Calibration of partial factors for actions in the Eurocodes accounting for biases in climatic load maps

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ABSTRACT: In view of the development of the 2nd generation of structural Eurocodes, a discussion on standard optimization by means of the calibration of partial factors for actions is currently ongoing. In the paper, the calibration of partial factors for permanent and variable loads is discussed, with a specific focus on the role of hidden safeties, which are generally introduced in the design according to the National Annexes to the Eurocodes when dealing with climatic actions. A procedure to account for a safe-sided bias in snow and wind maps, which is found relevant for several countries in Europe, is presented. The influence of the detected biases in the evaluation of reliability levels and the calibration of partial factors is thus investigated with reference to a portfolio of representative structures and limit states, including six different materials and mechanical properties governing the design resistance (structural steel yield strength, concrete compressive strength, re-bar yield strength, glulam timber bending strength, solid timber bending strength, and masonry compressive strength). The results confirm the importance to properly account for such safe-sided assumptions in the calibration process, following a consistent approach with the definition of climatic load maps at national level.

1. INTRODUCTION

In the development of the 2nd generation of structural Eurocodes (CEN, 2013), a discussion on standard optimization by means of the calibration of partial factors on actions is currently ongoing. An *ad-hoc-group* in charge of preparing a JRC Science and Policy Report on "Reliability Background in the Eurocodes" was established in 2019 within the Sub-Committee 10 of CEN/TC250, responsible for the evolution of the Eurocode EN1990 "Basis of Structural and Geotechnical design". After a three-year work, the final draft of the report is now under review for publication (Vrouwenvelder et al., 2022).

Calibration of partial factors is a complex task, that requires accounting for the uncertainties associated with the actions, their stochastic models and their combination, structural models, mechanical properties of different materials, as well as resistance modeling of a wide class of structural elements, duly considering the relevant failure modes, representing as closely as possible the built environment.

Partial factors in the first generation of the Eurocodes (2007) were mainly calibrated based on past experience and have proven satisfactory performance; in the recent years the development of numerical integration approaches significantly increased the implementation of higher-level reliability methods, making it possible deeper investigations. Examples of calibration procedures are described in (Ellingwood et al., 1980) (Sorensen et al., 1994) (Köhler et al., 2019) (Nadolski et al., 2019), and informative guidance is being included as an annex to the second generation of the Eurocodes' head code "Basis of Structural and Geotechnical Design" prEN1990:2022 (CEN, 2022). This guidance forms the basis for the calibration procedure implemented and discussed in the present paper.

The results of code optimization procedures often suggest an increase of partial factors for climate-related loads, such as wind and snow, together with a reduction of partial factors for permanent loads (Köhler et al., 2019). In the reliability computations this tendency is numerically motivated by the higher variability of climatic actions with respect to the permanent loads. However, the safe-sided assumptions, also referred to as "*hidden safety*" (Teichgräber et al., 2022) or biases, which are generally introduced in the Eurocodes and in their implementation at national level to approximate real climatic loads as a means to indirectly cover a part of the epistemic uncertainties affecting their definition, are often neglected in the reliability computations, leading to an underestimation of the reliability levels of structures designed according to the Eurocodes. This aspect was already discussed in (Croce et al., 2019) concerning the definition of snow load maps in Europe and plays a significant role in the calibration process as it will be shown in this study.

In the paper, a procedure for the calibration of partial factors for actions, duly considering the role of biases in snow and wind maps, is presented. The proposed methodology is discussed with reference to a portfolio of representative structures and related limit states reflecting the current European construction market. Optimization functions for the investigated partial factors are presented highlighting the role of biases in climatic actions with respect to the unbiased situations. Finally, conclusions are drawn with reference to the current set of partial factors on actions recommended in the Eurocodes, which are, in any case, to be defined at national level. The results of this study are also intended to assist National Standard Bodies in this task.

2. BIAS IN CLIMATIC LOAD MAPS

Characteristic values of climatic actions given in the National Annexes to the relevant Eurocode parts, generally provide conservative estimates if compared to the results of local extreme value analysis of measured data (Croce et al., 2019), (Teichgräber et al., 2022).

A bias, b_{Q_j}, can be defined as the ratio between the characteristic value of the action derived from the statistical analysis of high-quality data collected by national Meteorological Offices and those given by the relevant National Annex.

Estimation of biases in ground snow load and wind pressure maps was carried out by the authors for several European countries in (Formichi et al., 2023).

In the following computations, we refer to Germany, where a mean value of 0.71 and a coefficient of variation of 0.17 were obtained for the bias on ground snow loads, while a mean value of 0.83 and a coefficient of variation of 0.27 were derived for the bias on wind velocity pressure.

3. PARTIAL FACTOR CALIBRATION

The calibration approach followed in the study is consistent with the provisions given in the informative Annex C of prEN1990:2022 (CEN, 2022) and can be summarized by the following steps:

- Definition of a portfolio of structural elements representative of the most common structural materials and limit states, weighted according to their estimated relative frequency w_i. In this study a portfolio of six different materials and mechanical properties governing the design resistance (structural steel yield strength, concrete compressive strength, rebar yield strength, glulam timber bending strength, solid timber bending strength, and masonry compressive strength) is investigated as in (Köhler et al., 2019). The weights for the six material properties are derived analyzing data of the European Construction Sector collected in the PRODuction COMmunautaire (PRODCOM) dataset. Average values for EU27 in 2019 show that concrete is still the most frequently used material (relative production's percentage around 58%), followed by structural steel (27%), timber

(10%), and masonry (5%). The weights for the six material properties are thus derived according to the average values at European scale and are listed in Table 1.

Table 1: Investigated portfolio and relative weights.

N.	*Material and Limit state*	$w_{R,i}$
1	*Structural steel yielding strength (bending)*	*27 %*
2	*Concrete compressive strength*	*10 % (*)*
3	*Rebar yield strength (bending)*	*48 % (*)*
4	*Glulam timber (bending)*	*7 % (**)*
5	*Solid timber (bending)*	*3 % (**)*
6	*Masonry compressive strength*	*5 %*

(*) The subdivision of the failure mechanisms of r.c. members is done considering the prevailing modern design requests in terms of ductility of r.c. sections
(**) The relative weight of glulam timber is chosen to reflect the prevailing current use of this material in new structures.

- Definition of the target reliability index β_t for the selected reference period. In reliability-based calibration process, target reliability is set by the National Standardization Bodies (NSBs), that are responsible, in each CEN country, for the definition of safety levels for civil engineering structures during their whole design service life. In this study, we refer to CC2, the "Normal" consequence class, to which belong most of the structures designed according to the Eurocodes; reference is thus made to a target reliability index β_t=3.8 for the 50-years reference period as recommended in prEN1990:2022 (CEN, 2022).
- Definition of the reliability elements to be calibrated within a sufficiently wide variability range for the optimization purposes. This study is focused on partial factors on actions, while partial factors on resistances are kept unchanged from the default values in the Eurocodes. More in detail, a four-dimensional grid (N_1xN_2xN_3xN_4) is defined to cover the selected range of variability of partial factors on permanent loads γ_G = 1.1-1.35, snow loads γ_S = 1.5-3, wind actions γ_W =1.5-2.5 and imposed loads γ_Q= 1.5-2.
- Design of the *i*-th structural member in the portfolio according to the selected set of reliability elements ($\gamma_{G,hjlm}$, $\gamma_{S,hjlm}$, $\gamma_{W,hjlm}$, $\gamma_{Q,hjlm}$), where h =1,…, N_1, j =1,…, N_2, l =1,…, N_3, m =1,…, N_4. For the *i*-th structural member three different designs are analyzed, combining permanent loads in turn with snow, wind and imposed loads, using the pertinent partial factors in the set γ_{hjlm}.
  For each load combination the analysis is extended to consider the effects of the variation of the different proportions between permanent and self-weight (a_G=1.0 for self-weight only) and variable and permanent loads (a_Q=1.0 for variable loads only). The range of variation $a_G = 0.6 - 1$ is considered as in (Köhler et al., 2019) and (Teichgräber et al., 2022), while for a_Q values, ranges and associated weights are defined according to load ratios Q_k/G_k reported in (Ellingwood et al., 1980). Load ratios are converted in a_Q values according to the relationships given in (Vrouwenvelder et al., 2022). For snow loads, $a_Q \cong \chi = \frac{Q_k}{(G_k+Q_k)}$, while for wind and imposed load $a_Q \cong \frac{\chi}{1,4-0,4\chi}$. The resulting a_Q values and the associated weights are reported in Table 2, 3 and 4 for snow, wind and imposed load respectively.
  The design of the *i*-th structural member is carried out adopting expression [8.12] in prEN1990:2022 (former expression [6.10] in EN1990:2002) for load combination

$$p_{ij} = \frac{\gamma_{R,i}}{r_{k,i}}\left[\left(1-a_Q\right)\gamma_G\left\{a_G\, g_{Sk} + (1-a_G) g_{Pk}\right\} + \gamma_Q\, a_Q\, q_{k,j}\right] \quad (1)$$

where $r_{k,i}$, g_{Sk} , g_{Pk} , $q_{k,j}$ are the characteristic values of the resistance, self-weight, permanent load, and variable action j, $\gamma_{R,i}$ is the partial factor for resistance i given by the relevant Eurocode part, which is equal to 1.0 for structural steel yield strength, 1.5 for concrete compressive strength, 1.15 for rebar yield strength, 1.25 for glulam timber bending strength, 1.30 for solid timber bending strength, and 1.5 for masonry compressive strength. As already presented and discussed in (Croce et al., 2022), adoption of alternative expressions [8.13] leads to average lower reliability indexes with respect to [8.12].

The following generic standardized limit state function g is thus adopted in the study for each material i and variable load j

$$g(\mathbf{X}, p_{ij}) = p_{ij}\Theta_{\mathrm{R,i}}R_i - \Theta_{\mathrm{e}}\left\{(1 - a_Q)[a_G G_S + (1 - a_G)G_P] + a_Q \Theta_{Q,j} Q_j\right\} \quad (2)$$

where $\mathbf{X} = (R_i, G_S, G_P, Q_j, \Theta_{\mathrm{R,i}}, \Theta_{\mathrm{e}}, \Theta_{Q,j})$ is the vector of random variables involved in the limit state; R_i, G_S, G_P, and Q_j are the standardized random variables for the resistance, self-weight, permanent load, and variable action, whose mean values are assumed equal to 1, $\Theta_{\mathrm{R,i}}$ represents the model uncertainty for the resistance, Θ_{e} represents the model uncertainty in the calculation of load effects, and $\Theta_{Q,j}$ the load model uncertainty. When the bias, b_{Q_j} in the *j-th* climatic variable action is introduced in design, Eq. (2) becomes:

$$p_{ij} = \frac{\gamma_{R,i}}{r_{k,i}}\left[(1 - a_Q)\gamma_G\left\{a_G\, g_{Sk} + (1 - a_G) g_{Pk}\right\} + \gamma_Q\, a_Q\, \frac{q_{k,j}}{b_{Q,j}}\right] \quad (3)$$

and the limit state function

$$g(\mathbf{X}, p_{ij}) = p_{ij}\Theta_{\mathrm{R,i}}R_i - \Theta_{\mathrm{e}}\left\{(1 - a_Q)[a_G G_S + (1 - a_G)G_P] + a_Q \Theta_{Q,j} Q_j B_{Q_j}\right\} \quad (4)$$

In Eq. (3) the bias is introduced in a deterministic way considering for example the value obtained at a given location or the average value for a specific region, while in Eq. (4) the uncertainty in the bias for different locations in the investigated region is considered by means of the random variable B_{Q_j} .

- Calculation of the reliability index for the designed members under different load combinations, according to the stochastic models for the random variables in the limit state function. The reliability index associated to each element of the four-dimensional grid γ_{hjlm} is evaluated as a weighted average of the three reliability indexes, accounting for the estimated relative frequency of the variable action governing the design.
- Evaluation of the optimization function

$$D(\gamma_{hjlm}) = \sum_i w_i \left(\beta_i(\gamma_{hjlm}) - \beta_t\right)^2 \quad (5)$$

for each grid element and identification of the optimal set of partial factors $\gamma_{opt} = \{\gamma_{G,opt}, \gamma_{S,opt}, \gamma_{W,opt}, \gamma_{Q,opt}\}$, leading to the minimum of the optimization function.

Table 2: a_Q values and weights, snow (S) and permanent (G) actions.

N.	S_k/G_k						
	0.25	*0.50*	*1.00*	*1.50*	*2.00*	*3.00*	*5.00*
	a_Q						
	0.20	*0.33*	*0.50*	*0.60*	*0.67*	*0.75*	*0.83*
1	*0*	*0.10*	*0.20*	*0.25*	*0.35*	*0.07*	*0.03*
2,3	*0.30*	*0.40*	*0.20*	*0.05*	*0.05*	*0*	*0*
4,5	*0*	*0.02*	*0.16*	*0.32*	*0.32*	*0.18*	*0*
6	*0.36*	*0.36*	*0.20*	*0.06*	*0.02*	*0*	*0*

Table 3: a_Q values and weights, wind (W) and permanent (G) actions.

N.	W_k/G_k			
	0.50	*1.00*	*3.00*	*5.00*
	a_Q			
	0.33	*0.50*	*0.75*	*0.83*
1-6	*0.25*	*0.25*	*0.25*	*0.25*

Table 4: a_Q values and weights, imposed (Q) and permanent (G) actions.

N.	Q_k/G_k						
	0.25	*0.50*	*1.00*	*1.50*	*2.00*	*3.00*	*5.00*
	a_Q						
	0.20	*0.33*	*0.50*	*0.60*	*0.67*	*0.75*	*0.83*
1	*0*	*0.10*	*0.20*	*0.25*	*0.35*	*0.07*	*0.03*
2,3	*0.10*	*0.45*	*0.30*	*0.10*	*0.05*	*0*	*0*
4,5	*0*	*0.05*	*0.26*	*0.26*	*0.26*	*0.12*	*0.05*
6	*0.36*	*0.36*	*0.20*	*0.06*	*0.02*	*0*	*0*

4. RESULTS

The probabilistic models adopted for actions, resistances, and model uncertainties involved in the limit state functions, are summarized in Table 5. They reflect the current state-of-art knowledge on the investigated random variables and are consistent with previous works in the field (Köhler et al., 2019) (Vrouwenvelder et al., 2022) (Formichi et al., 2023). However, some modifications are done especially concerning the rebar yielding strength where a lower fractile than 5% is adopted to better simulate actual data on steel production in Europe (European Commission, 2013). In fact, looking for example at the data collected in (European Commission, 2013) for yielding strength of B450C rebars of different diameters used in Italy, the ratio between the characteristic value adopted for design (450 N/mm^2) and the mean value obtained from numerous tests (528 N/mm^2) is about 0.85 thus significantly lower than the 5% fractile (0.93) which is generally adopted in previous studies (Köhler et al., 2019) (Vrouwenvelder et al., 2022).

Table 5: Summary of probabilistic models adopted in the study.

Random variable	***X***	***Distr. type***	**Mean (μ)**	***V***	**Char value *(Fractile)***	***Ref.***
Resistance Modeling						
Steel bending	θ_{R1}	*Logn.*	*1.15*	*0.05*	*1.00*	*(Vrouwenvelder et al., 2022)*
Concrete compression	θ_{R2}	*Logn.*	*0.97*	*0.14*	*1.00*	*(CEN, 2021)*
Concrete bending	θ_{R3}	*Logn.*	*1.03*	*0.07*	*1.00*	*(CEN, 2021)*
Glulam bending	θ_{R4}	*Logn.*	*1.00*	*0.10*	*1.00*	*(JCSS, 2001)*
Solid timber bending	θ_{R5}	*Logn.*	*1.00*	*0.10*	*1.00*	*(JCSS, 2001)*
Masonry	θ_{R6}	*Logn.*	*1.16*	*0.18*	*1.00*	*(Vrouwenvelder et al., 2022)*
Material strenght						
Steel yielding strength	R_1	*Logn.*	*1.00*	*0.05*	*0.83*	*(European Commission, 2013)*
Concrete compr strength	R_2	*Logn.*	*1.00*	*0.10*	*(0.05)*	*(CEN, 2021)*
Rebar yielding strength	R_3	*Logn.*	*1.00*	*0.045*	*0.85*	*(European Commission, 2013)*
Glulam bending strength	R_4	*Logn.*	*1.00*	*0.15*	*(0.05)*	*(JCSS, 2001)*
Solid timber bending strength	R_5	*Logn.*	*1.00*	*0.20*	*(0.05)*	*(JCSS, 2001)*
Masonry compr. strength	R_6	*Logn.*	*1.00*	*0.16*	*(0.05)*	*(Jäger and Pech, 2015)*
Uncertainty load effect calcul.						
Statically indetermiate frames	$\theta_{c.l}$	*Logn.*	*1.00*	*0.10*	*none*	*(Vrouwenvelder et al., 2022)*
Self-weight						
Self-weight (steel)	$G_{s.1}$	*Normal*	*1.00*	*0.025*	*1.00*	*(Vrouwenvelder et al., 2022)*
Self-weight (reinforced concrete)	$G_{s.2}$	*Normal*	*1.00*	*0.05*	*0.98*	*(Vrouwenvelder et al., 2022)*
Self-weight (glulam)	$G_{s.4}$	*Normal*	*1.00*	*0.10*	*0.95*	*(Vrouwenvelder et al., 2022)*
Self-weight (solid timber)	$G_{s.5}$	*Normal*	*1.00*	*0.10*	*0.95*	*(Vrouwenvelder et al., 2022)*
Self-weight (masonry)	$G_{s.6}$	*Normal*	*1.00*	*0.07*	*1.00*	*(Vrouwenvelder et al., 2022)*
Permanent load						
Permanent load	G_P	*Normal*	*1.00*	*0.10*	*0.95*	*(Ellingwood et al., 1980)*
Variable loads						
Wind time-invariant part	θ_{Q1}	*Logn.*	*0.97*	*0.28*	*1.05*	*(Formichi et al., 2023)*
Wind velocity pressure	Q_1	*Gumbel*	*1.00*	*0.16*		*(Formichi et al., 2023)*
Bias in wind velocity pressure	B_{Q1}	*Logn.*	*0.83*	*0.27*	*0.83*	*(Formichi et al., 2023)*
Snow time-invariant part	θ_{Q2}	*Logn.*	*0.81*	*0.26*	*0,80*	*(Formichi et al., 2023)*
Snow load on ground	Q_2	*Gumbel*	*1.00*	*0.22*		*(Croce et al., 2021)*
Bias in snow load on ground	B_{Q2}	*Logn.*	*0.71*	*0.17*	*0.71*	*(Formichi et al., 2023)*
Imposed load model	θ_{Q3}	*Logn.*	*1.00*	*0.10*	*1.67*	*(Gulvanessian et al., 2005)*
Imposed load (office)	Q_3	*Gumbel*	*1.00*	*0.35*		*(Gulvanessian et al., 2005)*

Assuming the probabilistic models described in Table 5, reliability analyses are carried out by means of Monte Carlo simulations and the calibration of partial factors is performed according to the procedure illustrated in the previous section. In the calibration process, to consider the relative frequency of the different variable actions governing the design, weights are taken equal to 0.1, 0.3, and 0.6 for snow, wind, and imposed loads respectively. These values are chosen based on engineering judgment, reflecting the relevance of each variable load in the design of the most common structural elements in buildings. The frequencies considered in this study can be regarded as average values for continental climate, while it is expected that in warmer or colder climates the frequency of structural members whose design is governed by snow loads can be slightly different.

The reliability levels obtained for the investigated portfolio adopting the EN1990 partial factors are the first significant results, and are illustrated in Table 6, with reference to three different optimization cases: "*No Bias*" for climatic actions considered in the design and reliability analysis of the structural elements in the portfolio; bias included only in the design according to Eq. (3), "*Deterministic Bias*"; and directly in the reliability analysis, Eq.(4), "*Random Bias*".

Table 6: Average reliability levels β for the portfolio according to EN1990 recommended partial factors.

Limit state N.	*No Bias*	*Deterministic Bias*	*Random Bias*
1	*3.68*	*3.86*	*3.77*
2	*3.94*	*4.09*	*4.02*
3	*3.90*	*4.06*	*3.98*
4	*3.48*	*3.65*	*3.57*
5	*3.48*	*3.62*	*3.57*
6	*4.23*	*4.36*	*4.30*
Weighted Average	***3.82***	***3.98***	***3.90***

It is worth to note that the weighted average reliability indexes obtained by using the recommended set of partial factors in EN1990 result higher than the target (3.8) for all optimization cases and most of the limit states. Moreover, the results clearly highlight the influence of bias in climatic actions on reliability levels, looking for example at limit state N.1 (structural steel yielding), β results equal to 3.68 when bias is not considered, and increases to 3.86 when deterministic bias is included in the analysis.

The variation of average reliability levels with the investigated set of partial factors is shown in Figure 1, where a unique partial factor $\gamma_{Q,all}$ calibrated for all variable actions is assumed in the calculations. $\gamma_{Q,all}$ is equal to 1.76, 1.70, and 1.63 for the "*No Bias*", "*Random Bias*", and "*Deterministic Bias*" respectively.

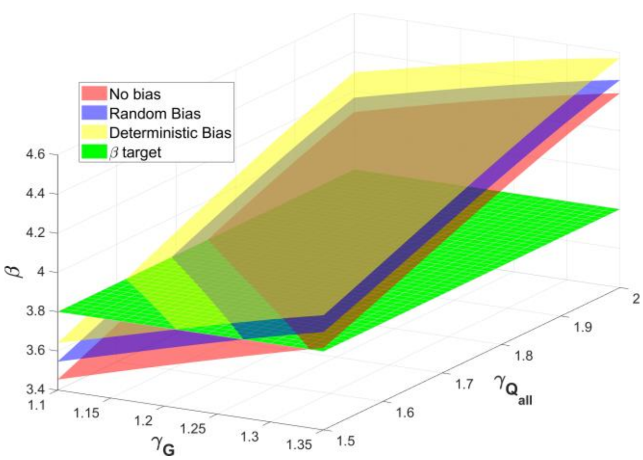

Figure 1: Variation of average reliability levels assuming a unique partial factors for snow, wind, and imposed loads.

The optimal partial factors for permanent, snow, wind, and imposed loads, calibrated independently according to the three optimization cases are summarized in Table 7.

Table 7: Calibrated partial factors.

Action	*No Bias*	*Random Bias*	*Deterministic Bias*
Permanent	*1.10*	*1.10*	*1.10*
Snow	*2.52*	*1.96*	*1.80*
Wind	*2.14*	*2.00*	*1.76*
Imposed	*1.56*	*1.56*	*1.56*

Comparing the obtained results with the recommended set of partial factors given in EN1990, some considerations should be done.

First, it should be considered that the optimization functions may show a relatively large "flat" region around the minimum, making the choice of the optimal couple not trivial and the appropriate selection of the basic assumptions very important. In fact, due to the flatness of the optimization surface, even small changes in the adopted probabilistic models for the random variables in the limit state function may lead to significantly different couples of optimal partial factors. This aspect is confirmed looking at the optimization surfaces in Figure 2, where minimum values are shown together with the areas corresponding to percentage difference from the minimum of +5% (dashed contour) and +10% (continuous contour).

Secondly, it should be also noticed that it is doubtful that such low values of partial factors obtained for permanent loads from the optimization would be acceptable in the design practice, as already observed in (Ellingwood et al., 1980). Moreover, since such low values of partial factors for permanent actions are nearly equal to the quota (γ_{Sd}) of the partial factor which is associated the uncertainty of the action and/or action effect model, they are not able to cover even small unfavorable deviations of the actual representative values of the actions from the theoretical ones, which are the bases for the calibration of γ_f.

Therefore, adopting for example the same restriction on γ_G given in (Ellingwood et al., 1980), i.e. $\gamma_G = 1.2$, calibrated optimal values of $\gamma_{Q,all}$ would decrease becoming 1.66, 1.61, and 1.55 for the three calibration cases, thus approaching the recommended value of 1.5 given in EN1990. Finally, assuming $\gamma_G = 1.35$ as in EN1990, optimal values for $\gamma_{Q,all}$ would be 1.57, 1.52, and 1.47.

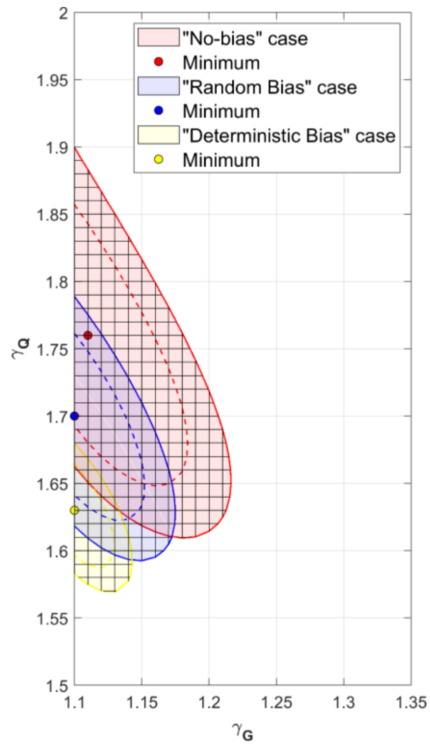

Figure 2: Values of partial factors for permanent and variable actions in the region +5% and +10% with respect to the minimum.

5. CONCLUSIONS

Calibration of partial factors for actions is a challenging task under discussion in view of the development of the second generation of the structural Eurocodes. The calibration involves several assumptions about: the definition of a relevant portfolio of structures and limit states, the evaluation of weights to be associated to the representative structures and load ratios based on their relative frequency in engineering practice, the probabilistic models of random variables included in the limit states, and so on.

In this context, the modeling of climatic actions, such snow and wind, which are generally characterized by high variability, is crucial. The appropriate modeling of relevant uncertainties in the loading chain should be carried out also considering the actual definition of the reference load values in climatic load maps. In fact, the presence of safe-sided biases in climatic load maps provided by National Annexes to the Eurocodes significantly affects the reliability computations and the calibration of partial factors as shown in the paper for a relevant case study.

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