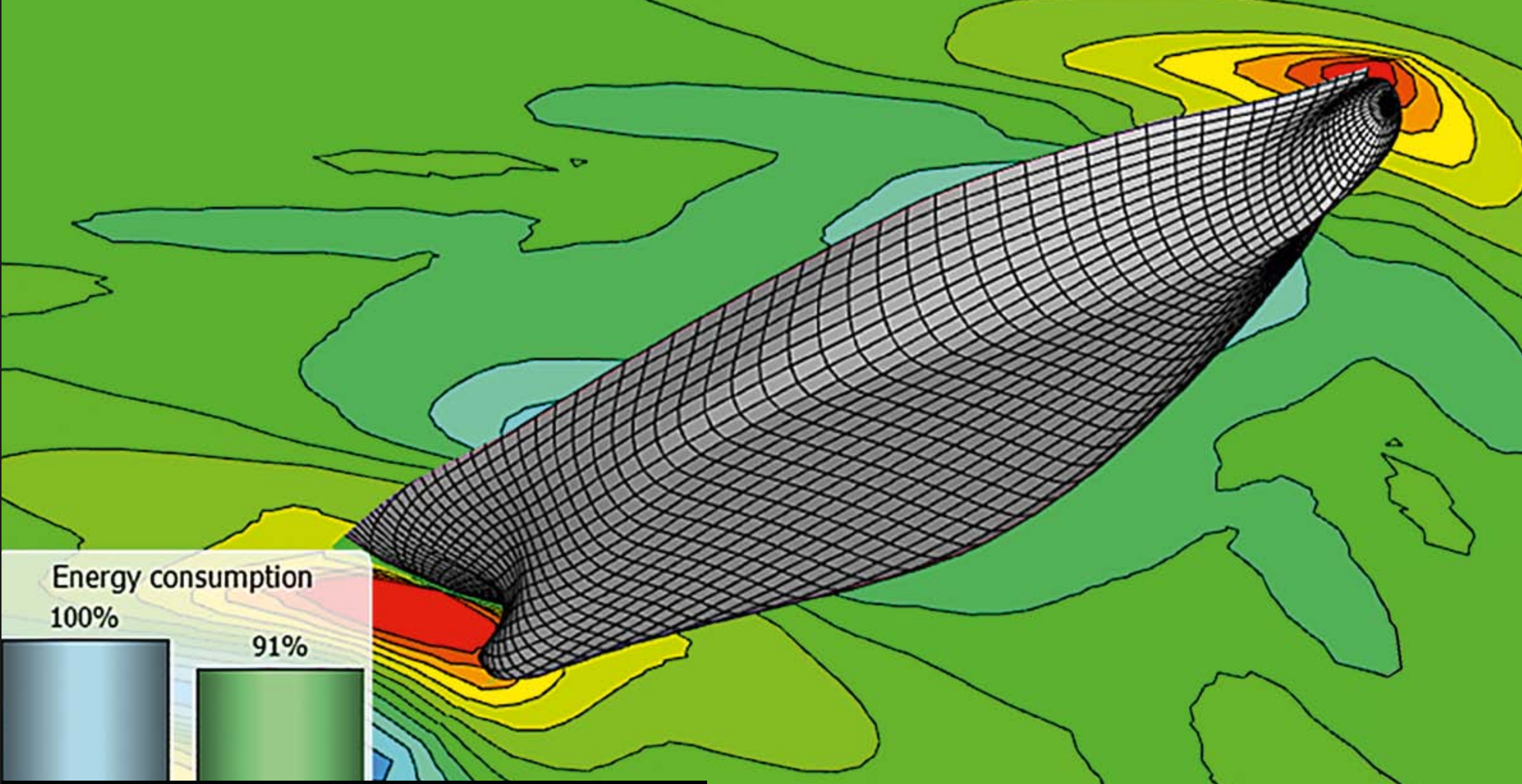


OPTIMIZATION AND ROBUSTNESS ANALYSIS IN SHIP DESIGN

By using optiSLang in combination with FRIENDSHIP-Framework and SHIPFLOW, a ship hull geometry optimization and robustness evaluation were conducted with an automated process chain and a minimum amount of solver runs.

Optimization task

In this presented case study, a given ship hull geometry is optimized by using optiSLang in combination with FRIENDSHIP-Framework and SHIPFLOW. The geometry is initially imported to FRIENDSHIP-Framework and transformation strategies are configured in order to deform the shape automatically by changing a set of design variables. Figure 1 shows the imported geometry in FRIENDSHIP-Framework. The generated design variants are analyzed by using the marine CFD software SHIPFLOW and Dynardo's optiSLang.

In the first stage, some hydrostatic calculations are configured in FRIENDSHIP-Framework in order to keep track of the ship hull's center of buoyancy (CB) and its displacement (V). The CB longitudinal position (XCB), as well as V, are allowed to vary only in a certain range with regard to the baseline design so that they are defined as inequality constraints.
Three different regions of the ship hull are deformed. For global changes of the geometry, a Generalized Lackenby Transformation [1] is applied. It allows shifting the inner part of the hull in a smooth way by entering delta values for XCB and V, such as a change of -1% for XCB and 1.5% for V (note that in marine applications, the change of V is usually defined via the change of the prismatic coefficient CP). When deforming the hull, it is also important to consider so-called hard points which are positions that need to lie strictly within the hull such as points for container arrangements.

Moreover, the stability of the hull needs to be guaranteed for which a characteristic stability value (KM) of the hull is used. It can be received from the hydrostatic calculation for each new design and needs to be larger than a specified minimum value. This minimum KM-value and the hard point positions lead to additional inequality constraints.
For more local changes of the aft part (skeg/transom) and the forward bulb geometry, curve and surface shift functions are utilized. See figure 2 for an example where the bulb is shifted upwards. The amount of the shift is controlled by a user-defined function curve. In this work, the bulb is smoothly moved in x-, y- and z-direction where each direction is configured with a separate shift function.

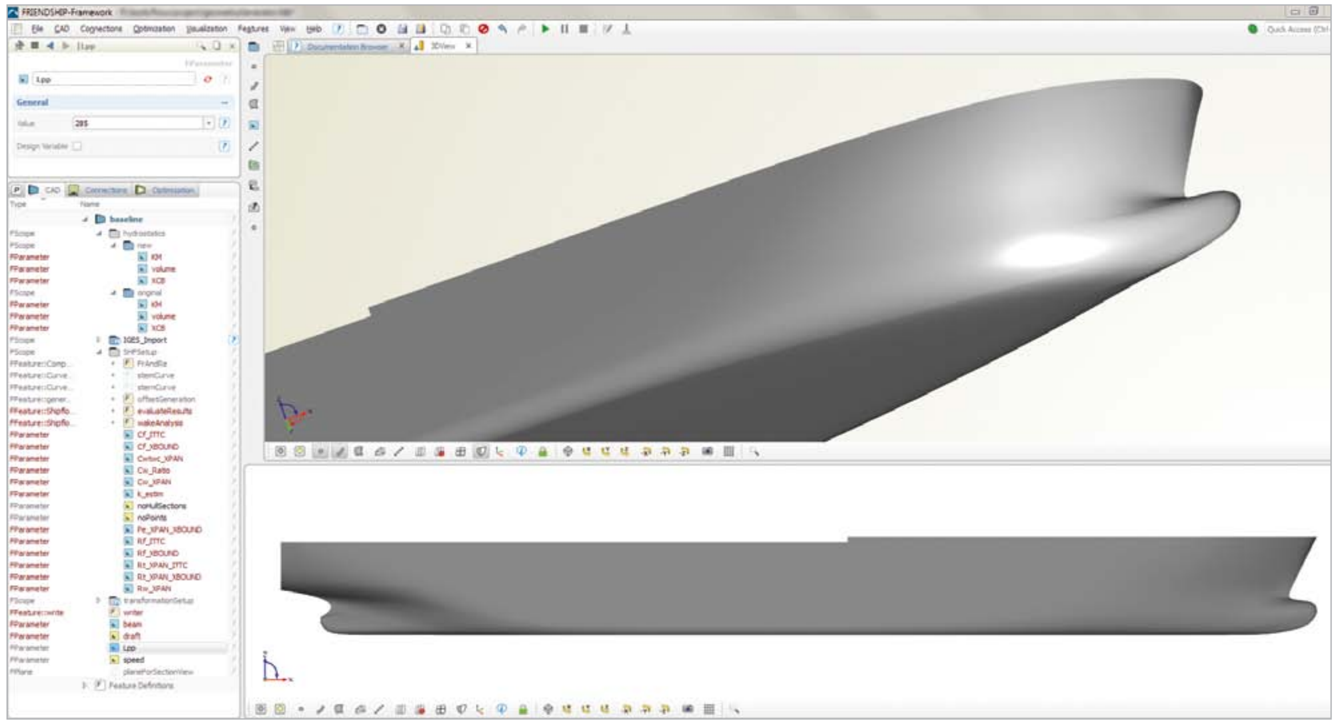


Fig. 1: Ship hull shown in FRIENDSHIP-Framework

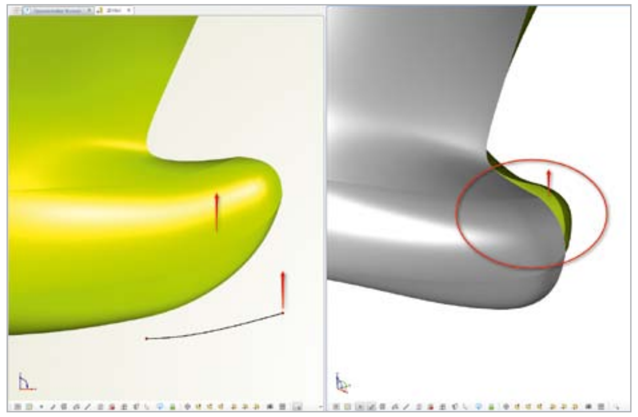
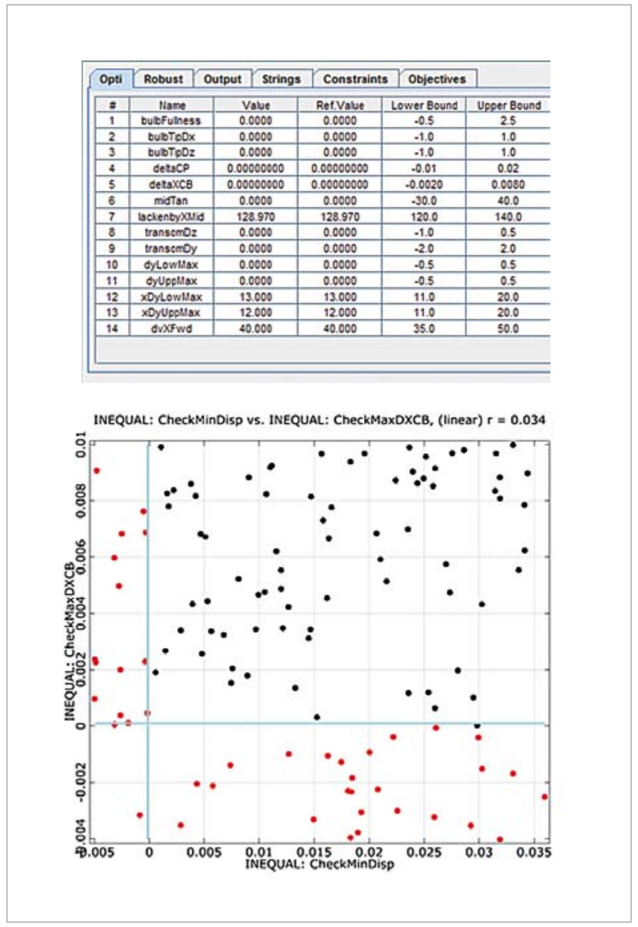


Fig. 2: Upwards deformation of the bulb using a shift transformation that is controlled by a user-defined function curve.

Sensitivity analysis

Defining 14 design parameters (see figure 3 top) with upper and lower bounds, as given in this table, and the performance-relevant responses, the sensitivity analysis is performed using a latin hypercube sampling in three steps to explore the total design space as thoroughly as possible. An extrapolation of the design parameter's bounds can be used in every step to extend the optimization potential. But of course, as a consequence, this results in more samples which are located in the unfeasible design space, as seen in the lower portion of figure 3.

The modification of the parameter bounds is simply based on an extrapolation of the so called Metamodels of Optimal Prognosis (MOP). For example, in case of the violation of the maximal longitudinal center position, the assigned control

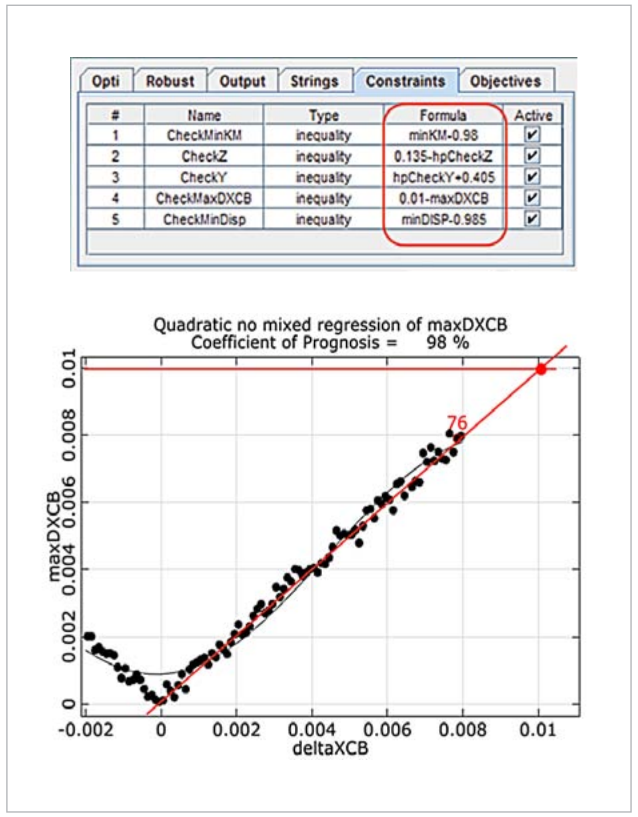


Opti | Robust | Output | Strings | Constraints | Objectives

#	Name	Value	Ref.Value	Lower Bound	Upper Bound
1	bulbFulness	0.0000	0.0000	-0.5	2.5
2	bulbTipDx	0.0000	0.0000	-1.0	1.0
3	bulbTipDz	0.0000	0.0000	-1.0	1.0
4	deltaCP	0.00000000	0.00000000	-0.01	0.02
5	deltaXCB	0.00000000	0.00000000	-0.0020	0.0080
6	midTan	0.0000	0.0000	-30.0	40.0
7	lackenbyXMid	128.970	128.970	120.0	140.0
8	transomDz	0.0000	0.0000	-1.0	0.5
9	transomDy	0.0000	0.0000	-2.0	2.0
10	dyLowMax	0.0000	0.0000	-0.5	0.5
11	dyUppMax	0.0000	0.0000	-0.5	0.5
12	xDyLowMax	13.000	13.000	11.0	20.0
13	xDyUppMax	12.000	12.000	11.0	20.0
14	dvXFwd	40.000	40.000	35.0	50.0

Fig. 3: Lower and upper bounds to define the box constrains used within optimization

parameter of the hull's center of buoyancy can be enhanced up to 0.01 (see figure 4).



Opti | Robust | Output | Strings | Constraints | Objectives

#	Name	Type	Formula	Active
1	CheckMinKM	inequality	minKM-0.98	✔
2	CheckZ	inequality	0.135-hpCheckZ	✔
3	CheckY	inequality	hpCheckY+0.405	✔
4	CheckMaxDXCB	inequality	0.01-maxDXCB	✔
5	CheckMinDisp	inequality	minDISP-0.985	✔

Fig. 4: Extrapolation of the design parameters to make accessible optimization potential

Parameter	Description
Design parameters and random variables	
Bulb Fullness	Global fullness of the bulb geometry i.e. smooth changes to the bulb's width
Bulb Tip DX	Longitudinal position of the bulb tip
Bulb Tip DZ	Vertical position of the bulb tip
Delta CP	Percental change of the prismatic coefficient that allows smoothly increasing or decreasing the hull's displacement V
Delta XCB	Change of the longitudinal position of the hull's center of buoyancy
Mid Tan	Additional control of Generalized Lackenby Transformation, controls the middle tangent of the displacement shift function
X Mid	Additional control of Generalized Lackenby Transformation, controls the longitudinal mid position of the displacement shift function
Transom DZ	Vertical shift of the transom's lower edge in z-direction
Transom DY	Width of the transom, i.e. transom shift in y-direction, 5 additional variables for the skeg part for smoothly shifting the geometry in y-direction
Random variables	
Sref	Wetted surface at zero speed
dens	Water density
visc	Water kinetic viscosity
Lpp	Length between perpendiculars
Re	Reynolds Number
Response values and objectives	
CWTWC	Wave resistance coefficient from transverse wave cut
CW	Wave resistance coefficient from pressure integration
CF	Frictional resistance coefficient
Constraints	
hpCheckY	Hard points check in y-direction (HP: positions that are required to be strictly within the hull)
hpCheckZ	Hard points check in z-direction
maxDXCB	Maximum percental change allowed for longitudinal position of the hull's center of buoyancy
minDISP:	Minimum displacement for modified hull shape
minKM	Minimum KM-value for modified hull shape (KM: characteristic stability value of the hull)

Table 1: Design parameters and random variables

For each new design a CFD analysis is triggered using SHIPFLOW. As a result, the response values of the Table 1 are returned and used for setting up an objective function:

$$Rt = (1.0 \cdot CWTWC + 1.2 \cdot CF)\left(0.5 \cdot dens\left(Re\frac{visc}{Lpp}\right)^2 Sref \cdot Lpp^2\right)$$

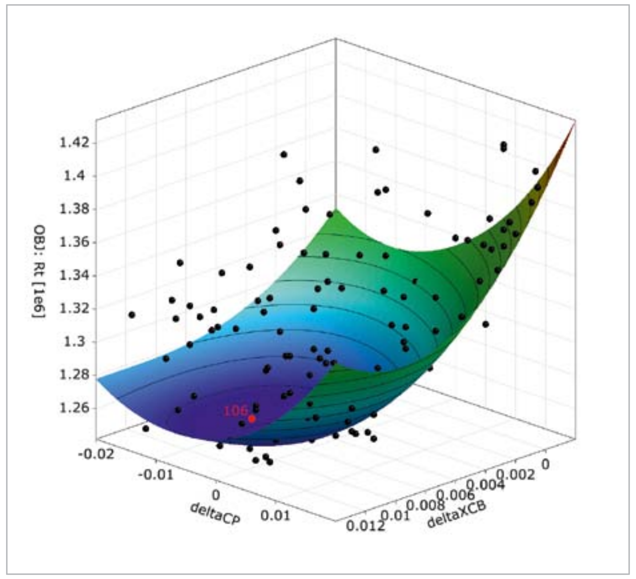


Fig. 5: Surrogate model of the objective function Rt, approximated as meta-model of optimal prognosis in the subspace of the both most important design variables.

Optimization

The constrains, as shown in Table 1, have to be checked during the optimization process to ensure the hard point checks in y- and z-direction, the maximal longitudinal center position and the characteristic stability of the hull. The surrogate model of the objective function Rt, as shown in Figure 5, is

Response value	Initial design	Sensitivity analysis	Evolutionary optimization	Sequential quadratic programming
CWTWC [$\times 10^{-4}$]	2.27	1.02	0.766	0.666
CF [$\times 10^{-3}$]	1.44	1.43	1.42	1.42
Design evaluations	1	312	1	192

Table 2: Results of the ship design optimization with 506 design evaluations, in summary.

approximated as meta-model of optimal prognosis based on 312 design evaluations of a latin hypercube sampling. This meta-model is used for pre-optimization in the total dimensional design space using an evolutionary algorithm. The resulting best design is used as a starting point for a gradient-based optimization using a sequential quadratic programming algorithm with additional 192 design evaluations. Table 2 collect the results of these optimization steps.

Robustness evaluation

In engineering problems, randomness and uncertainties are inherent and may be involved in several stages, for example in the ship design with material parameters and in the manufacturing process and environment. To evaluate the mean design improvements, their possible deviations and the estimated exeedence probabilities, a robustness analysis is carried out. The histograms of the objective terms as result of the 120 design evaluations show a significant improvement of the weighted objective function with large exeedance probabilities (92% and 95%) in comparison with the initial values of CWTWC and CF. Besides the small mean value shift of the optimized CWTWC value, the given distributions show a robust design improvement of the wave resistance coefficient and the frictional resistance coefficient of the hull shape.

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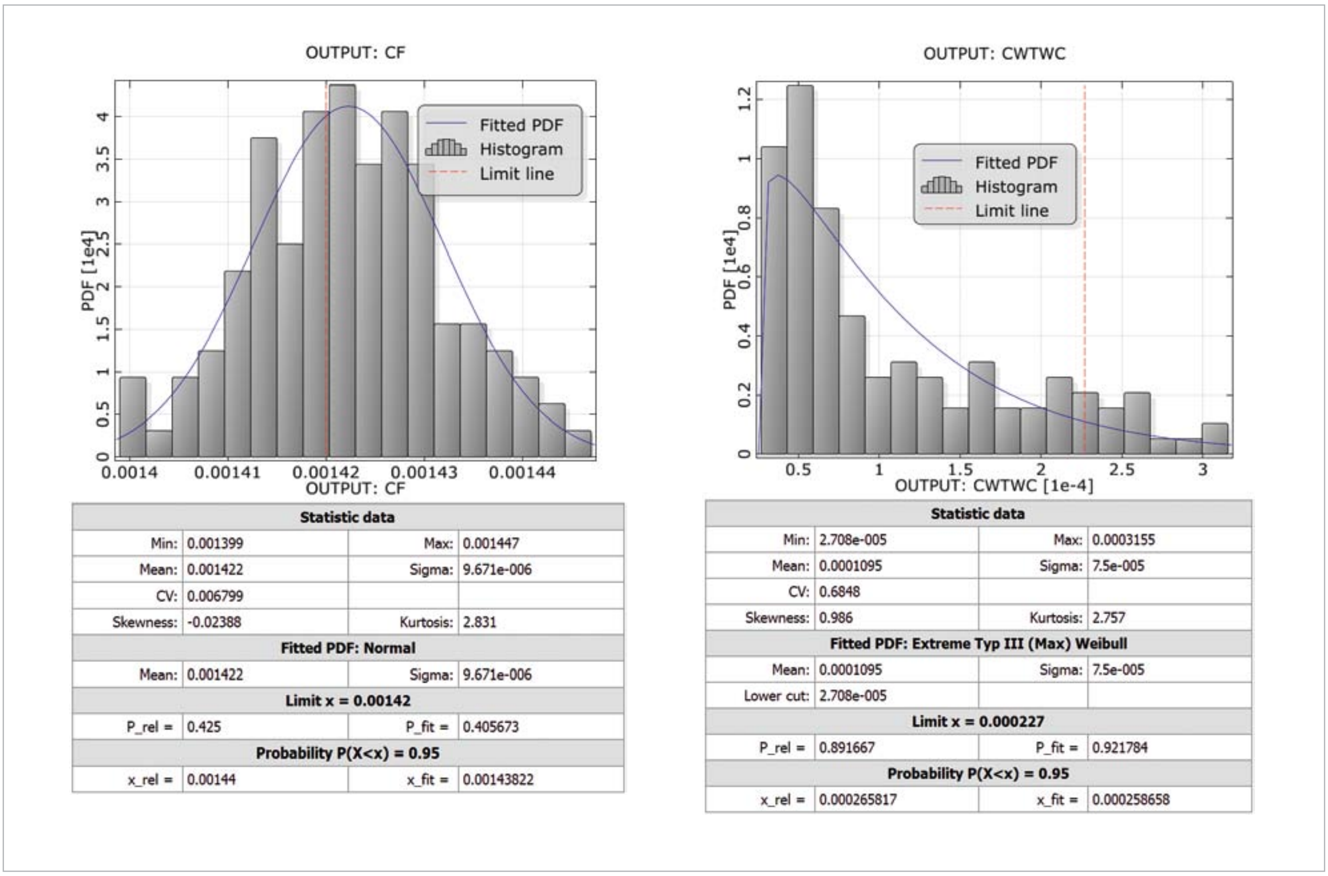

Fig. 6: Histograms of the objective terms as result of the robustness analysis.