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CSP and PV Solar Tracker Optimization Tool

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Abstract

The support structure of CPV and PV trackers and heliostats are one of the most important cost elements of a solar plant because they typically contribute of ~20% - ~30% to the total cost of the system. Consequently, it is important to reduce the cost of solar trackers or heliostats as much as possible to improve the economic viability of a solar plant.

In this paper, a new method is presented for optimizing trackers with arbitrary design and geometry. It is based on linear optimization and implemented as a custom-built finite element library, developed by the author. The user can choose from a set of configurable tracker geometries, which is extensible by arbitrary tracker geometries defined using a text file, and let the software optimize the amount of steel required for the support structure. Stress and buckling (lateral and local) validations are performed in conformity to Eurocode EN 1993-1-1 - Design of steel structures. Wind load assumptions are taken from the wind tunnel studies of Peterka and Derickson and applied as non uniform load distributions on the tracker surface. Additional national standards can be considered by setting appropriate safety factors for wind and dead load.

In summary, this software represents a powerful tool for optimizing and performing a preliminary design of CSP and PV structures with the potential to reduce developing times significantly. The results of the performed investigation could be used to determine the specific weight of a tracker in kg/m² as a function of the wind speed and tracker area with respect of the tracker aspect ratio.

Keywords: Heliostat; Wind load; Aspect ratio; Design; PV; CPV; Tracker; Optimization; Eurocode; CSP; FEM

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1. Introduction

In recent years, due to climate change and the global energy crisis the interest in renewable energy sources has been steadily increasing. Concentrated solar power systems, heliostats and solar trackers in general are continuously tracking the sun during the day in order to maximize the amount of collected energy. One of the most important cost factors of a solar tracker is the amount of material used for the support structure. In comparison to other cost factors the choice of geometry and design of the support structure offers significant potential for optimization.

For a shell or solid models the preferred design method is topological optimization. Nowadays, the preliminary design is made on the basis of simplified models using beams and/or trusses. After recognizing the main critical points detailed shell or solid models are made and investigated separately or embedded in the global structure. Using a simplified beam structure, linear programming is a way to achieve the best outcome in a given finite element model considering a list of boundary conditions and trying to minimize an objective function. In our case the objective function is to minimize the weight of a tracker. In this paper, we present a tool for carrying out a preliminary design of a solar tracker through such a linear optimization.

Nomenclature

$v_m(z)$	mean wind velocity at a height z above terrain (m/s)	z	height above ground (m)
v_b	basic wind velocity is 10 minute mean wind velocity with an annual risk of being exceeded of 0.02 (m/s)	z_0	roughness length (m)
$v_p(z)$	peak wind velocity is 3 second gust wind speed at height z above terrain (m/s)	$z_{0,II}$	roughness length for ground category II, $z_{0,II}$ = 0.05 (m)
		K	mode shape factor, K = 0.2(–)
c_r	roughness factor (–)	I_v	turbulence intensity (–)
c_{prob}	probability factor for annual exceedence (–)	p	annual exceedance probability (–)
n	exponent of power law, n = 0.5 (–)	r_a	tracker width to height aspect ratio (–)

2. Tool description

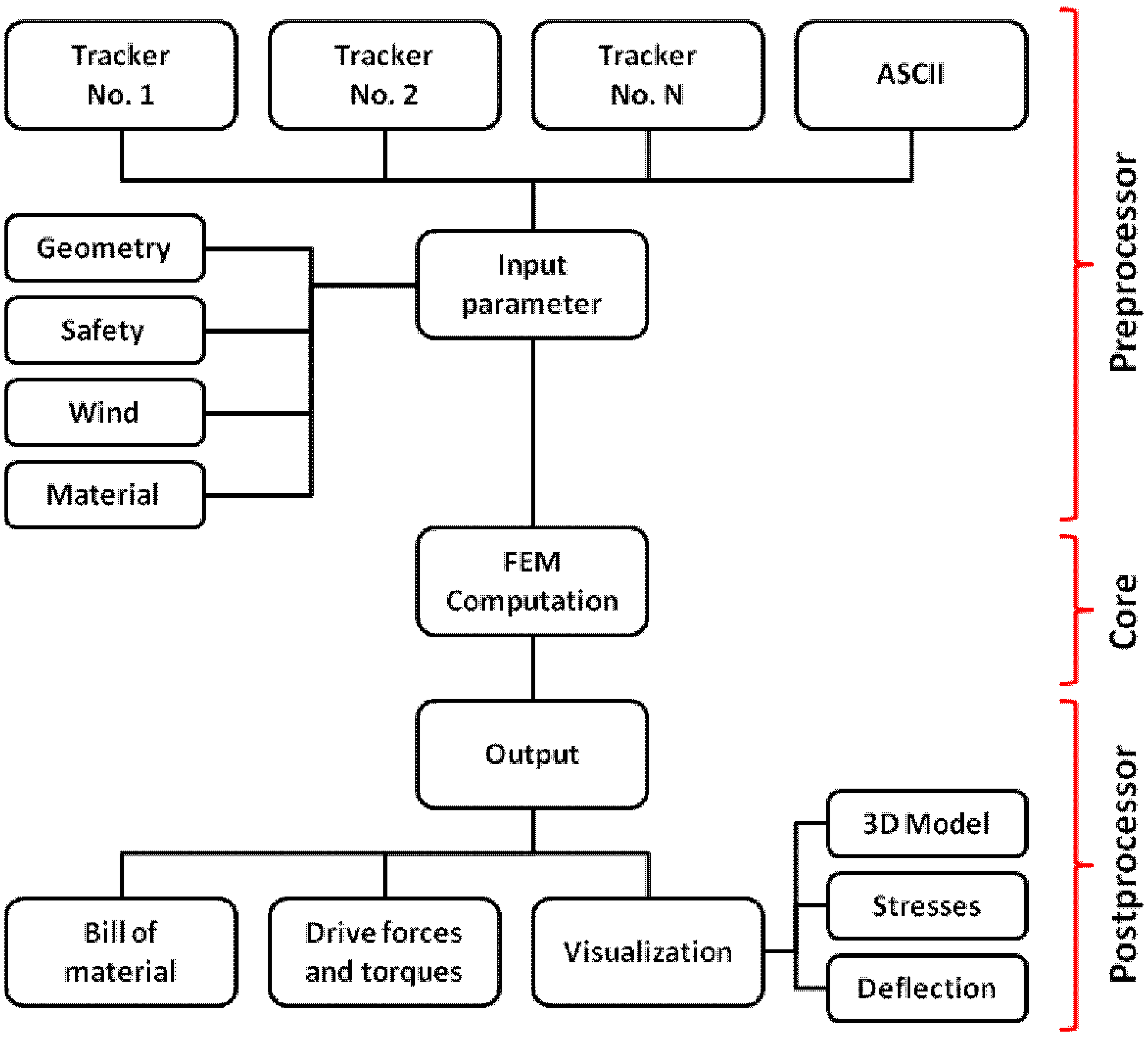

Figure 1: Flowchart describing the internal work flow of the application.

The chart, describing the internal workflow of the software, is divided into three parts:

- Preprocessor: handling all input parameters
  - tracker geometry: width, height, ground clearance
  - safety factors for wind load and dead load
  - wind parameters: wind speed, wind load cases, field factor
  - material related data: steel grade
- Core: implementing the FEM analysis and the optimizations routines
- Postprocessor: result evaluation and stress visualizing

In the following subsections the main parts preprocessor, core and postprocessor are described in more detail.

2.1. *Preprocessor*

The preprocessor is the part of the software where the input parameter: safety factors, wind loads and geometry are specified. It is also the place where the user has to select a certain tracker from No. 1 to No. N. At this stage the tool has only one implemented default tracker which can be selected.

According to the country specific building code safety factors for dead and wind load have to be specified. The default values represent the safety factors in conformity to Eurocode EN 1990 - Basis of structural design [5]. It is also possible to set one of the safety factors to unity and to analyze the impact of the other one only.

For the structural design the relevant wind velocity is defined as a 3-second-gust speed at 10 m above ground, that is exceeded on average only once in 50 years. A wind profile according to terrain category II (area with low vegetation) is used to determine the wind speed at the height of the center of the tracker module area (see eq. 1):

$$v_m(z) = c_r(z) \cdot c_{prob} \cdot v_b \tag{1}$$

$$c_r(z) = 0.19 \cdot \left(\frac{z_0}{z_{0,II}} \right)^{0.07} \cdot \ln\left(\frac{z}{z_0} \right) \cdot v_b \tag{2}$$

The life time of the structure was considered to be 20 years and according to Eurocode 1991-1-4 - General actions on structures - Wind actions [6] the following probability factor is considered:

$$c_{prob} = \left[\frac{1 - K \cdot \ln(-\ln \cdot (1-p))}{1 - K \cdot \ln(-\ln(0.98))} \right]^n \tag{3}$$

The calculation of the wind forces and moments acting on the tracker are based on the wind tunnel testing of Peterka and Derickson [1]. The investigated heliostats are nearly square in shape and the influence of the aspect ratio is not known from the evaluated and documented in [1]. Therefore, an additional aspect ratio factor presented in the work of Pfahl [2] was considered in the calculation of the wind loading. In [1] the peak loads are determined by multiplying the mean wind speed with the non-dimensional drag force / moment peak coefficients. The conversion from gust to mean wind speed is accomplished using equations (4) and (5).

$$v_b(z) = \frac{v_p(z)}{\left[1 + 7 \cdot I_v(z)\right]^{\frac{1}{2}}} \tag{4}$$

$$I_v(z) = \ln\left(\frac{z}{z_0}\right)^{-1} \tag{5}$$

The field factor allows to consider the influence on wind loading if solar trackers are placed in an array. Depending on the field density, external fences and position of the tracker in the field a multiplying factor could be determined using the Generalized Blockage Area (GBA) method described from Peterka and Derickson in [1].

The load cases to be analyzed are defined in the form represented in Figure 2. Tracker elevations and wind directions are specified by the user.

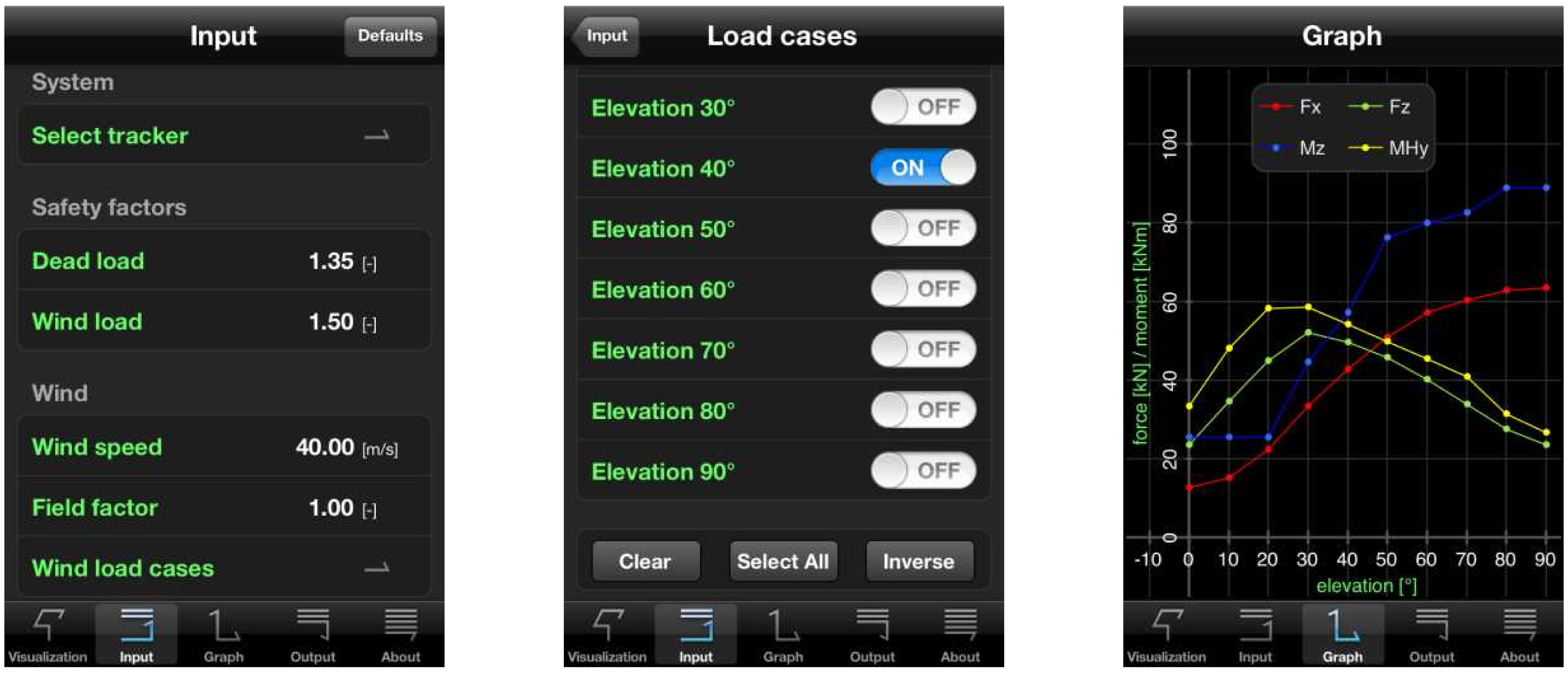

Figure 2: (left) Input form provided for tracker parameterization on the, (center) Specification of a reduced set of relevant elevation positions and wind directions for faster computation times, (right) Visualization of forces and moments acting on the tracker,

Further the width and height dimensions of the tracker are specified. The ground clearance is the distance of the reflector rim to the ground at elevation 90° (sunrise position).

The weight of all modules is calculated from the tracker area and the specific module weight. For the tracker design the user has the possibility to choose from three different steel grades with the following yield stresses: 235 N/mm², 275 N/mm², 355 N/mm².

2.2. *Core*

The analysis is carried out in the finite element core developed by the author. The FEM library is verified trough a comparative calculation using Sofistik [9]. Stress and lateral buckling calculations, which are imbedded into the library, were proven trough an analytical approaches. The core is implemented as a C++ light-weight library, developed to suit the hardware and software capabilities of modern mobile devices and stand alone desktop machines. The few implemented finite elements (truss, beams and multi freedom constraints) provide great versatility allowing to perform structural analysis beyond the field of solar trackers.

Beside the stress and displacements calculations a lateral buckling analysis is performed for all members of the tracker according to EN 1993-1-1 - Design of steel structures [7]. Cross section classification according to Eurocode was used to avoid local buckling failure meaning that the class 4 cross sections were not considered. The core interface makes it possible to use not only cross section given in EN 10210 - Hot finished structural hollow sections [8] but also any kind of cross section library.

The two steps optimization procedure is run first with assumed cross sections. With the results a proper cross section is selected for all members and in a second step the results are verificated again.

The effects of vibrations, acting perpendicular to the wind direction, induced by vortex shedding are not part of the FEM library.

2.3. *Postprocessor*

The graph tab as depicted in Figure 2c is the place where all forces and moments acting on the tracker are visualized. These values can be used to dimension the tracker's elevation and azimuth drives.

The bill of material (see screenshot in Figure 3b) summarizes the amount of required steel and distinguishes between five different structural elements: purlins, purlin support beams, cross beams, torsion beam and the post. For every structural element the optimized cross section and the total weight are listed.

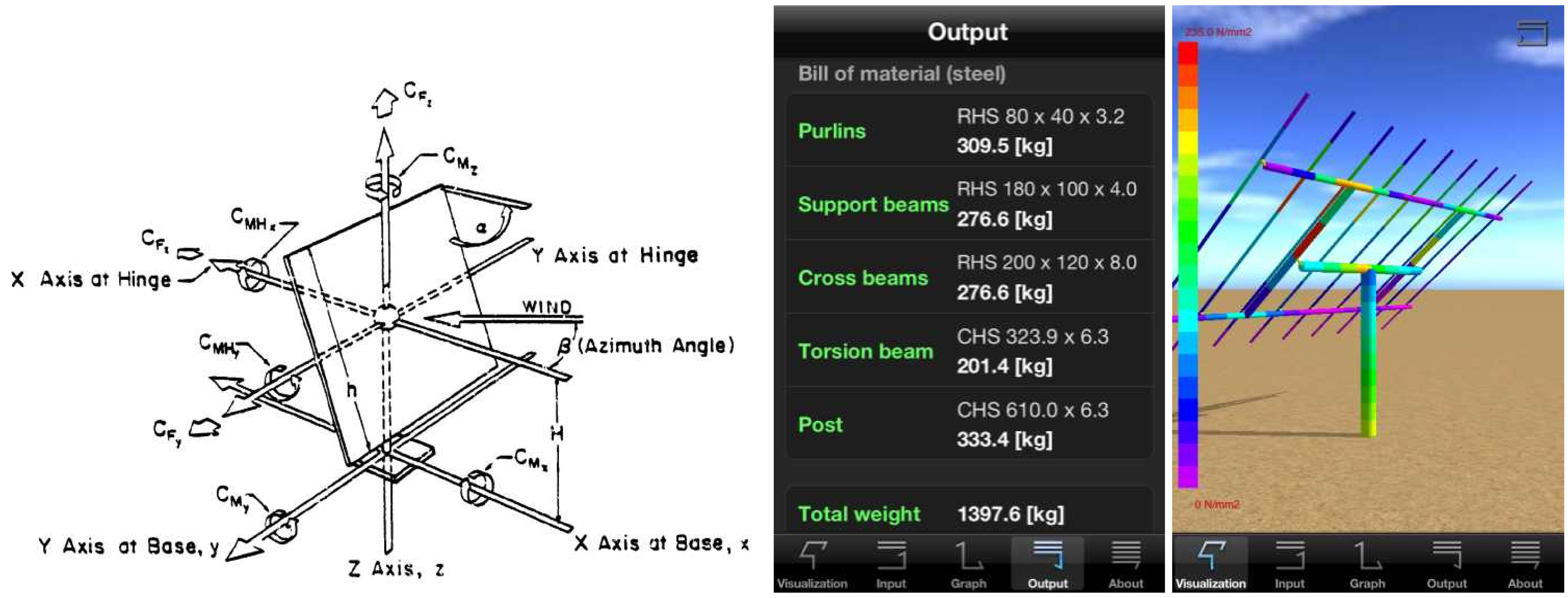

Figure 3: (a) Definition of the used coordinate system based on [1] for uniformity reasons (b) Bill of material, (c) Tracker 3d visualization

3. Definition of the case study

To demonstrate how the tool can be used in practice the developed finite element library was used to perform a linear optimization of a specific solar tracker in order to minimize the steel weight of the tracker.

In the following, the geometry of the tracker, area size and the relation between single members was parameterized in a way which allows to change the entire geometry with the single change of the two variables: width and height. The latter are directly dependent on the area and on the tracker aspect ratio. Some parameters like tracker height above ground and the distance between the purlins are set to default values and not changed during the entire study.

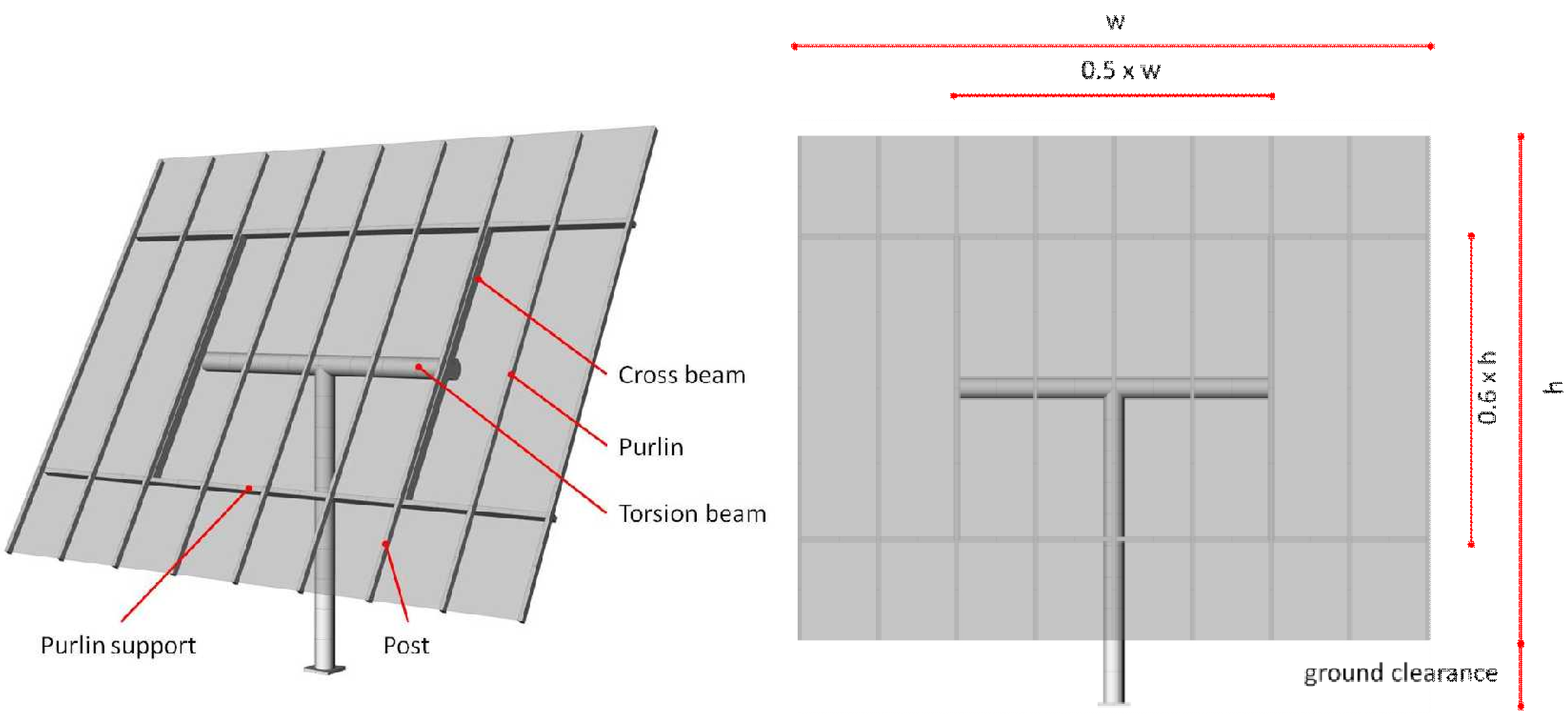

Figure 4: (a) Tracker structure elements, (b) Parameterization

- Tracker height above ground: 0.50 m
- Maximum distance between purlins: ⩽ 1.0 m

Figure 4 shows the dependencies between the structural elements of the tracker. The length of the cross beam and the distance between the support beams were fixed to specific values based on a separate investigation not further mentioned here. The distance between the purlin support beams was fixed to 60 % of the height of the tracker and the cross beams to 50 % of its width.

For convenience and fast result evaluation the FEM library, discussed in the previous section, was compiled to a stand alone desktop tool which was run with the following parameters.

- tracker aspect ratio [-]: 0.5, 1.0, 1.2, 1.5, 2.0
- tracker area [m²]: 1, 5, 10, 15, 20, 25, 30 to 150 in 5 m² steps
- wind speed [m/s]: 0, 5, 10, 15, 20, 25, 30 to 100 in 5 m/s steps

Additionally, two operation modes were investigated: go to stow and stow position. The stow position is intended to be the one with the smallest impact due to the wind loading. For most trackers including the one used in this investigation elevation 0° is chosen to be the stow position. For each mode the analyzed elevations positions and wind directions are enumerated in the following:

Go to stow
- elevation [°] : 0 to 90 in 5° steps
- wind direction [°] : 0 to 180 in 15° steps

Stow position:
- elevation [°] : 0
- wind direction [°] : 0 to 180 in 15° steps

Load combination and design code was set to EN 1990 - Basic of structural design [5] respectively EN 1993 - Design of steel structures[7]. The steel grade was fixed to S235 in conformity to EN 10210 [8].

4. Results and discussion

The results are evaluated separately for both operation modes. The weight of the tracker is plotted in contour charts for each aspect ratio. The blank area in the upper right corner is empty as respective trackers are not feasible due to exceeded allowable stresses or lateral buckling. In some cases, changing the steel grade of a single member can turn a previously unfeasible tracker into a feasible one.

It can be observed that the wind loads vary significantly with the aspect ratio of the tracker. Trackers with a large aspect ratio are lighter than trackers with smaller one at fixed area and wind speed. It should be underlined, that this investigation only considers only the amount of steel used.

The following figures show the specific mass of the tracker in kg/m² as a function of wind speed and tracker area for selected aspect ratio

4.1. *Operation mode: Go to Stow*

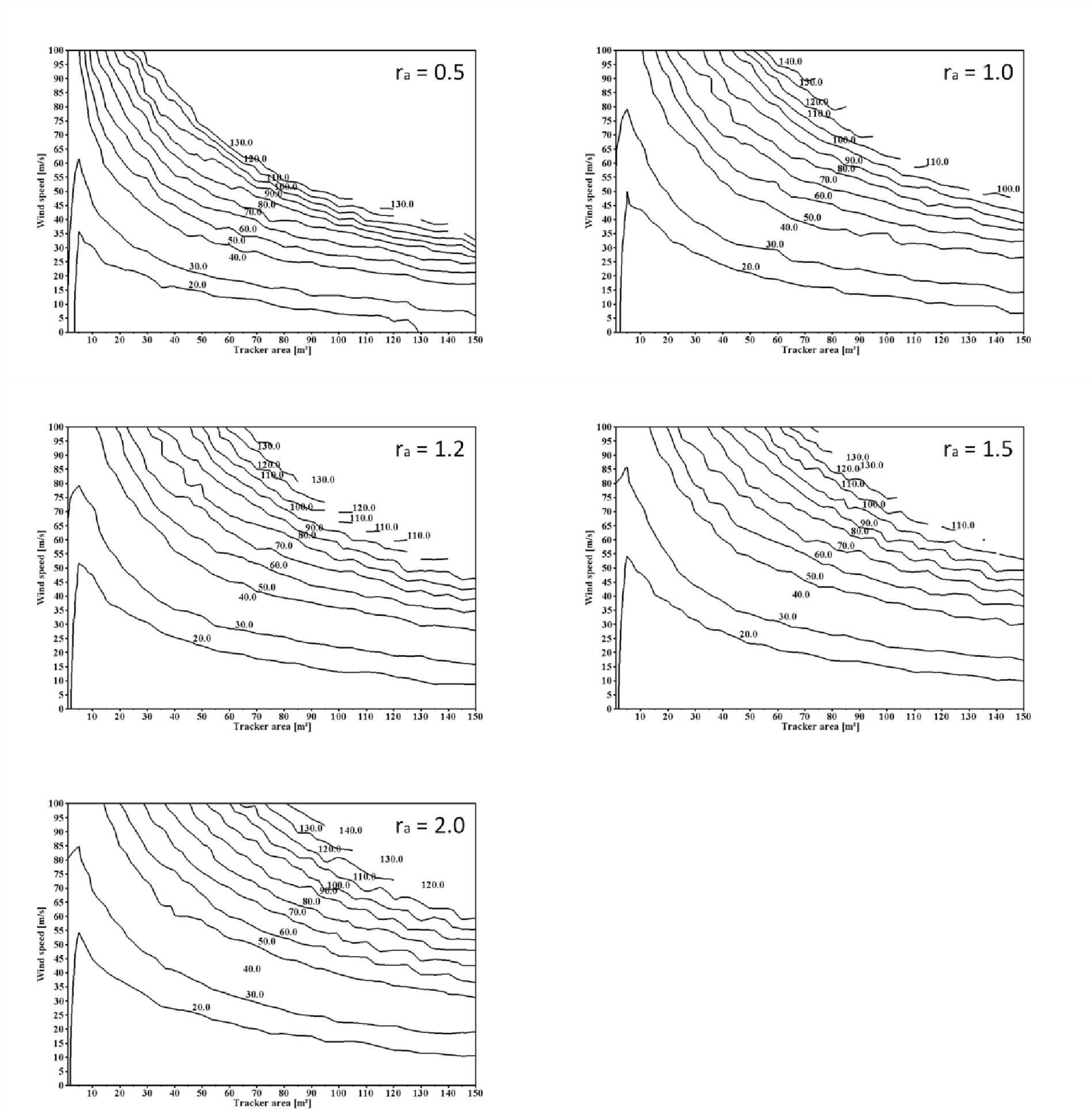

Figure 5: Specific mass of tracker in kg/m² as a function of wind speed and tracker area for selected aspect ratio

4.2. *Operation mode: Stow*

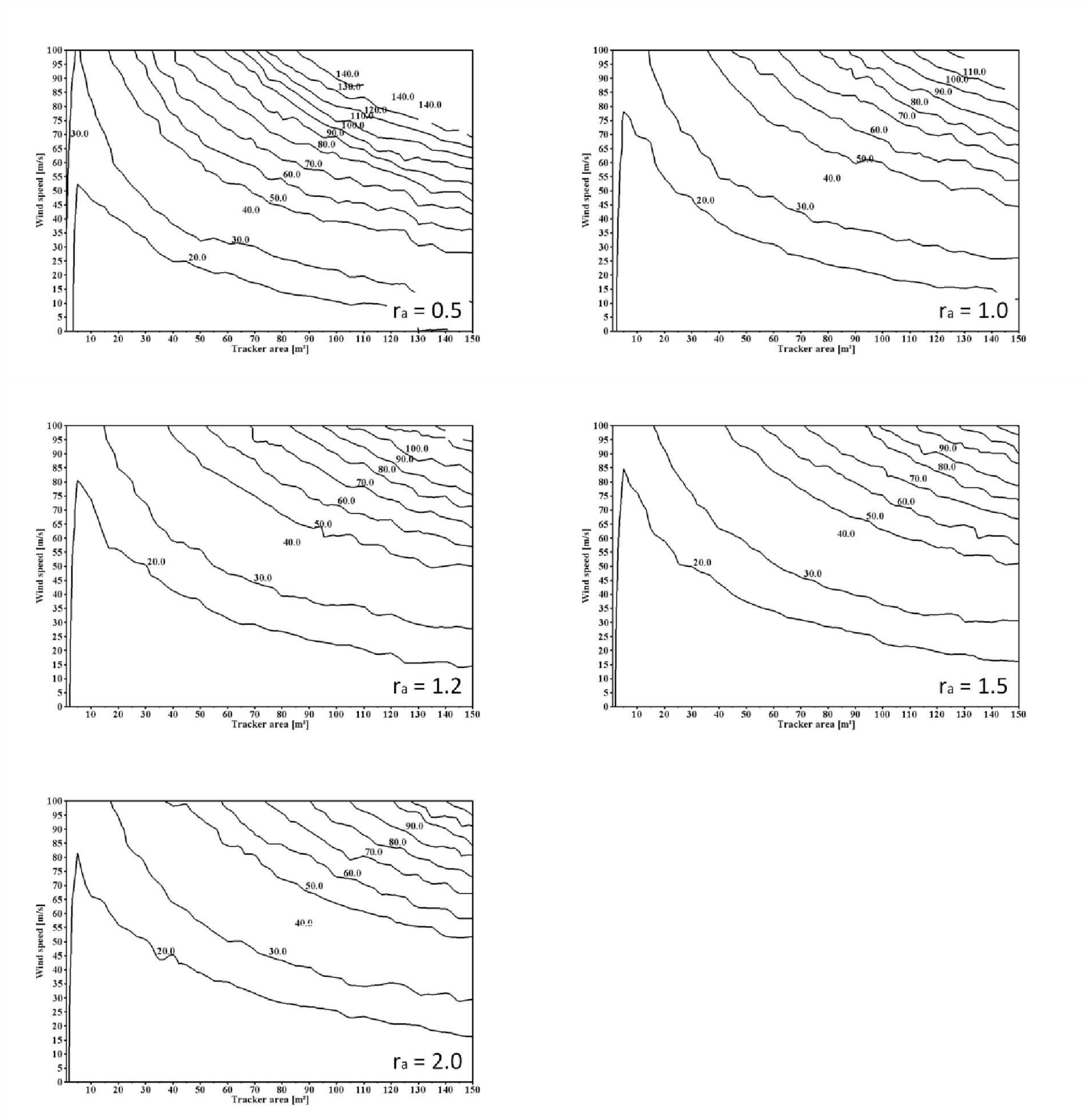

Figure 6: Specific mass of tracker in kg/m² as a function of wind speed and tracker area for selected aspect ratio

4.3. *Isometric representation of the results*

The isometric representation emphasize the difference between the single aspect ratio $r_a = 0.5$ and $r_a = 2.0$ for the different operation modes.

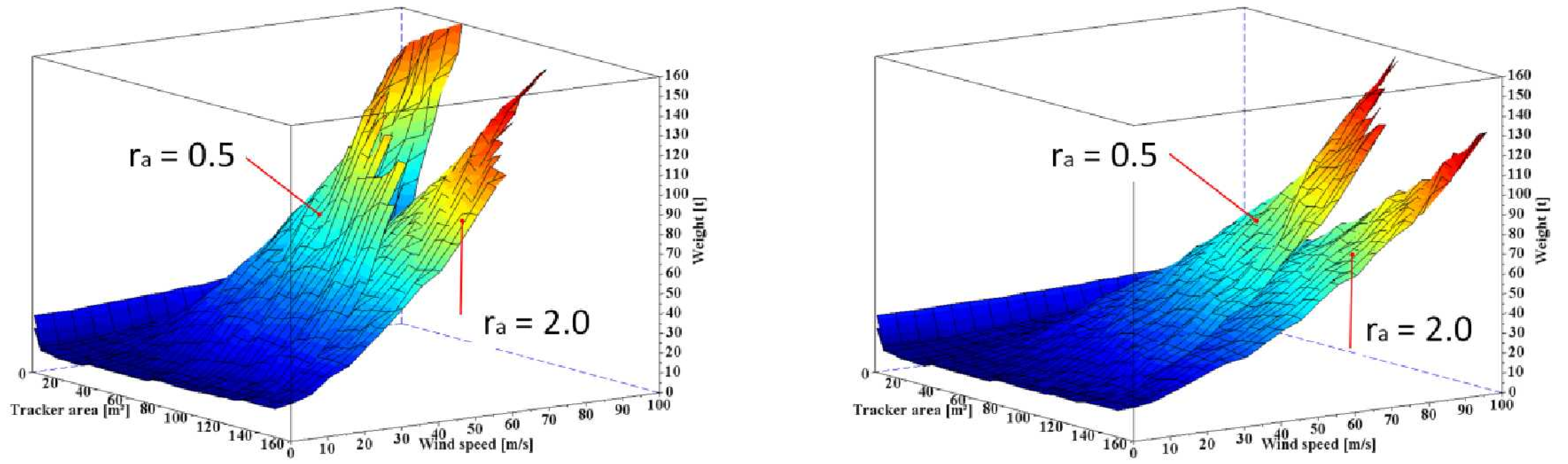

Figure 7: (left) Operation mode: Go to Stow, (right) Operation mode: Stow

5. Conclusion and outlook

Results of public available wind tunnel tests have been combined with an FEM library and a set of PV tracker to create a software tool that allows quick and user friendly preliminary design and optimization of the investigated structure. For a final design additional wind tunnel testing should be performed in order to reduce the amount of steel for the support structure even more. Seismic analysis and the effect of temperature load has to be consider in a extended detail design. Techno-economical approach will require additional investigations of optical quality, deflection and costs to determine the lowest levelized cost of energy (LCOE). Our intention is to create a data base of heliostats, CPV and PV trackers that will allow end users to choose an economic system for their site under considering the local environmental conditions and country codes.

Acknowledgments

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