9 Sustainability index and weighting coefficients for Case 6.

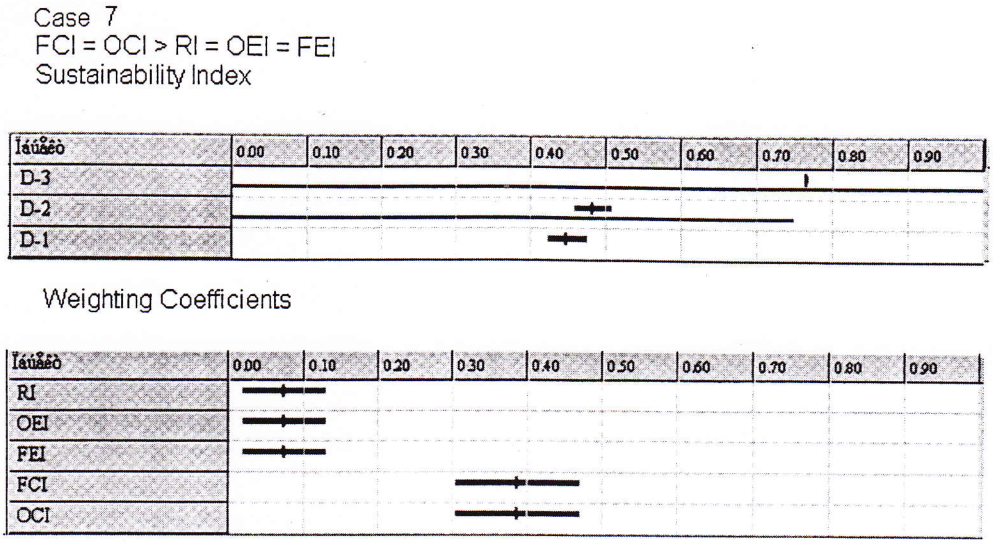


Figure 10 Sustainability index and weighting coefficients for Case 7.

give priority to Option 3, followed closely by Option 1. However, the low value of the probability of dominancy between Options 1 and 3, with a value close to 0.5, proves that this case is not realistic.

Case 7

In order to investigate the effect of total cost on the priority among the three heat sink options considered, Case 7 was created with equally high weighting (nearly 0.4) given to the two Cost Indicators and lower weighting to the other three indicators. Figure 10 presents the Sustainability Index and Weighting Function values for Case 7 and reveals the strong advantage enjoyed by the least-energy design, Option 3. It should be noted that this Case is highly realistic, with a probability value of nearly unity between Case 3 and Case 2.

CONCLUSIONS

Sustainability assessment was shown to provide a useful technique for selecting the environmentally optimal configuration among the most promising heat sink designs for an advanced microprocessor application, including the lowest pumping power, the least mass of material, and the lowest total (fabrication and operation) energy for the cooling specifications. Although a detailed thermo-economic analysis was used to highlight the relative advantages of these specific designs, the multicriteria assessment methodology was seen to provide the capability to integrate diverse sustainability indicators and weightings in a single Sustainability Index.

For a majority of the Cases under consideration, Option 3—the least total energy—was seen to consistently yield the highest Sustainability Index, confirming that under a variety of constraints, the least energy design is the environmentally optimal choice.

It should be noted that there are differences in the reliability of the results of the various cases considered, as well as different standard deviations among the selected options within the individual cases. It should also be noted that there are combinations of weighting coefficients applied to the various Sustainability Indicators that could lead to the selection of the least mass and lowest pumping power options as the most sustainable designs.

While the authors believe these Cases help define the environmentally optimal design for advanced heat sinks, many other combinations of weighting factors and their mutual constraints could be explored. Such a comprehensive application of this methodology may lead to the better understanding of the effect of different indicators to the priority list obtained by use of the Sustainability Index Rating.

NOMENCLATURE

E_T	energy used for cooling, kWh
H	fin height, m
$h_{\text{fin,local}}$	heat transfer coefficient, W/m^2 K
k_{air}	air thermal conductivity, W/m K
L	length of the heat sink base, m
M	heat sink mass, kg
m, n	number of indicators
N	number of fins
Pr	Prandtl number
Q	additive aggregative function
q	heat sink dissipation for all segments, W
q_i	normalized specific indicators
s	fin spacing, m
t	fin thickness, m
t_l	lifetime operating hours of the fan/heat sink combination, h

U_m	mean air velocity, m/s
W	width of the heat sink base, m
w_i	weight coefficient
W_{pp}	pumping power of fan, kW
$w^{(t)}$	weight vectors
X	dimensionless axial distance
x	distance along the stream tube from the fin entrance to the patch, m

Greek Symbols

α	thermal diffusivity, m^2/s
ν	air kinematic viscosity, m^2/s
θ_B	fin-to air temperature difference, K

Notation

D1	smallest pumping power design
D2	least mass design
D3	lowest energy design
FEI	Formation Energy Indicator
FCI	Formation Cost Indicator
OCI	Operation Cost Indicators
OEI	Operation Energy Indicator
RI	Resource Indicator

REFERENCES

[1] Computer Industry Almanac Inc., Nearly 600 Million Computers-in-Use in Year 2000, Press release, November 3, 1999.

[2] AAVID Thermal Product Inc., Products Data Sheet, 2000.

[3] Intel Corporation, AP-905 Pentium® III Processor Thermal Design Guidelines Application Note, 1999.

[4] LCA committee report, Japan Aluminum Association, 1999.

[5] Chang, J. Y., Yu, C. W., and Webb, R. L., Identification of Minimum Air Flow Design for a Desktop Computer Using CFD Modeling, *Proc. I-Therm 2000 Conf.*, Las Vegas, NV, vol. 1, pp. 330–339, 2000.

[6] Holahan, M. F., Kang, S. S., and Bar-Cohen, A., A Flowstream-Based Analytical Model for Design of Parallel Plate Heat Sinks, ASME HTD-329, National Heat Transfer Conference, vol. 7, pp. 63–71, 1996.

[7] Iwasaki, H., Sasaki, T., and Ishizuka, M., Cooling Performance for Plate Fins for Multichip Modules, *Proc. Intersociety Conf. Thermal Phenomena*, pp. 144–147, 1994.

[8] Kakac, S., Shah, R. K., and Aung, W., Handbook of Single-Phase Convective Heat Transfer, 2nd ed., Wiley & Sons, New York, pp. 35–42, 1987.

[9] Bar-Cohen, A., Prstic, S., Yazawa, K., and Iyengar, M., Design and Optimization of Forced Convection Heat Sinks for Sustainable Development, *Proc. EURO Conf.*, Lisbon, Portugal, 2000.

[10] Afgan, N. H., and Carvalho, M. G., *Sustainability Assessment Methodfor Energy Systems*, Kluwer Academic Publisher, Boston, 2000.

[11] Bayes, T., An Essay Toward Solving a Problem in Doctrine of Chances, *Biometrika*, vol. 45, pp. 296–315, 1958.

[12] Hovanov, N., Fedotov, Y., and Zakharov, V., The Making of Index Numbers Under Uncertainty, *Environmental Indices: Systems Analysis Approach*, EOLSS Publishers Co., Oxford, pp. 83–99, 1999.

[13] Hovanov, N., *Analysis and Synthesis of Parameters Under Information Deficiency*, St. Petersburg State University Press, St. Petersburg, 1996. (Monograph, in Russian.)

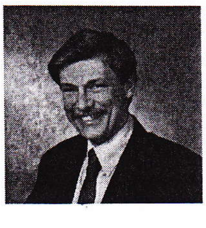
[14] Hovanov, N., Kornikov, V., and Seregin, I., Qualitative Information Processing in DSS ASPID-3W for Complex Objects Estimation Under Uncertainty, *Proc. Int. Conf. "Informatics and Control"*, St. Petersburg (Russia), pp. 808–816, 1997.

[15] Hovanov, A. N., and Hovanov, N. V., DSSS "ASPID—3W" Decision Support System Shell, Registered by Federal Agency for Computer Programs Copyright Protection Russia Federation, Num. 960087, 22 September 1996.

Naim Hamdia Afgan is a Fellow of the Islamic Academy of Sciences and a Member of the Academy of Sciences and Art of Bosnia and Hercegovina, and is the UNESCO Chair Holder for the UNESCO Chair for Energy Sustainable Management at the Instituto Superior Tecnico, Lisbon. Professor Afgan was one of the founders of the International Centre for Heat and Mass Transfer and served as Scientific and General Secretary of ICHMT for a number of years. He was the Member of Configuration Control Board of the Encyclopaedia of Life Support Systems. Professor Afgan's book, *Sustainability Assessment of Energy Systems*, was published by Kluwer Academic Publisher.

Maria da Graça Carvalho is a Full Professor at the Mechanical Engineering Department of Instituto Superior Técnico (Technical University of Lisbon) since June 1992. In 1983, she obtained her Ph.D. at the Imperial College in London. She has participated in and coordinated a large number of international R&D Projects. She has over 250 publications in scientific journals, books, and international conference proceedings to her credit. Her main field is the mathematical modeling of combustion and heat transfer phenomena. One of her specialties has been the development of general numerical predictions methods for engineering combustion equipment.

Suzana Prstic received her Master's Degree in Mechanical Engineering from the University of Minnesota in 2001 and began her professional career as a thermal engineer at Intel Corporation, Chandler, AZ. Her research interests are in thermal management of electronic systems. She is a member of SWE and ASME.



Avram Bar-Cohen is Professor and Chair of Mechanical Engineering at the University of Maryland, where he also continues his research and teaching interests in the thermal management of micro/nano systems. He is the Editor of IEEE's *Transactions on Components and Packaging Technologies*, and the co-author of two books, along with some 200 archival and referred conference publications. Dr. Bar-Cohen is a recipient of the ASME Heat Transfer Memorial Award, Worcester Reed Warner Medal, and Edwin F. Church Medal, and is a Fellow of ASME and IEEE.