Advanced Structural Optimization of a Heliostat with Cantilever Arms

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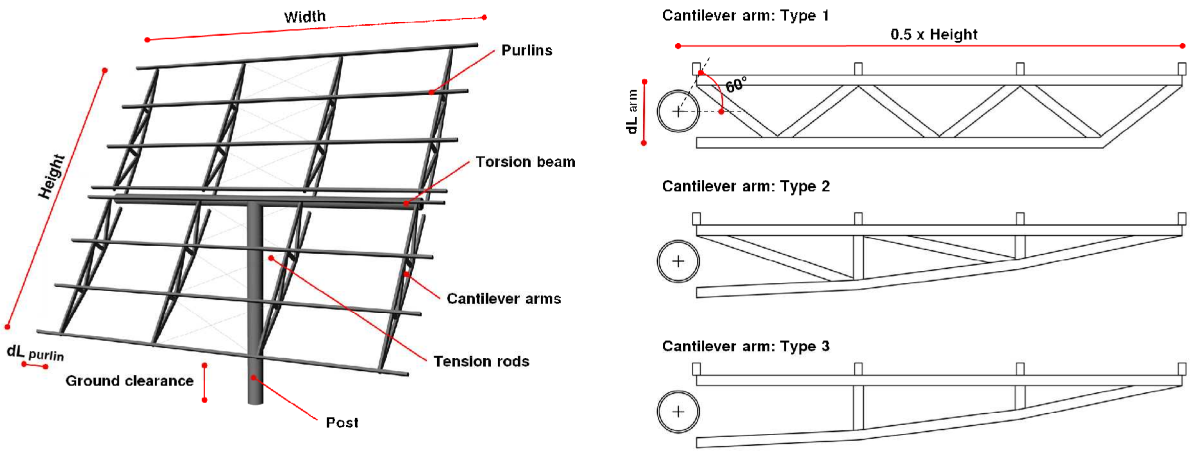
Abstract. The weight of the support structure of heliostats, CPV and PV trackers is important cost element of a solar plant and reducing it will improve the economic viability of a solar project. Heliostats with rectangular area (1 to 5 in 1 m² steps; 5 to 150 in 5 m² steps) and aspect ratios (0.5, 1.0, 1.2, 1.5, 2.0) were investigated under various winds speeds (0, 5 to 100 in 5 m/s steps) , wind direction (0 to 180° in 15° steps) and elevation positions (0 to 90° in 10° steps). Each load case was run with three different cantilever arms. The inclination angle of the chords and bracings was chosen so as to fulfill the geometrical boundary condition. Stress and buckling validations were performed according to Eurocode. The results of research carried out can be used to determine the specific weight of a heliostat in kg/m² as a function of the wind speed, tracker area and tracker aspect ratio. Future work should investigate the impact of using cold formed structural hollow sections and cross sections with thinner wall thickness which is not part of EN 10210.

INTRODUCTION

Solar thermal plans are getting increasingly important in the world energy supply. The higher the interest in this technology, the more important the design of the support structure of the heliostats becomes. Choosing the right surface area, aspect ratio, number of cantilever arms and arm geometry, leads to a more economic design. In previous works [1], the authors described a novel approach for optimizing and executing a preliminary design of CPV and PV solar tracker using a light finite element library adapted to run on modern mobile devices. The results obtained in this study can help to minimize the cost of a heliostat and choose its optimal size. The model can assist the work of researchers, design engineers and renewable energy investors and can be used as a convenient and quick-reference manual.

METHOD AND SPECIFICATIONS

The numerical calculations were performed on the heliostat described in Fig. 1a. The main parts of the finite element model are: purlins, cantilever arms, torsion beam, post and tension rods. The geometry was defined by the height, width and heliostat aspect ratio. The length of the purlin cantilever (dL_{purlin}) varies and is directly related to the numbers of cantilever arms. It has to ensure that the bending moments acting on the purlin over its outer support and in the middle of the first field between the cantilever arms are equal. This equality leads to uniform stress distribution and utilization of the purlins. Figure 1b illustrates the three different cantilever arm types investigated in this analysis: the first has two parallel upper and bottom chord; the second has a straight upper and parabolic shaped bottom chord; the third has the same chord characteristic as the second one but is constructed as Vierendeel truss with semi-rigid web connections. The height of the arms (dH_{arm}) has the following values: (1/8), (1/10) and (1/12) of the heliostat half height. The connection inclination angle between the cantilever arms and the torsion beam is set to 60°.



(a) (b)

FIGURE 1. (a) Structural members of the heliostat; (b) Three different cantilever arms.

The parameters describing the geometry, the position and the loading of the heliostat are separated in two main groups. The fixed parameters are set as defaults and are not changed during the whole process.

- Height above ground to the bottom edge of the mirror surface in sunrise position: 0.50 m.
- Maximum distance between purlins could not exceed: 1.00 m.
- Steel grade is S235 according to EN 10025.
- Hot finished structural hollow sections according to EN 10210.
- The assumed weight of the heliostat surface corresponds to 5 mm glass facets: 12.5 kg/m^2.

The second group contains parameters that are changed incrementally. The effect of dead weight acting on the structure was considered with the load case in which the wind speed is set to nil.

- Aspect ratio [-]: 0.5, 1.0, 1.2, 1.5, 2.0
- Heliostat area [m²]: 1 to 5 in 1 m² steps and 5 to 150 in 5 m² steps
- No. of cantilever arms [-]: 2, 4 and 6
- Wind speed: 0 to 100 in 5 m/s steps
- Elevation [°]: 0 to 90 in 5° steps
- Wind direction [°]: 0 to 180 in 15° steps
- Design working time [years]: 25

The study distinguished between two modes of operation: operational and survival mode. Heliostats in the operational mode were investigated in elevation positions from 0° to 90° and in the survival mode only in elevation 0° (for clarification the elevation 90° is the sunrise position). In both modes the wind direction was iterated from 0° to 180° in 15° steps.

Safety factors, load combinations, stress and global buckling validations were performed according to EN 1990 - Basis of structural design [6] and EN 1993-1-1 - Design of steel structures [7]. Following safety factors were used:

- Dead load: 1.35
- Wind load: 1.50

MAIN RESULTS AND DSICUSSION

The results were evaluated with the stand-alone finite element library described in [1] independently for both operational and survival mode and are separated in two chapters. The following considerations are valid for both of them.

The smallest specific weight of the heliostat [kg/m²] as a function of the heliostat area [m²] and the gust wind speed [m/s] is summarized in Fig. 2. Both Fig. 3 and Fig. 4 show all single parameters used in the finite element analysis, which contribute to this result. For example, for a common heliostat with 30 m² size and for a usual wind velocity of 20 m/s the minimum specific weight will be approx. 13.5 kg/m² (see Fig. 2). The optimized support structure will have 2 cantilever arms (see Fig. 3b) from Type 2 (see Fig. 3a) and a cantilever height of (1/10) of the half height of the heliostat (see Fig. 4a). According to the Fig. 4b the ideal aspect ratio for these boundary conditions will be 1.0.

Figure 5 illustrates together with Fig. 6 the maximum utilization of all members. This is the maximum utilization from both stress and global buckling verification. The value for the mean utilization could be found in the figure caption.

The white, not filled, area in the top right corner of the diagrams indicates that heliostats with this combination of wind speed and heliostat area are not feasible. Using higher steel grade or different hollow sections date base can fill this area partially.

Operational mode

Specific weight

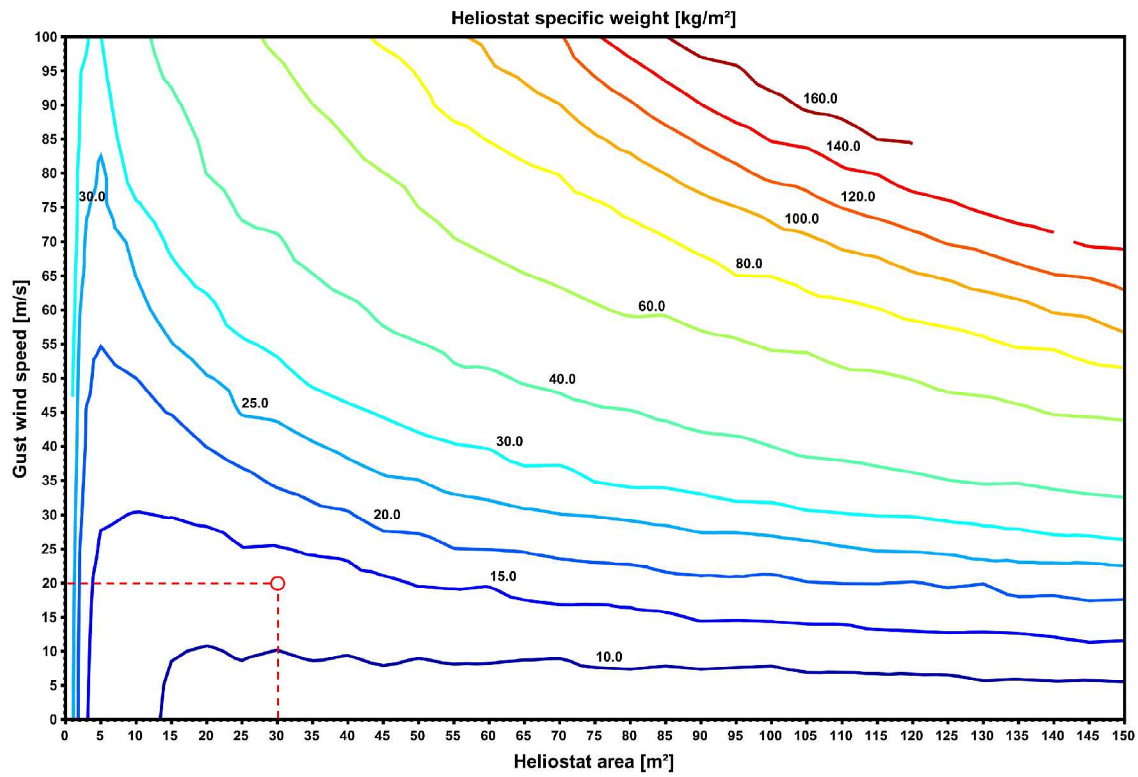
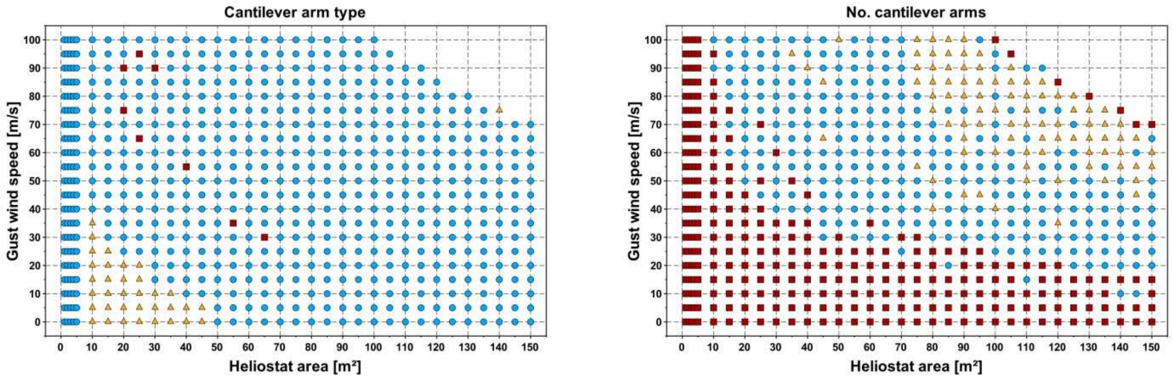


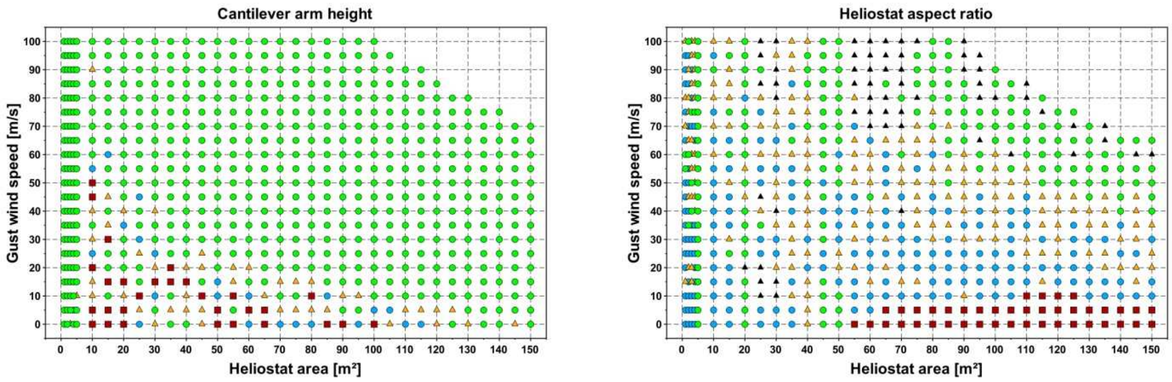
FIGURE 2. Specific weight of the heliostat [kg/m²] as a function of gust wind speed [m/s] and heliostat area [m²]

Incremental parameter



(a) ■ - Type 1; ● - Type 2; ▲ - Type 3 (b) ■ - 2; ● - 4; ▲ - 6

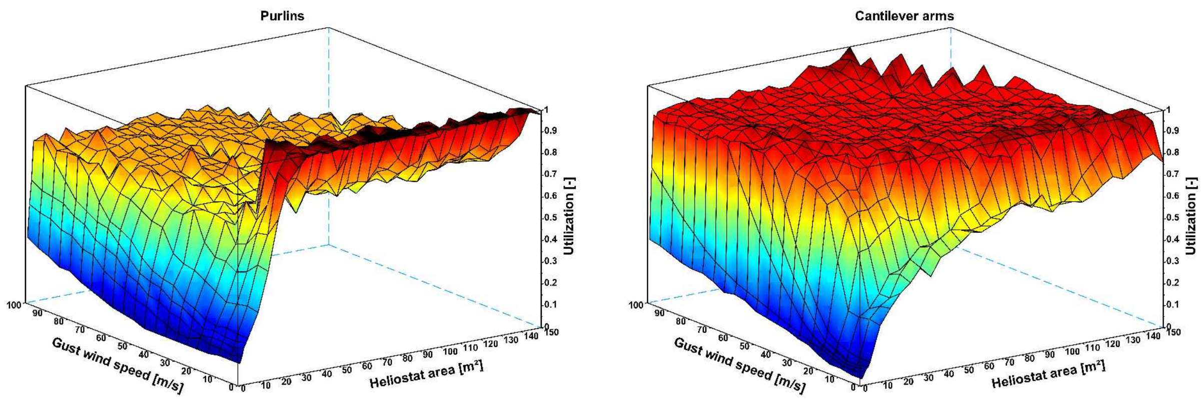
FIGURE 3. (a) Cantilever arm type; (b) Number of arms.



(a) ■ - (1/12); ● - (1/10); ▲ - (1/8); ● - (1/6); (b) ■ - 0.5; ● - 1.0; ▲ - 1.2; ● - 1.5; ▲ - 2.0

FIGURE 4. (a) Cantilever arm height as a function of the half height of the heliostat; (b) Heliostat aspect ratio.

Structural member maximal utilization



(a) (b)

FIGURE 5. (a) Purlin utilization: mean = 67.1%; (b) Cantilever arm utilization: mean = 77.7%.

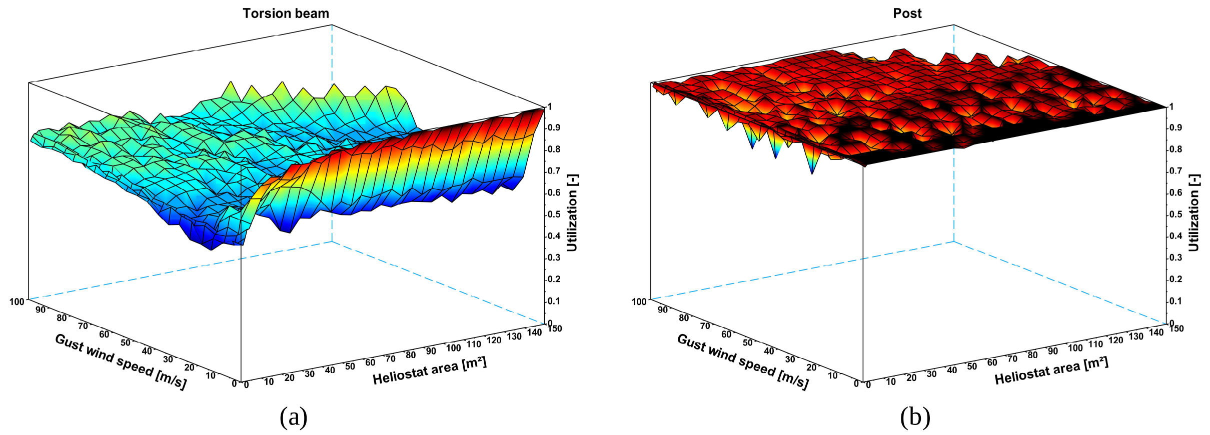


FIGURE 6. (a) Torsion beam utilization: mean = 71.4%; (b) Post utilization: mean = 98.4%

Survival mode

Specific weight

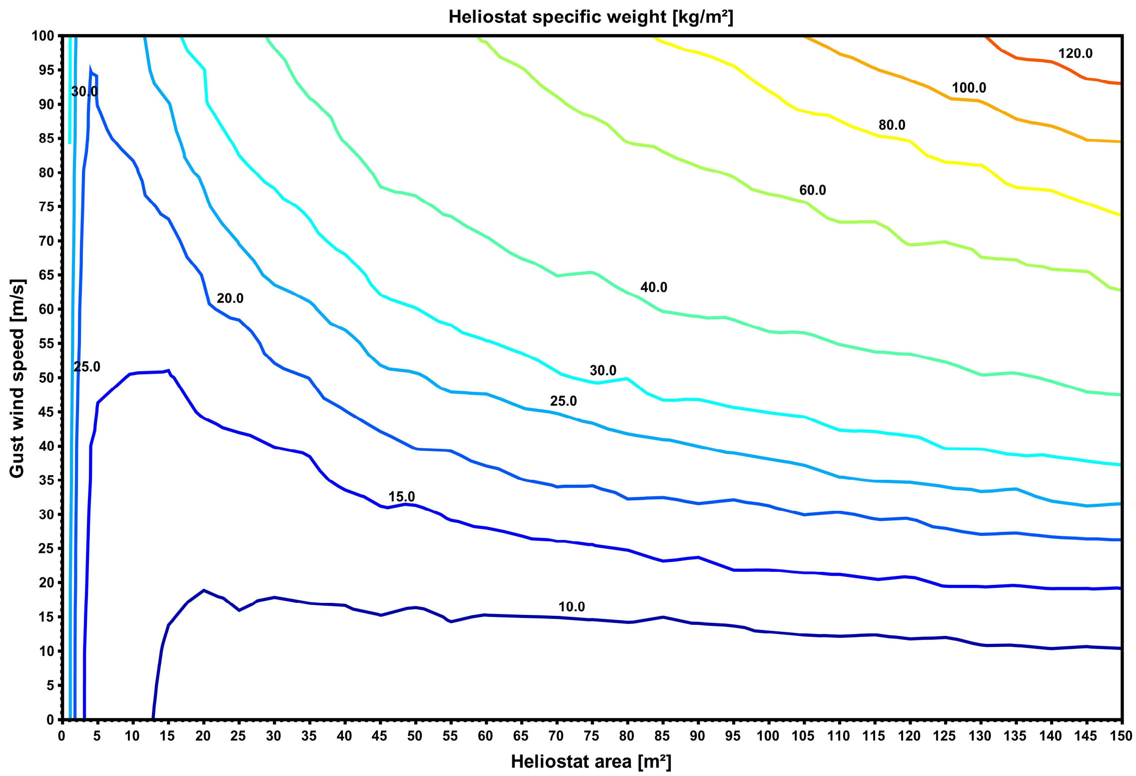
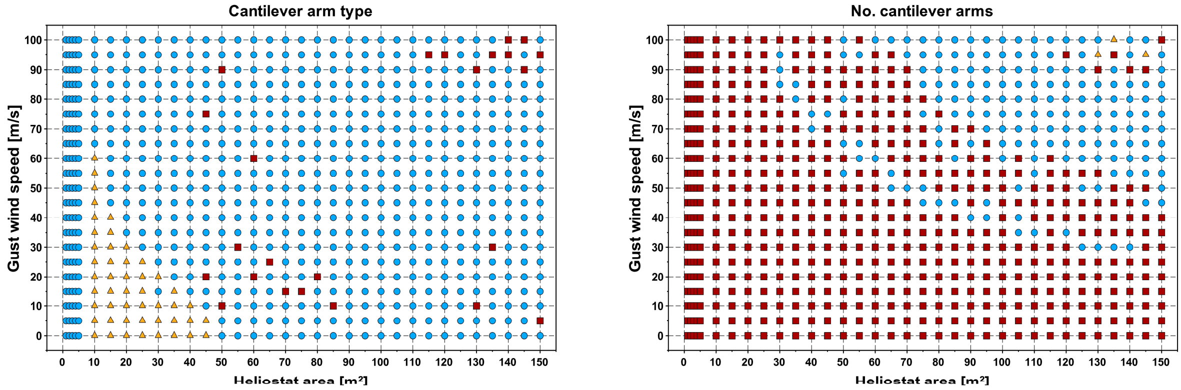


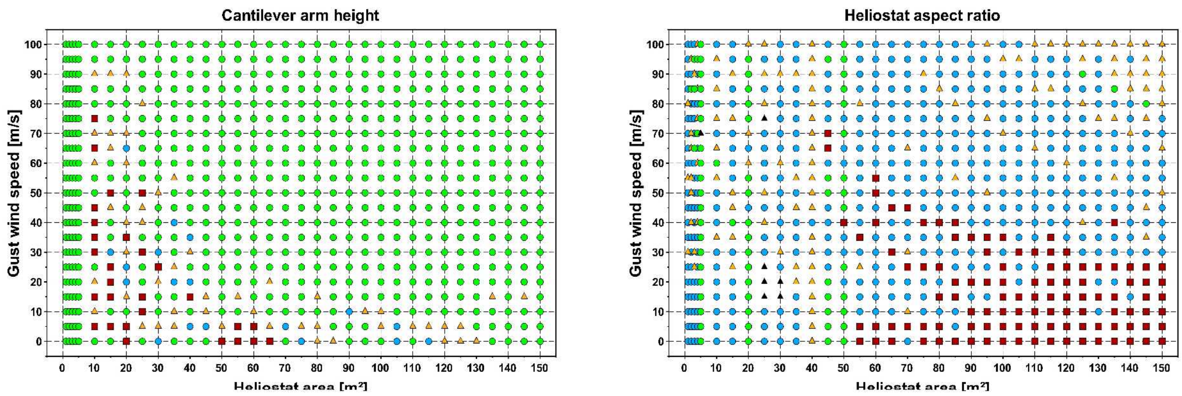
FIGURE 7. Specific weight of the heliostat in [kg/m²] as a function of gust wind speed [m/s] and heliostat area [m²]

Incremental parameter



(a) ■ - Type 1; ● - Type 2; ▲ - Type 3 (b) ■ - 2; ● - 4; ▲ - 6

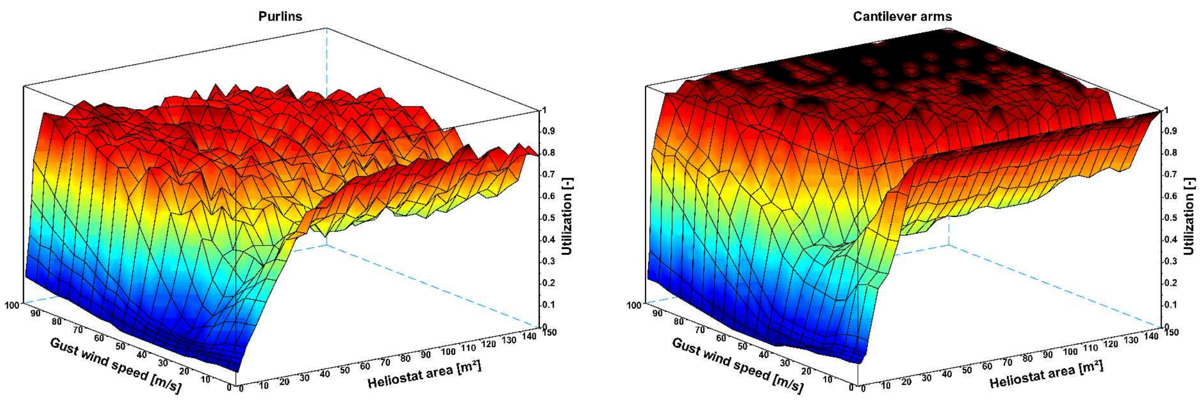
FIGURE 8. (a) Cantilever arm type; (b) Number of cantilever arms.



(a) ■ - (1/12); ● - (1/10); ▲ - (1/8); ● - (1/6) (b) ■ - 0.5; ● - 1.0; ▲ - 1.2; ● - 1.5; ▲ - 2.0

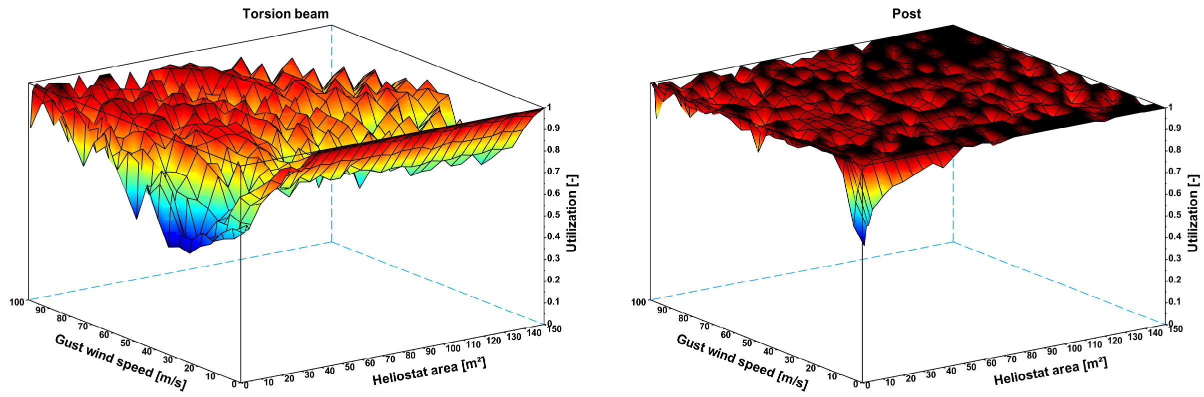
FIGURE 9. (a) Cantilever arm height as a function of the half height of the heliostat; (b) Heliostat aspect ratio.

Structural member maximal utilization



(a) (b)

FIGURE 10. Purlin utilization: 62.4%; (b) Cantilever arm utilization: 79.3%.



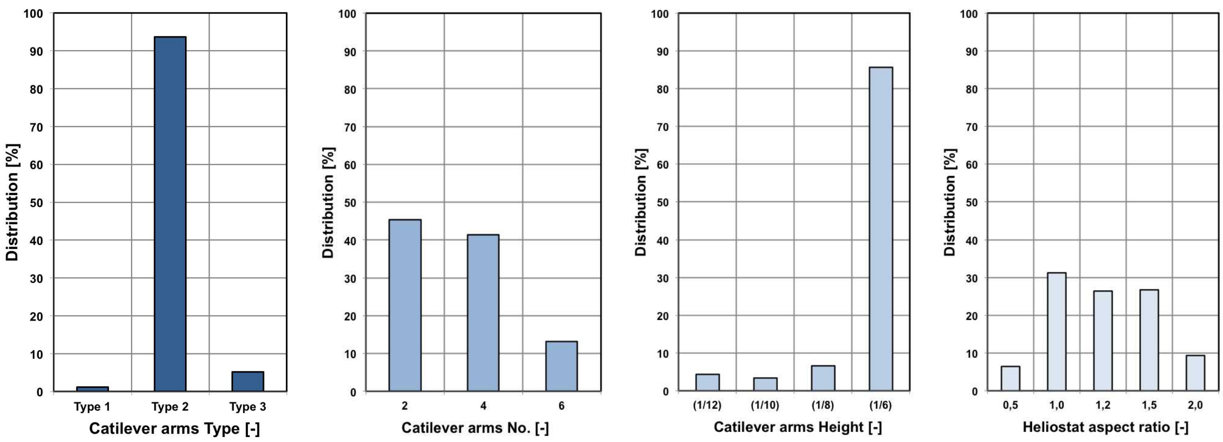
(a) (b)

FIGURE 11. (a) Torsion beam utilization: mean = 84.5%; (b) Post utilization: mean = 97.9%

CONCLUSIONS AND OUTLOOK

In operational mode the post has a mean utilization of 98.4%. The utilization for the purlins, for the cantilever arms and the torsion beam is between 67.0 % and 78.0 %. The purlins and the cantilever arms indicate a utilization drop for the heliostats with a surface area less then 5 m^2. The purlins and the torsion beam achieve their maximum utilization for wind speeds less than 15 m/s. Similar relations are observed also in the results for the survival mode. It has to be pointed that the cantilever arms reach their maximum utilization for wind speeds higher then 25 m/s and heliostat area greater then 15 m^2 and the torsion beam utilization raises from 71.4 % to 84.5 %. The lower utilization for both modes is due to the fact that the used EN 10210 does not contain rectangular and square cross sections with wall thickness thinner than 2.6 mm. Wall thicknesses from 0.8 mm to 1.6 mm, which are common for solar application, are not part of this standard. Using this type of cross sections will noticeably increase the mean utilization and decrease the weight for the single members.

The following figures are summarizing, separately for both operation modes, the percentage distribution of the investigated parameters.



(a) (b) (c) (d)

FIGURE 12. Distribution of the incremental changed parameter- Operational mode: (a) Cantilever arms type, (b) Number of cantilever arms, (c) Cantilever arm height, (d) Heliostat aspect ratio

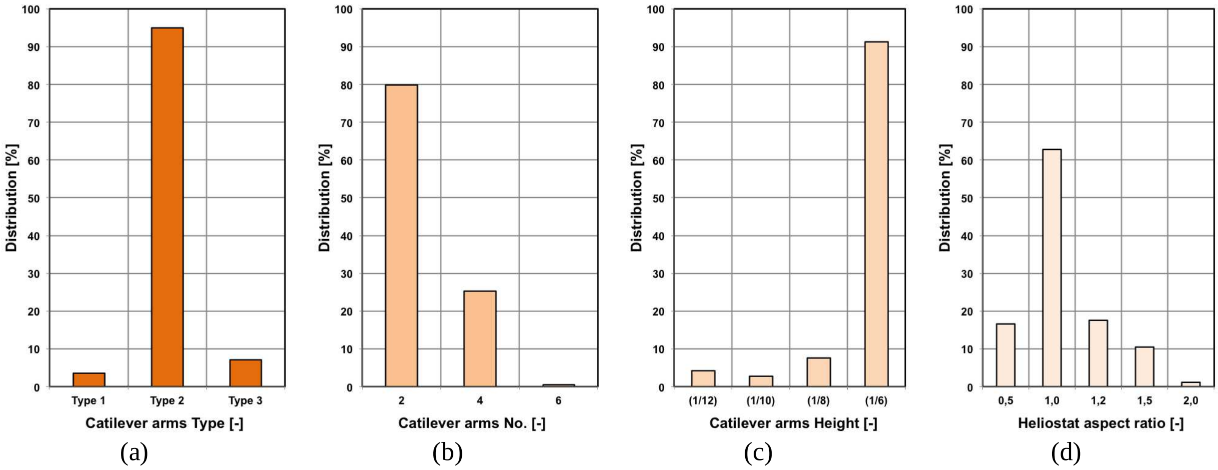


FIGURE 13. Distribution of the incremental changed parameter - Survival mode: (a) Cantilever arms type, (b) Number of cantilever arms, (c) Cantilever arm height, (d) Heliostat aspect ratio

If we try to find out a "cook recipe" for the perfect heliostat fitting to all given geometrical and environmental boundary conditions, then the heliostat for the operational mode will have two or four arms (Fig. 12b) of Type 2 (Fig. 12a) with a cantilever arm height of (1/6) of the half height of the heliostat (Fig. 12c). The aspect ratio will be spread between 1.0 and 1.5. In contrast to the operational mode, the optimized heliostat in the survival mode will be clearly defined with only two cantilever arms (Fig. 13a) and the aspect ratio will be fixed 1.0 (Fig. 13d).

Further work should investigations the effect of hollow sections with thinner wall thickness.

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REFERENCES

1. Zlatanov, H. and Bogdanov, D. (2014): Design optimization of PVPP with solar trackers, SIELA 2014, Bourgas, Bulgaria.
2. Peterka, J. A. and Derickson, R. G. (1992): Wind load design methods for ground based heliostats and parabolic dish collectors, Report SAND92-7009, Sandia National Laboratories, Springfield, USA.
3. Pfahl, Andreas et al. (2011): Determination of wind loads on heliostats, Proceedings SolarPACES 2011 Granada, SolarPACES conference 2011, 20.-23. Sept. 2011, Granada, Spain.
4. Heliomasters - HM Tracker Design, http://www.heliomasters.com
5. HM Tracker Design, https://itunes.apple.com/de/app/hm-tracker-design/id530290614
6. EN 1990:2010-12 - Basis of Structural Design
7. EN 1993-1-1:2010-12 - Design of steel structures
8. EN 10210:2006-07 - Hot finished structural hollow sections of non alloy and fine grain steels