Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2017) 000–000

Energy
Procedia

www.elsevier.com/locate/procedia

72nd Conference of the Italian Thermal Machines Engineering Association, ATI2017, 6-8 September 2017, Lecce, Italy

Optimization of an axial fan for air cooled condensers

G. Angelini[a]*, T. Bonanni[a], A. Corsini[a], G. Delibra[a], L. Tieghi[a], D.Volponi[a]

[a]*Sapienza University of Rome. Vie Eudossiana 18, Rome 00184*

Abstract

We report on the low noise optimization of an axial fan specifically designed for the cooling of CSP power plants. The duty point presents an uncommon combination of a load coefficient of 0.11, a flow coefficient of 0.23 and a static efficiency $\eta_{stat} > 0.6$. Calculated fan Reynolds number is equal to $Re = 2.85 \times 10^7$. Here we present a process used to optimize and numerically verify the fan performance. The optimization of the blade was carried out with a Python code through a brute-force-search algorithm. Using this approach the chord and pitch distributions of the original blade are varied under geometrical constraints, generating a population of over 24000 different possible individuals. Each individual was then tested using an axisymmetric Python code. The software is based on a blade element axisymmetric principle whereby the rotor blade is divided into a number of streamlines. For each of these streamlines, relationships for velocity and pressure are derived from conservation laws for mass, tangential momentum and energy of incompressible flows. The final geometry was eventually chosen among the individuals with the maximum efficiency. The final design performance was then validated through with a CFD simulation. The simulation was carried out using a RANS approach, with the cubic k - ε low Reynolds turbulence closure of Lien et al. The numerical simulation was able to verify the air performance of the fan and was used to derive blade-to-blade distributions of design parameters such as flow deviation, velocity components, specific work and diffusion factor of the optimized blade. All the computations were performed in OpenFoam, an open source C^{++}- based CFD library. This work was carried out under MinWaterCSP project, funded by EU H2020 programme.

Keywords: Type your keywords here, separated by semicolons ;

---

* Corresponding author. Tel.: +39 064 458 5914.
E-mail address: gino.angelini@uniroma1.it

1. Introduction

To be written

2. Optimization

Numerical design optimization was used to minimize the trailing edge noise of a single stage axial fan. Two geometric variables were varied (chord and pitch distribution) in order to provide a wide database of optimized individuals that can be used to search for solutions that can satisfy different geometrical constraints a posteriori selected. Imposed constraints assured the same total pressure rise delivered from the baseline fan. A blade element model was used to evaluate the aerodynamic performance of the fan and trailing edge noise. One potential design was selected from the set of simulations and the comparison with the baseline blade showed that it is possible to obtain an individual that both can reduce noise generation and increase the total to total efficiency.

Nomenclature

ch	chord length	[m]	Q	volume flow rate	[m^3/s]
ξ	pitch angle	[deg]	C_x	mean axial velocity	[m/s]
N_{ref}	number of reference sections	[-]	c_{ax}	axial velocity	[m/s]
K	number of nodes	[-]	U	rotation velocity	[m/s]
SPL	sound pressure level	[dB]	w	relative velocity	[m/s]
ψ	load coefficient	[-]	β	flow angle	[deg]
φ	flow coefficient	[-]	δ	deflection	[deg]
$\eta_{tot,stat}$	total static efficiency	[-]	W	specific work	[J/Kg]
$p_{tot,stat}$	total static pressure	[Pa]	DF	diffusion factor	[-]

2.1. Methodology

The most relevant noise source in the baseline fan is produced by the trailing edge. Trailing edge noise is caused by the vorticity shed from the trailing edge which produces local lift fluctuations. In the present study, a model for the trailing edge noise was combined with an aerodynamical model for rotor-only fans. For a given rotor geometry and fan operating conditions, the analysis tool provided the trailing edge noise and flow characteristics (e.g., velocity triangles, fan efficiency and pressure rise).Numerical model used for the generation of the database is implemented in AxLab, a tool for performance analysis of ducted axial fans. This software is based on a blade element axisymmetric principle. The rotor blade is divided into a number of streamlines. For each of these streamlines relations for velocities pressure are derived from incompressible conservation laws for mass, tangential momentum and energy. The complexity of 3D flow is partially reproduced by the juxtaposition of the flow conditions on the meridional plane and the circumferential plane. The analysis model for the noise emission is based on the model developed by Fukano et al [ref].

2.2. Description of the baseline blade

The baseline blade is a single stage axial fan for cooling of CSP power plants.The duty point of baseline blade presents an uncommon combination of dimensionless global duty parameters: a load coefficient of 0.11, a flow coefficient of 0.23 and a static efficiency > 0.6. Airfoil thickness distribution used for each section is an optimized version of NASA LS 417 distributed on a circular arc camber line. Geometry of the baseline blade is represented inside AxLab software by means of eleven radial blade sections. Following charts report performance data evaluated by Axlab. In Figure 1 are presented values of dimensionless global duty parameters and static efficiency.

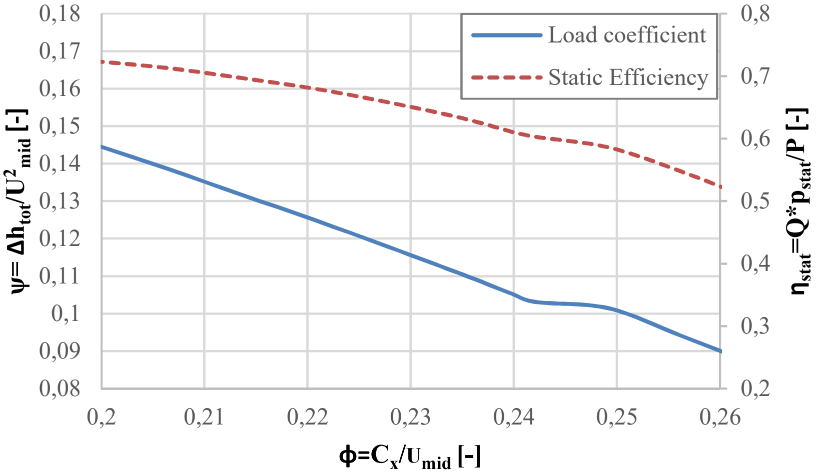

Figure 1 - static efficiency η_{stat} and load coefficient ψ vs flow coefficient φ

2.3. Pitch and chord optimization

Optimization process take into account both variation in pitch angle and blade chord of each section of the blade. In order to identify the variation of pitch and chord distributions, the following methodology was selected:

- Along the blade span are identified a number of reference sections N_{ref} ;
- On each of those sections, values of pitch and chord are selected on an arbitrary number of nodes K .
- Pitch and chord distributions are forced to have values indicated on values of nodes K in correspondence of the prescribed reference section. Final distribution to be tested will be approximated by a polynomial function $\xi\ (R)$ where $deg(\xi)$ will be equal to $Nref\text{-}1$.

In particular, during pitch optimization were selected 6 reference sections and for each of those section 7 nodes. Nodes were selected considering a pitch variation of the baseline configuration of +/- 30%, +/- 20%, +/- 10% and 0%. Instead for the chord length optimization were selected 5 reference sections and for each of those 6 nodes considering a chord variation of the configuration of the baseline configuration of + 30%, +/- 20%, +/- 10% and 0% for the first two reference sections while for the rest - 30%, +/- 20%, +/- 10% and 0% (see Figure 2). In order to avoid excessive distorted or unrealistic geometries we decided to insert following criteria:

1. Decreasing pitch: $\xi\ (R_i) < \xi\ (R_{i+1}>R_A)$;
2. Limited pitch distortion: $\xi\ (R_i) - \xi\ (R_{i+1}) < 8°$;
3. Limited chord distortion: $l_c\ (R_i) - l_c\ (R_{i+1}) \leq 0.1\ m$;
4. Weight limit: $w_{Baseline\ blade} < w_{Individual}$.

Application of constraints 1-4 brings the number of individuals from ~ $6{\times}10^{11}$ to 206275 reducing the computational cost at 2/1000 of the total. Blade weight was simply evaluated numerically integrating the chord length across the blade span, considering a linear thickness distribution from 13% to 9%. Each simulation was run with AxLab on a Linux server using 40 processors and the total computational time was of about 7 days. The software evaluates every geometry. If the total pressure rise provided results different from the imposed value, hub pitch (ξ_{hub}) of the blade is modified in order to obtain the target value with an error of 0.1% on total pressure rise.

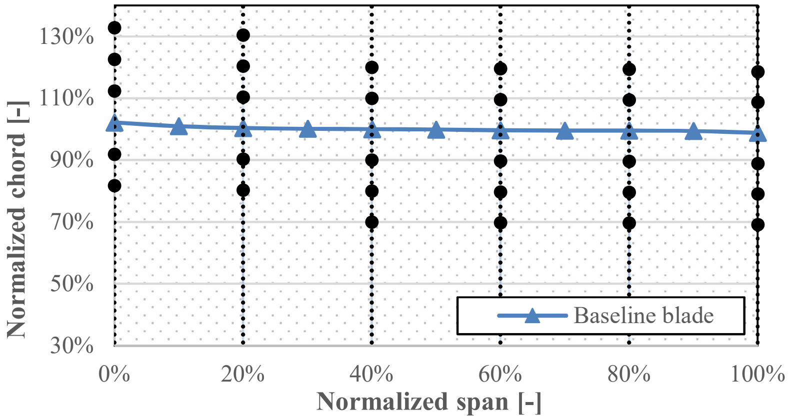

Figure 2 - Range of chord length variation with evidenced reference sections Nref and nodes K

All tested configuration were stored into a database: each element is identified by values of gain in terms of total efficiency $\Delta\eta_{tot}$ and gain in sound pressure level ΔSPL. In Figure 3(a) are presented results from the database for all tested configuration. Again a detail of Figure 3(a) is provided into Figure 3(b) in order to have an insight in the region of interest of the database.

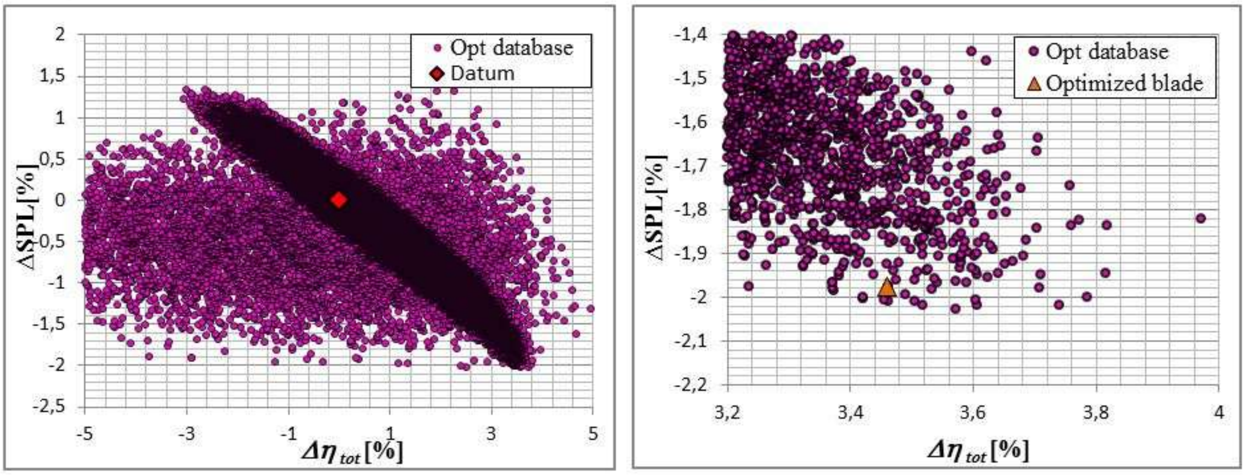

Figure 3 - Database of simulations performed during pitch and chord optimization; (b) detail of figure 3(a)

Results demonstrate that a notable noise reduction and efficiency increase can be obtained. Even if it is difficult to clearly identify a selection of optimal solutions (e.g. a Pareto Front), one element was selected from all the data following the main goal of increasing η_{tot} and to decrease as much as possible SPL. Table 1 reports the main features of candidate.

Table 1- Selected individual features in terms of static efficiency and noise emission

Individual name	η_{stat} [%]	*SPL*[dB]	$\Delta\eta_{stat}$[%]	*ΔSPL*[dB]	ξ_{hub} [deg]
Optimized blade	64.003	95.630	2.783	-1.9745	-2.767

The first result of this optimization process is that Opt II element reduced the blade weight of 10% and incremented the fan static efficiency more than 2%. Also results on blade noise emission seems to be promising.

3. CFD

Here a comparison between the new blade design with the datum, especially in term of static pressure and static efficiency is performed. Due of the lack of experimental data, a validation of the CFD simulation has not been possible. The same numerical approach, however, has been successfully applied for the prediction of the duty point performance of the datum, as shown in Table 2.

Table 2 - Datum blade CFD results vs experimental

	Experimental	*CFD*	*Error [%]*
Δp [ψ]	0.09323	0.08712	0.065
η_s [-]	56.0	57.76	0.031

3.1. CFD Details

Computations were carried out with the C^{++} open-source code OpenFOAM 2.3.x using the *simpleFoam* solver for steady computations of incompressible flows. The Generalized Algebraic Multi-Grid solver was used for pressure, while all the other equations were solved with a *smoothSolver*. Convergence threshold was set to 10^{-7} for pressure and to 10-5 for the other quantities. Turbulence modelling relied on the low-Reynolds cubic model of [ref]. The model solves two transport equations for k and ε.

3.2. Grid details, computational domain and boundary conditions

The computational domain entails one blade-to-blade passage, with periodic boundary conditions imposed at mid-pitch. The domain extends 1 chord up- and 1.5 down-stream of the blade leading and trailing edge. The computational grid, Figure, entails 10.5M hexahedra clustered along the endwalls and the blade profile. The mesh has 400 cells on the blade surface and 240 cells in the endwall to endwall direction, 30 of which are in the tip clearance. Mesh quality indicators are summarized in Table 3. The low skewness of the mesh was achieved using periodic boundaries with Arbitrary Mesh Interface technology. The inflow mass flow was specified, with a level of turbulence equal to 5%. At the outlet of the domain convective boundary conditions were specified. Over solid the upper endwall velocity was imposed equal to zero, and for the blade and the lower endwall velocity was imposed coherently with the full speed of the fan. k and ε were set to zero over all the solid walls following a well-known redefinition of the ε equation.

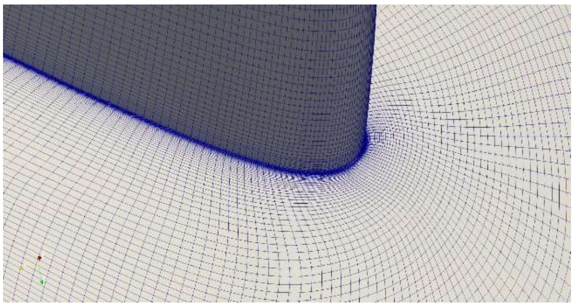

Figure 4 - Detail of the computational grid at the junction between blade and endwall

Table 3 - Mesh quality and y+ values

	Minimum	*Maximum*	*Average*
Volume ratio	1	4.8	1.1
Aspect ratio	1	160	9.7
Skewness	0	0.61	0.12
Min. included angle	23.5	90	63.5
y^+	0.67	5.2	2.77

4. CFD Results

Computations were performed for 40000 iterations, until the full convergence of pressure and blade torque. A good match between the 3D simulation results and the synthetic model numerical approach has been found, at least for most of the span of the blade. Near the upper endwall, where the leakage vortex causes a fully three-dimensional development of the flow, CFD simulation was able to better represent fluid physic. Here we show a comparison between AxLab and CFD results.

4.1. CFD vs AxLab

The span-wise analysis of some flow characteristics is shown in Figure 5. As expected, the main mismatch between the synthetic and the fully three-dimensional approach relies in the representation of the flow close the upper and the lower endwalls. Axial velocity distribution appears to follow the same trend in the synthetic analysis, while the CFD fields show a deficit due of the tip leakage vortex. The β_{inf} and δ graphs reveals an aerodynamic unloading of the lower sections, also witnessed by the DF distribution. The CFD matched such behavior. Benefits of this unloading are clearly known both for efficiency and noise reduction, while the differences detected in work and β_2 angle distributions are found to be almost inconsistent. Specific work is moved through the tip of the blade.

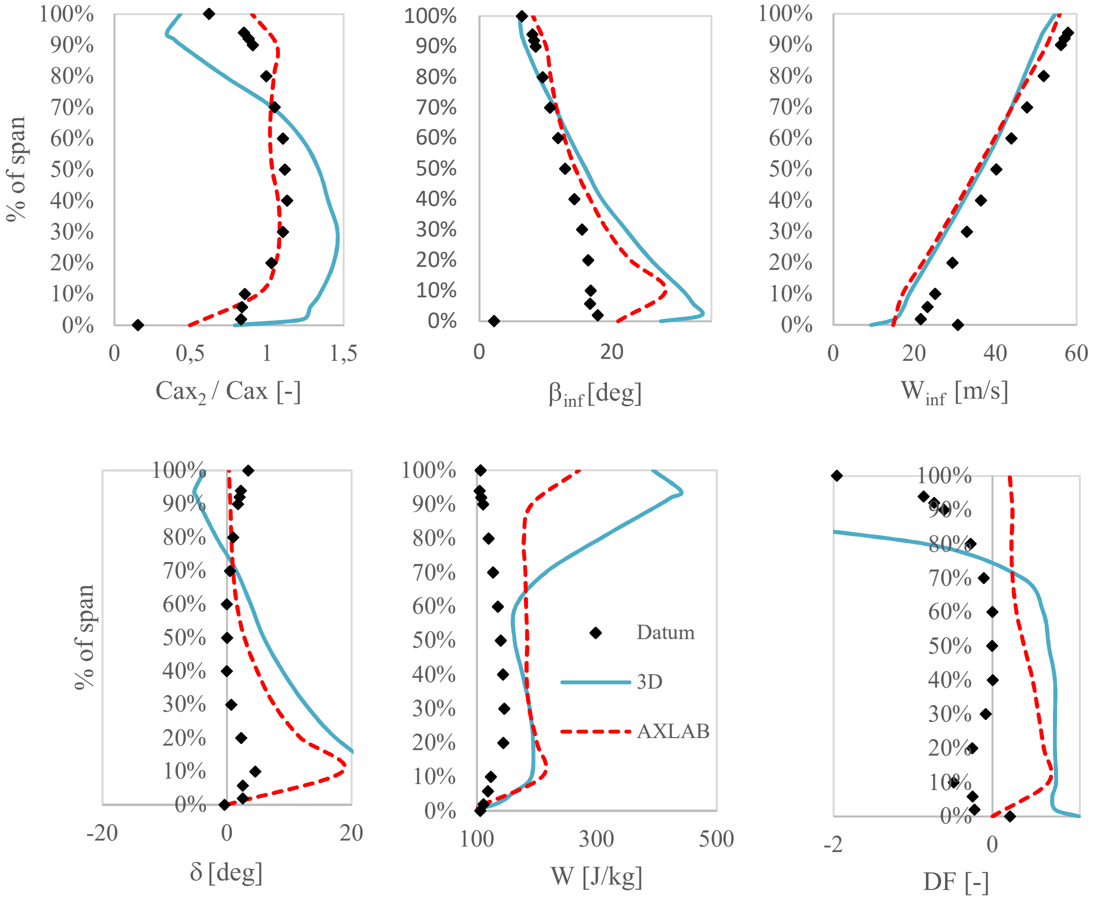

Figure 5 - Spanwise analysis of the optimized blade (AxLab & CFD) vs datum blade CFD

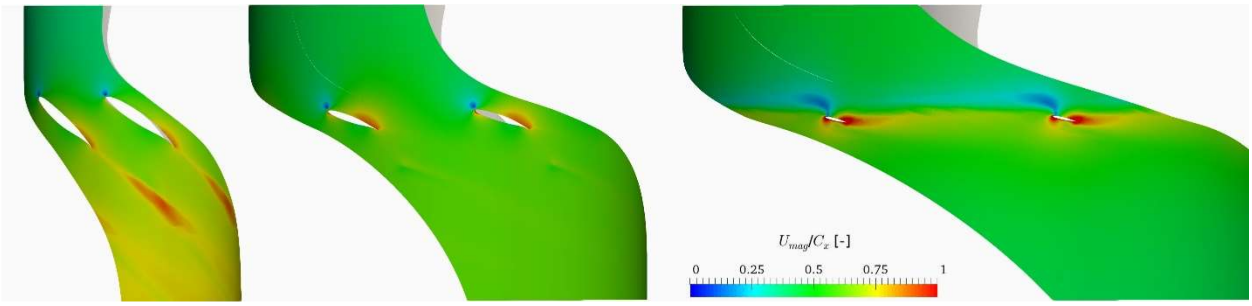

Figure 6 – Normalized velocity fields for different span percentages (a) 10%; (b) 50%; (c) 98%

4.2. Mean Flow Properties

The analysis of velocity field is the proof of the effectiveness of the optimization procedure. Flow is fully attached to the blade along all the blade span, without phenomena of recirculation, as highlighted by Figure [fig]. Velocity fields reflects specific work distribution. A further analysis can be performed through the helicity visualization, which reveals some key aspects on the flow (Figure [7]). The most prominent feature is constituted by the presence of a turbulent structure close to the hub of the blade, occupying the first 15 % of the blade span. Here, the high magnitude of helicity can be attributed to the corner vortex caused by the junction between the hub of the blade and the lower endwall. Higher values of helicity can also be observed in a small region close to the upper endwall, where the tip leakage vortex is strongly clustered to the wall. At approximately the 70 % of the blade span a region of medium helicity, caused by the flex in the chord distribution of the blade.

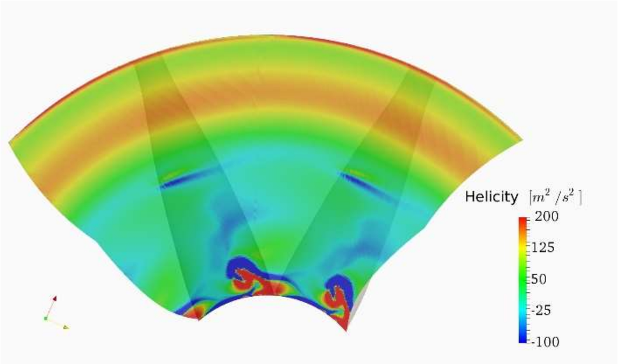

Figure 7 – Helicity field at 0.5c from the t.e. of the blade

4.3. Tables

All tables should be numbered with Arabic numerals. Every table should have a caption. Headings should be placed above tables, left justified. Only horizontal lines should be used within a table, to distinguish the column headings from the body of the table, and immediately above and below the table. Tables must be embedded into the text and not supplied separately. Below is an example which the authors may find useful.

Table 1. An example of a table.

An example of a column heading	Column A (t)	Column B (t)
And an entry	1	2
And another entry	3	4
And another entry	5	6

4.4. Construction of references

References must be listed at the end of the paper. Do not begin them on a new page unless this is absolutely necessary. Authors should ensure that every reference in the text appears in the list of references and vice versa. Indicate references by [1] or [2] or [3] in the text.

Some examples of how your references should be listed are given at the end of this template in the 'References' section, which will allow you to assemble your reference list according to the correct format and font size.

4.5. Section headings

Section headings should be left justified, bold, with the first letter capitalized and numbered consecutively, starting with the Introduction. Sub-section headings should be in capital and lower-case italic letters, numbered 1.1, 1.2, etc, and left justified, with second and subsequent lines indented. All headings should have a minimum of three text lines after them before a page or column break. Ensure the text area is not blank except for the last page.

4.6. General guidelines for the preparation of your text

Avoid hyphenation at the end of a line. Symbols denoting vectors and matrices should be indicated in bold type. Scalar variable names should normally be expressed using italics. Weights and measures should be expressed in SI units. All non-standard abbreviations or symbols must be defined when first mentioned, or a glossary provided.

4.7. File naming and delivery

Please title your files in this order 'procedia acronym_conference acronym_authorslastname'. Submit both the source file and the PDF to the Guest Editor.

Artwork filenames should comply with the syntax "aabbbbbb.ccc", where:

- a = artwork component type
- b = manuscript reference code
- c = standard file extension

Component types:

- gr = figure
- pl = plate
- sc = scheme

- fx = fixed graphic

4.8. Footnotes

Footnotes should be avoided if possible. Necessary footnotes should be denoted in the text by consecutive superscript letters[1]. The footnotes should be typed single spaced, and in smaller type size (8 pt), at the foot of the page in which they are mentioned, and separated from the main text by a one line space extending at the foot of the column. The Els-footnote style is available in the MS Word for the text of the footnote.

Please do not change the margins of the template as this can result in the footnote falling outside printing range.

5. Illustrations

All figures should be numbered with Arabic numerals (1,2,3,….). Every figure should have a caption. All photographs, schemas, graphs and diagrams are to be referred to as figures. Line drawings should be good quality scans or true electronic output. Low-quality scans are not acceptable. Figures must be embedded into the text and not supplied separately. In MS word input the figures must be properly coded. Preferred format of figures are PNG, JPEG, GIF etc. Lettering and symbols should be clearly defined either in the caption or in a legend provided as part of the figure. Figures should be placed at the top or bottom of a page wherever possible, as close as possible to the first reference to them in the paper. Please ensure that all the figures are of 300 DPI resolutions as this will facilitate good output.

The figure number and caption should be typed below the illustration in 8 pt and left justified [***Note:*** one-line captions of length less than column width (or full typesetting width or oblong) centered]. For more guidelines and information to help you submit high quality artwork please visit: http://www.elsevier.com/artworkinstructions Artwork has no text along the side of it in the main body of the text. However, if two images fit next to each other, these may be placed next to each other to save space. For example, see Fig. 1.

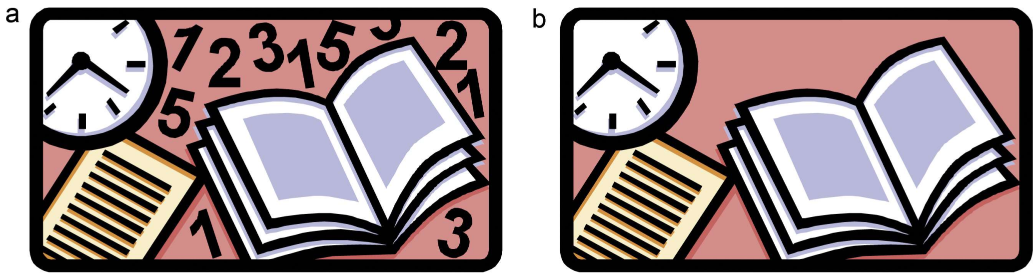

Fig. 1. (a) first picture; (b) second picture.

6. Equations

Equations and formulae should be typed in MathType, and numbered consecutively with Arabic numerals in parentheses on the right hand side of the page (if referred to explicitly in the text). They should also be separated from the surrounding text by one space.

---

[1] Footnote text.

$$\rho = \frac{\vec{E}}{J_C(T = \text{const.}) \cdot \left(P \cdot \left(\frac{\vec{E}}{E_C} \right)^m + (1 - P) \right)} \tag{1}$$

4. Online license transfer

All authors are required to complete the Procedia exclusive license transfer agreement before the article can be published, which they can do online. This transfer agreement enables Elsevier to protect the copyrighted material for the authors, but does not relinquish the authors' proprietary rights. The copyright transfer covers the exclusive rights to reproduce and distribute the article, including reprints, photographic reproductions, microfilm or any other reproductions of similar nature and translations. Authors are responsible for obtaining from the copyright holder, the permission to reproduce any figures for which copyright exists.

Acknowledgements

Acknowledgements and Reference heading should be left justified, bold, with the first letter capitalized but have no numbers. Text below continues as normal.

References

[1] Filippini, Massimo, and Lester C. Hunt. (2011) "Energy demand and energy efficiency in the OECD countries: a stochastic demand frontier approach." *Energy Journal* 32.2 (2011): 59-80.

[2] Filippini, Massimo, and Lester C. Hunt. (2012) "US residential energy demand and energy efficiency: A stochastic demand frontier approach." *Energy Economics* 34.5 (2012): 1484-1491.

Instructions to Authors for Word template

1. Locking of Copyright:

The copyright line is locked in the Procedia templates. The author may not edit the same and making it editable only PSMs. If there are any copyright changes required, you are requested to contact Journal Manager through Guest Editors. For editable the below mentioned steps must be followed:

Steps:

- Click on copyright statement
- Click on **Properties** in **Developer** tab
- Remove the checks from **Content control cannot be deleted** and **Contents cannot be edited** under **Locking** and then Press **ok**

2. Docm format:

We have added macros in the Word templates for the below mentioned features. And since macros are not supported in doc and docx format we created the templates of all Procedia titles in .docm format.

- Removal of all highlights
- Accept track change
- Locking of Rules

If .docm format needs to convert in docx format then the following steps must be performed:

Steps:

- Press **Alt F11**
- Click on **Project (JID_Template)**
- Enter "thomson" in Project Password
- Click on Microsoft Word Objects
- Click on **ThisDocument** under **Microsoft Word Objects**
- Delete all macros under **General**
- After deletion close the **Code** and **Project (JID_Template)** windows
- From **File** menu click on save as type **.docx** option

3. Comments added in the margin in Word master templates:

There are instances where author raising queries on what to do with key information lines such as “volume, page numbers”, “Conference title per issue” and “Copyright entity, year, copyright company Elsevier Ltd./B.V./Inc. and Organizer Name” in the copyright statement and for these concerns the comments have been inserted in the Word template to guide Author/JM about the information to be inserted by them in these fields.

Comments removal from Print: In Word 2007 and 2010 the comments present in a document get printed by default. If the authors do not want to get the comments appearing in print, the authors must remove the comments from the Word template before printing by changing the Print markup setting of word using the following steps:

Steps:

- Click the **File** tab
- Click **Print**
- Under **Settings**, click the arrow next to **Print All Pages**
- Click **Print Markup** to clear the check mark

Instructions to Authors pages to be excluded from Print:

- Click the **File** tab
- Click **Print**
- Under **Setting**, Type page numbers and/or page ranges separated by commas counting from the start of the document or the section. For example, type 1, 3, 1-5

4. PDF creation from Word master template:

While creating PDF from Word template the below given steps should be followed to avoid difference in trim size and margins and to avoid decrease in resolution and size of the figure images of the Word template and the PDF created.

Steps in Word 2007 and 2010:

- Click the **File** tab
- Click **Print**
- Under **Printer** tab, select **Adobe PDF**
- Click **Printer Properties** link
- Under **Adobe PDF Settings** tab, click on **Edit** button
- Click on **Images** folder under **Standard**
- Make **Downsample** and **Compression** fields under **Color Images** and **Grayscale Images** "**Off**". And in **Monochrome Image**s field make only Downsample "Off'
- Then click on **OK** and given name of the setting in **File name** tab and click on **save**
- Then again Under **Adobe PDF Settings** tab, click on **Edit** button
- Then click on **Color** folder
- Choose **Leave Color Unchanged** option under **Color Management Policies** tab then click on **OK**
- Lastly click on **OK** in **Adobe PDF Settings** tab
- Click **Save As**
- Under **Save as type**, click the arrow next to **PDF (*.pdf)**
- Click **Save**

In Word 2003 the PDF can be created by using “Convert to Adobe PDF” symbol in tool bar or the required paper size can be adjusted in the Adobe PDF settings given in the Properties tab on the Print option. Please follow the above steps to avoid decrease in resolution and size of the figure images.

5. Reference style used in Energy Procedia:

Title	**Reference style**
EGYPRO	3 Vancouver Numbered