SHAPE OPTIMIZATION OF VENTILATION ELEMENTS FOR PROTECTIVE CLOTHING BY USING METAMODELING APPROACH

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Abstract. There are different types of protective clothing available to protect human body from different external conditions such as rain, dust, direct sun radiation, insect access and their bites. The problem of overheating of the body may arise when such proactive clothing is required to wear in warm environment or heavy workload conditions. This is because the outer layer of cloth lacks sufficient air permeability, which causes the accumulation of warm and moist air at the body and causes discomfort. To enhance air exchange, various closable vents and open spaces of clothing have been developed. However, this only results in a partial improvement in air exchange, and reducing mechanical strength of the clothing. The mechanical strength of the clothing can be increased by attaching appropriate ventilation elements at the inner side of ventilation holes, which may permit proper air exchange as well as restrict direct access of insects to the body. The design of elements involving fluid flows usually is based on time-consuming Computational Fluid Dynamics (CFD) simulations. In this paper metamodeling approach different order polynomial local and global as well as kriging approximations are compared for shape optimization purposes of ventilation elements. The main goal is to identify the geometrical shape of the element that causes the least amount of flow energy losses along the cell flow channel, which can also be known from pressure difference. For this a multistep procedure was realized to achieve the best results. 1) Planning the position of control points of Non-Uniform Rational B-Splines (NURBS) for obtaining elements with a smooth shape. 2) Building geometrical models using Computer Aided Design (CAD) software SolidWorks in conformity with the design of the experiment. 3) Calculation of responses for a complete model using Computer Aided Engineering (CAE) software SolidWorks Flow Simulation. 4) Building metamodels for responses based on the computer experiment. 5) Using metamodels for shape optimization. 6) Validating the optimal design using CAE software for the complete model.

Keywords: shape optimization, ventilation element, metamodel, flow simulation, protective jacket.

Introduction

The variety of ventilation systems [1; 2] of protective clothing can be used to prevent overheating of the human body. Efficiency of the air exchange between the external environment and the internal under clothing microenvironment greatly depends on the shape of the used ventilation elements. This study focuses on shape optimization of the ventilation elements for protective clothing by the metamodeling approach. Metamodels, also known as approximations, response surfaces or surrogate models, are used to save the time required for optimization because the solving methods for complete models typically include computationally complex algorithms [3]. Time consuming Computational Fluid Dynamics (CFD) simulations are often used as the foundation for the design of systems incorporating fluid flows.

The Efficient Global Optimization (EGO) [4; 5] technique specifically based on kriging is now frequently utilized to handle deterministic optimization issues requiring such expensive models [6; 7]. For computationally intensive simulations, kriging or Gaussian Process (GP) regression has gained popularity as a metamodeling method because it offers surfaces with variable complexity (potentially interpolative) within a probabilistic framework [8].

In this work for the shape optimization of ventilation elements software KEDRO [9] is used, it allows planning of experiments, building metamodels and using these metamodels for global optimization. Recently, the direct parameterization approach of CAD-based geometry [10] is becoming more and more effective and widely applicable due to the development of automated design software and highly efficient metamodeling methods [11; 12].

Model components and boundary conditions

The comparative analysis of the different ventilation elements in our previous studies [13] showed that most perspective in sense of minimal flow losses are elements with torus shape cut-out in the core (Fig. 1). Now we try to investigate the effect of adding different shape outer rings to this core element that may be preferable from the strength and technological point of view.

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The present study is based on further shape optimization of an outer ring of the ventilation element. Two design variables – length of straight lines R60 and R90 (see Fig. 1 and Fig. 2) with subsequent lower and upper bounds are introduced: 1) $0.36 \leq R60 \leq 2$; 2) $0.01 \leq R90 \leq 2.5$. The bottom end points of these lines are cotrol points for NURBS [10] that define a smooth shape of the outer ring of the ventilation element.

For metamodel building Mean Square Distance Latin Hypercube (MSDLH) design of the experiment for 2 factors is used (Fig. 3).

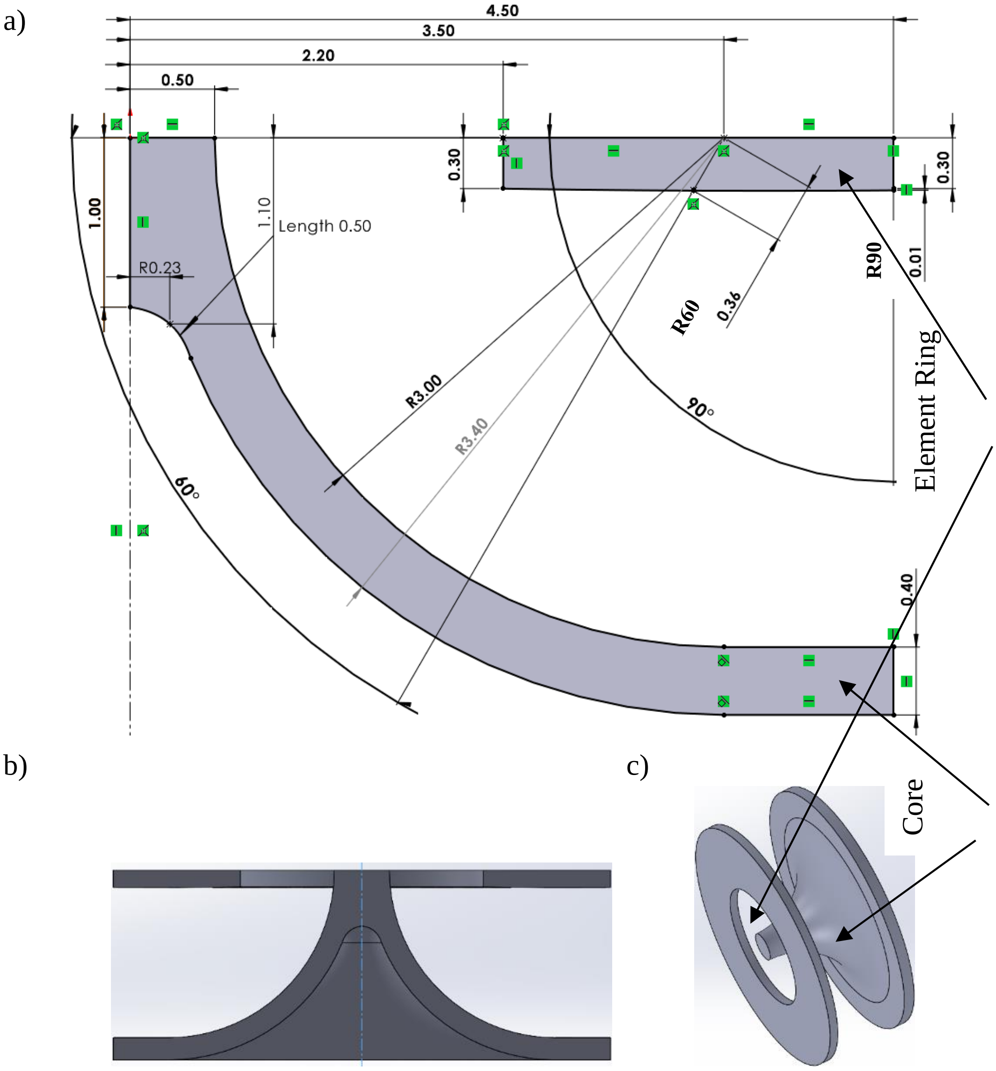


Fig. 1. **Ventilation element CAD model with lower bounds of design variables:** a – 2D sketch for CAD revolve feature of the element (the ring is coincident with the outer layer of clothing in this case); b – 3D cross-section view; c – isometric view

Fig. 1 and 2 show minimum and maximum dimensions of the element ring, while Fig. 3a depicts generated Design of Experiment (DOE) with 12 numerical values of design within the specified range, in which the factors X1 and X2 are the coordinates of the element ring where R60 refers to coordinate points at 60º and R90 refers to coordinate points at 90º in the 2D sketch. This DOE is generated in KEDRO and from obtained values, 12 geometric designs of elements are created with the use of SolidWorks. SolidWorks Flow Simulation is utilised to obtain pressure and temperature for each generated element. The model of a body (refers to human body) and jacket are developed and built into a simple elliptical shape, with the body remaining in the centre and the jacket covering it with a uniform gap of 3.4 mm, in order to simplify the complexity in this study (Fig. 4).

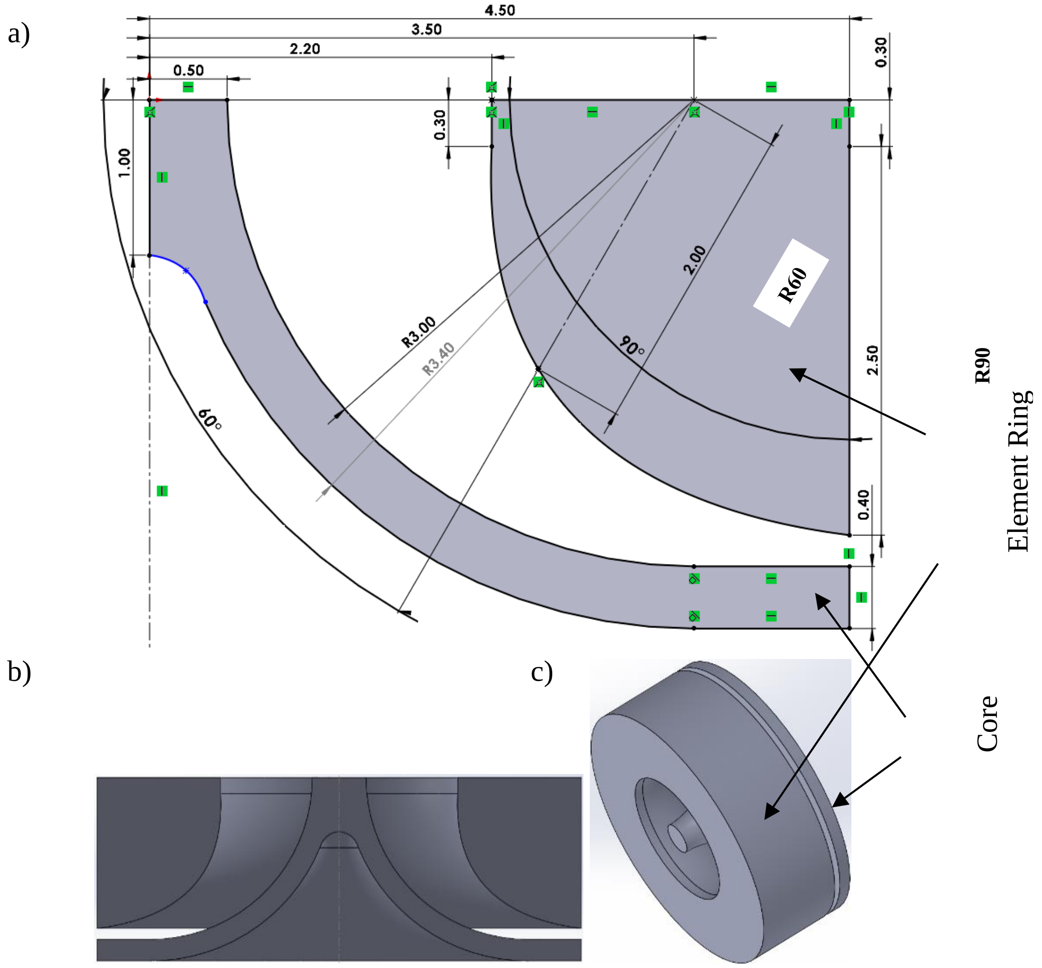
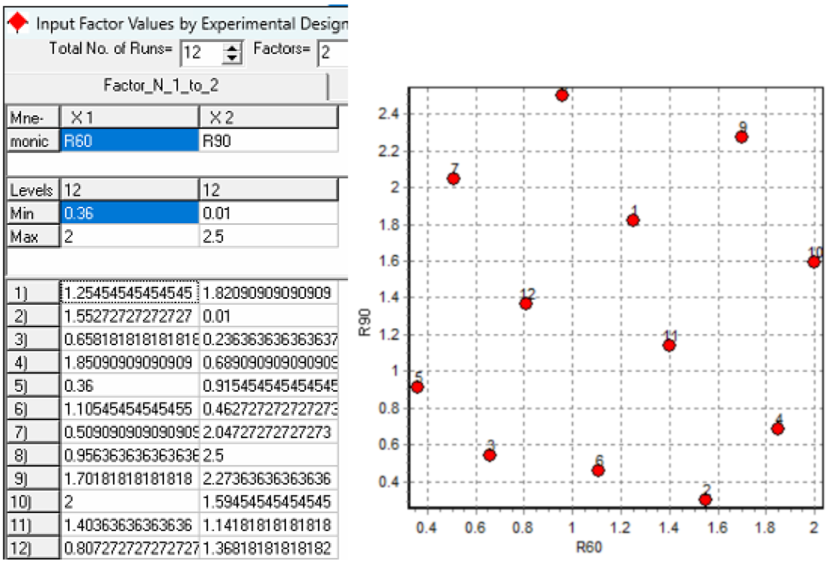


Fig. 2. **Ventilation element CAD model with upper bounds of design variables:** a – 2D sketch for CAD revolve feature of the element; b – 3D cross-section view; c – isometric view


Input Factor Values by Experimental Design

Total No. of Runs= 12 Factors= 2

Factor_N_1_to_2

Mne-monic	X 1	X 2
	R60	R90
Levels	12	12
Min	0.36	0.01
Max	2	2.5
1)	1.25454545454545	1.82090909090909
2)	1.55272727272727	0.01
3)	0.658181818181818	0.236363636363637
4)	1.85090909090909	0.689090909090909
5)	0.36	0.915454545454545
6)	1.10545454545455	0.462727272727273
7)	0.509090909090909	2.04727272727273
8)	0.956363636363636	2.5
9)	1.70181818181818	2.27363636363636
10)	2	1.59454545454545
11)	1.40363636363636	1.14181818181818
12)	0.807272727272727	1.36818181818182

Fig. 3. **MSDLH DOE with 12 trials for 2 factors generated by KEDRO:** a – numerical values; b – graphical representation

Fig. 4 shows a schematic diagram of the model design of the body and jacket, where there is a single inlet of 4.4 mm diameter at the front and 10 outlets of 4 mm diameters at the backside of the jacket. A single ventilation element is attached to the inlet hole in a gap between the body and jacket, while no elements are attached at outlets. The simulation study is done with 12-ventilation elements generated with the help of the metamodel, the obtained results are used as the input in KEDRO for the optimization. In the flow simulation investigation, the initial air temperature of 20 ºC and the air pressure of 101325 Pa are used as standard values. Two distinct inlet air velocities of 4 and 8 $m \cdot s^{-1}$ are used in the investigation. At the beginning of the simulation, different materials with certain properties are assigned to the jacket and body. These material properties are listed in Table 1. The average human body temperature is taken as 36.5 ºC and the heat generation rate of the body (normal walking condition) as 200 W [14].

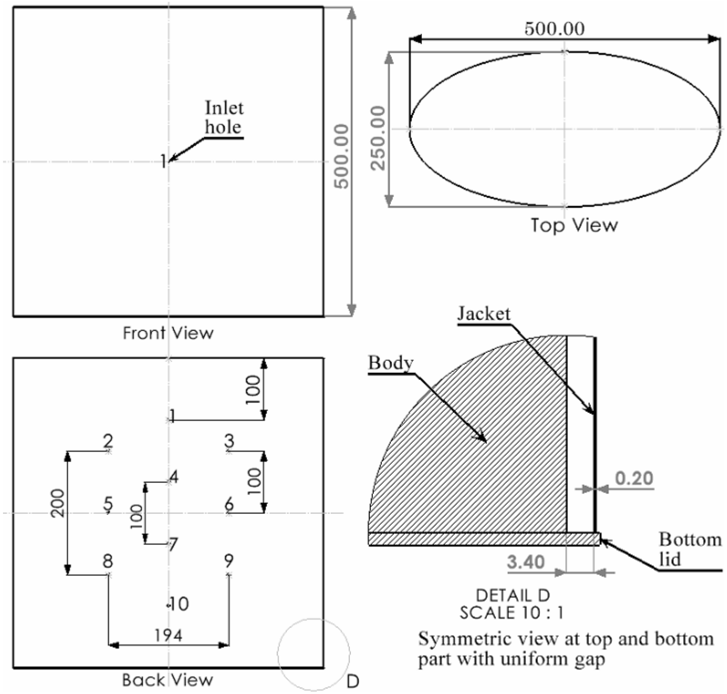


Fig. 4. **Model design of body and jacket (elliptical) [15]**

Table 1

Material Properties [16; 17]

Material property	Human body	Jacket
Average density ($kg \cdot m^{-3}$)	985	1420
Specific heat ($J \cdot kg^{-1} \cdot K^{-1}$)	3500	1140
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.21	0.261

Assumptions/considerations in the Flow Simulation [15]:

- No air passes from the top and bottom part of the jacket (considered as closed); this is to study the effectiveness of the ventilation.
- The top and bottom parts in simulation have outer environmental effects.
- Radiation is not considered in the study, as the heat loss by radiation will be the same in all cases.
- Heat transfer through conduction and convection from the body to the jacket and to outer environment.

Results and discussion

Once all the parameters are set as discussed in the previous section, the flow simulation study is run for physical time of 5 seconds with one by one all 12 elements and the results are evaluated in terms of pressure and temperature. The obtained results for each case are presented in Table 2.

In Table 2, ΔP and ΔT refer to pressure and temperature difference respectively, which are calculated from the obtained values of pressure and temperature by the flow simulation study. These calculated values of ΔP and ΔT are used as data for responses in KEDRO for further approximation and optimization. The kriging method is used here for approximation.

Table 2

Numerical values of the results

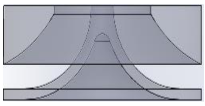
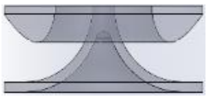
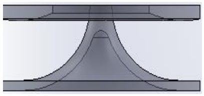
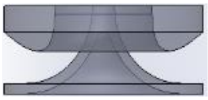
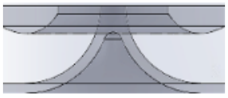
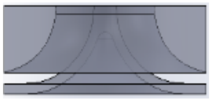
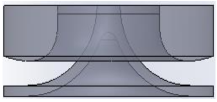
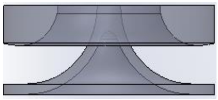
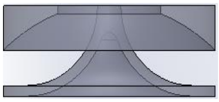
Element cross section shape	**Inlet velocity, m·s^{-1}**	**Values**	**Pressure, Pa**	**Δ*P*, Pa**	**Temperature, ºC**	**Δ*T*, ºC**
1 	4	Max	101331.16	5.55	36.50	7.5
		Min	101325.61		29.00	
	8	Max	101338.00	17.48	36.50	8.24
		Min	101320.52		28.26	
2 	4	Max	101331.07	6.17	36.50	6.2
		Min	101324.90		30.30	
	8	Max	101337.54	21.96	36.50	7.13
		Min	101315.58		29.37	
3 	4	Max	101331.51	6.06	36.50	8.05
		Min	101325.45		28.45	
	8	Max	101342.51	22.20	36.50	8.54
		Min	101320.31		27.96	
4 	4	Max	101332.92	8.49	36.50	7.24
		Min	101324.43		29.26	
	8	Max	101345.29	29.05	36.50	8.36
		Min	101316.24		28.14	
5 	4	Max	101331.59	5.89	36.50	7.38
		Min	101325.70		29.12	
	8	Max	101340.49	21.55	36.50	8.14
		Min	101318.94		28.36	
6 	4	Max	101331.23	5.74	36.50	6.91
		Min	101325.49		29.59	
	8	Max	101341.61	22.52	36.50	8.44
		Min	101319.09		28.06	
7 	4	Max	101333.92	8.25	36.50	7.04
		Min	101325.67		29.46	
	8	Max	101347.83	22.87	36.50	8.54
		Min	101324.96		27.96	
8 	4	Max	101359.86	34.4	36.50	6.64
		Min	101325.46		29.86	
	8	Max	101444.59	119.28	36.50	7.61
		Min	101325.31		28.89	
9 	4	Max	101341.56	18.83	36.50	6.91
		Min	101322.51		29.59	
	8	Max	101372.52	51.32	36.50	7.83
		Min	101321.20		28.67	
10 	4	Max	101336.65	13.92	36.50	7.27
		Min	101322.73		29.23	
	8	Max	101360.79	45.42	36.50	8.4
		Min	101315.37		28.10	
11 	4	Max	101331.09	5.7	36.50	6.76
		Min	101325.39		29.74	
	8	Max	101334.51	17.87	36.50	8.3
		Min	101316.64		28.20	
12 	4	Max	101331.08	5.56	36.50	6.68
		Min	101325.52		29.82	
	8	Max	101338.09	17.74	36.50	8.16
		Min	101320.35		28.34	

Fig. 5 shows kriging approximation by the response surface with experimental points. There are two main indicators to check the quality of approximation: Sigma Cross % and Max Rel Error. Here, Sigma Cross is the leave-one-out-cross-validation error and Max Rel Error is the maximum relative error (in relation to the experimental values).

$$\text{Sigma Cross} = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_{i(-i)}\right)^2}{n}} \tag{1}$$

where $\hat{y}_{i(-i)}$ – value of the approximated function for the input factor value x_i, if the approximation does not use the i-th experiment point;
n – the total number of experiment points.

A more informative indicator for the approximation quality is the relative cross-validation error (Sigma Cross%) as a percentage of Standard Deviation:

$$\text{Sigma Cross \%} = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_{i(-i)}\right)^2}{n}}}{STD} \times 100\%, \tag{2}$$

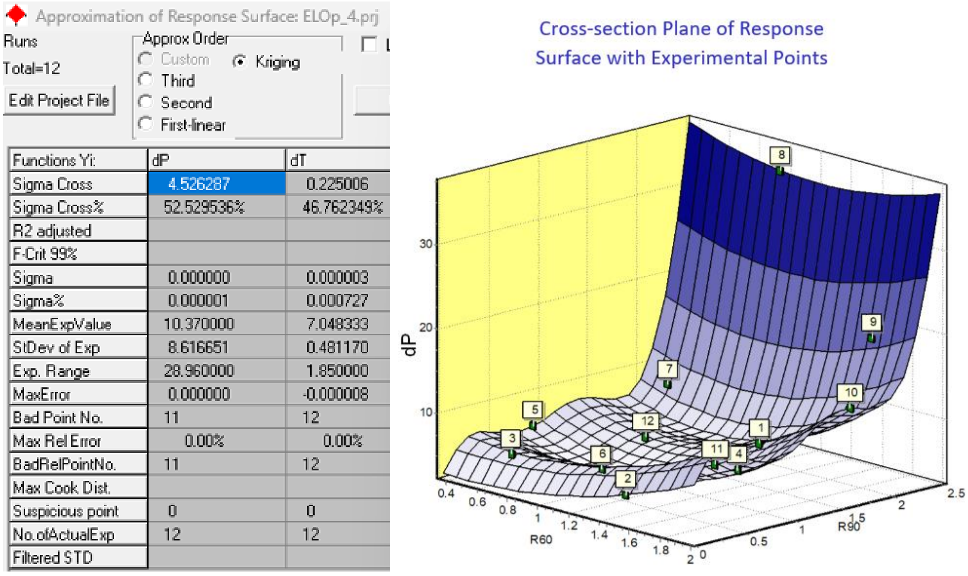
where STD – Standard Deviation:

$$STD = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \bar{y}_i\right)^2}{n-1}} \tag{3}$$

And $\bar{y}$ is the mean value of the response in the experimental points:

$$\bar{y} = \frac{\sum_{i=1}^{n} y_i}{n} \tag{4}$$

If Sigma Cross% is higher than 100%, the quality of approximation is very poor, while smaller Sigma Cross% provides a better quality of approximation. Similarly, the smaller the percentage of Max Rel Error, the better is approximation. Here the obtained value of Sigma Cross% is 52.52% and 0.001% is Max Rel Error, which indicate satisfactory quality of approximation. Fig. 6 shows optimization results based on minimum pressure difference criteria. To verify the obtained results, the flow simulation study is made again at the inlet velocity of 8 m·s^{-1} and the obtained results are used for approximation and optimization by repeating the same process.


Approximation of Response Surface: ELOp_4.prj

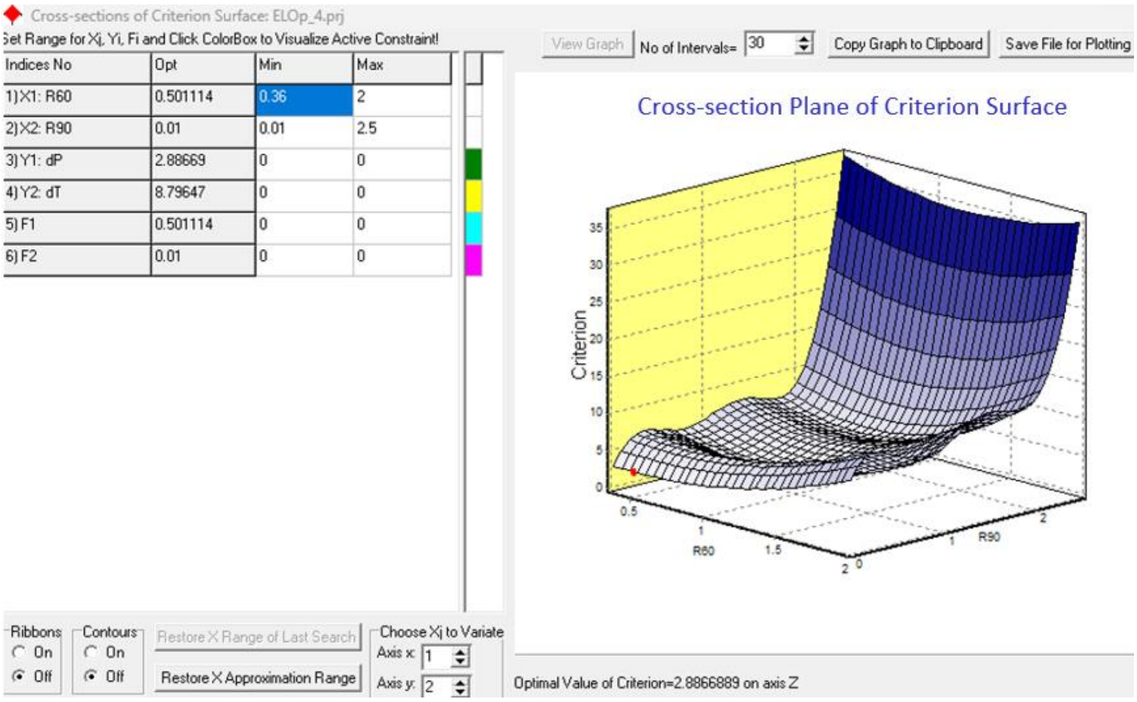
Runs

Total=12

Approx Order
○ Custom ● Kriging
○ Third
○ Second
○ First-linear

Functions Yi:	dP	dT
Sigma Cross	4.526287	0.225006
Sigma Cross%	52.529536%	46.762349%
R2 adjusted		
F-Crit 99%		
Sigma	0.000000	0.000003
Sigma%	0.000001	0.000727
MeanExpValue	10.370000	7.048333
StDev of Exp	8.616651	0.481170
Exp. Range	28.960000	1.850000
MaxError	0.000000	-0.000008
Bad Point No.	11	12
Max Rel Error	0.00%	0.00%
BadRelPointNo.	11	12
Max Cook Dist.		
Suspicious point	0	0
No.ofActualExp	12	12
Filtered STD		

Fig. 5. **Response Surface Δ*P* = *f* (*R*60, *R*90) using experiment with 12 trials for kriging approximation for case of wind velocity 4 m·s^{-1}**

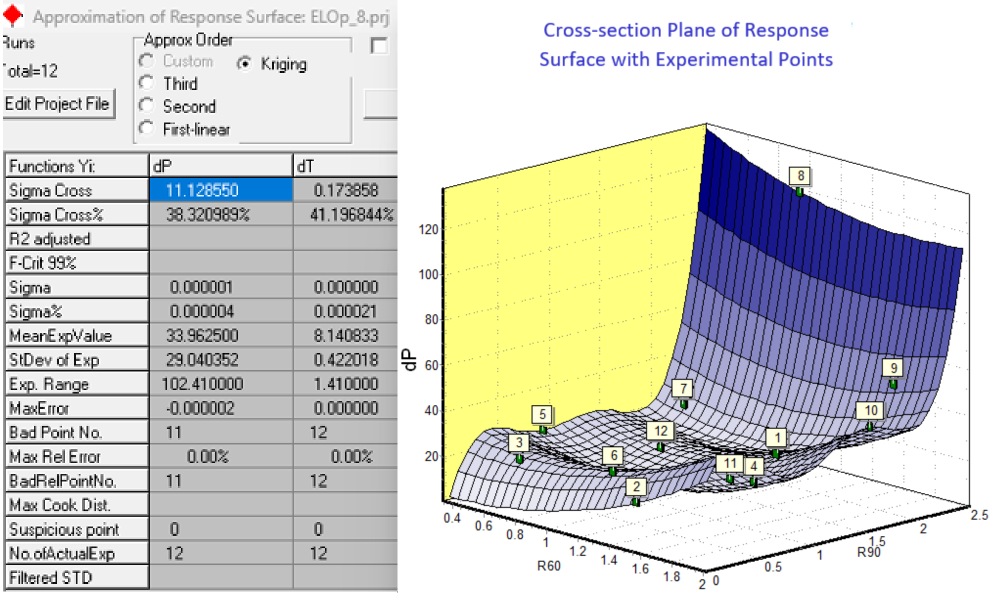


Indices No	Opt	Min	Max
1)X1: R60	0.501114	0.36	2
2)X2: R90	0.01	0.01	2.5
3)Y1: dP	2.88669	0	0
4)Y2: dT	8.79647	0	0
5) F1	0.501114	0	0
6) F2	0.01	0	0

Optimal Value of Criterion=2.8866889 on axis Z

Fig. 6. **Optimization results for case of wind velocity 4 m·s^{-1} (red point indicates global minimum of Δ*P*)**

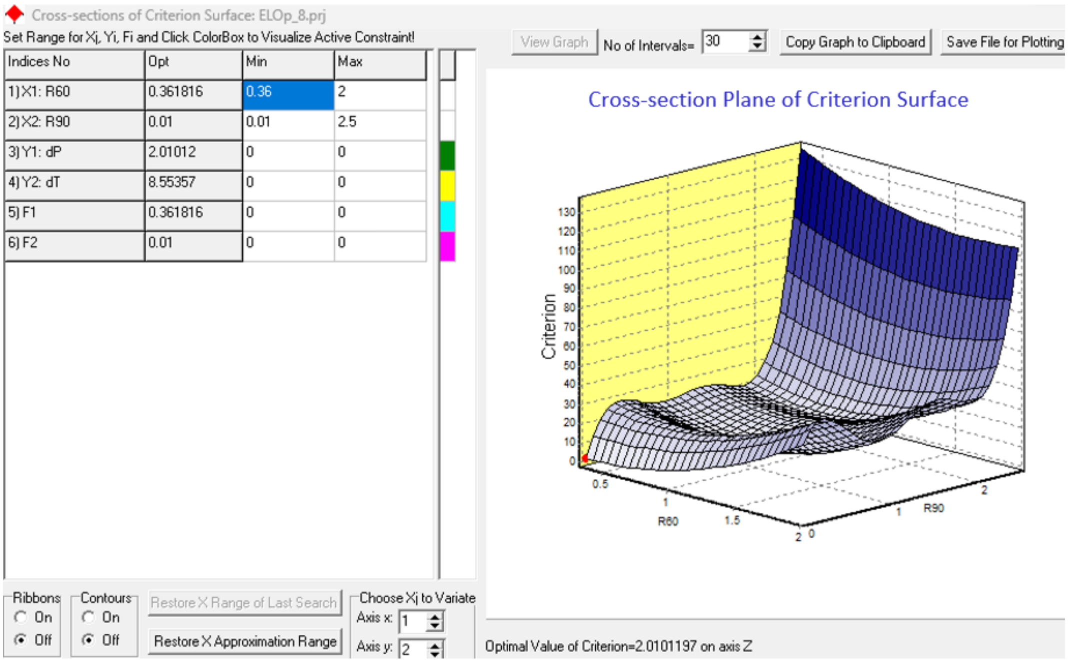
From Fig. 7 it is visible that the obtained value of Sigma Cross% is 38.32% shows improved quality of approximation than that of at 4 m·s^{-1} (52.53%). Moreover, the obtained values of optimization results at 4 and 8 m·s^{-1} are very close, which ensures reliability of the method and obtained results. This indicates that the optimum design variables for ventilation elements are R60 = 0.36 and R90 = 0.01 (Fig. 8).



Functions Yi:	dP	dT
Sigma Cross	11.128550	0.173858
Sigma Cross%	38.320989%	41.196844%
R2 adjusted		
F-Crit 99%		
Sigma	0.000001	0.000000
Sigma%	0.000004	0.000021
MeanExpValue	33.962500	8.140833
StDev of Exp	29.040352	0.422018
Exp. Range	102.410000	1.410000
MaxError	-0.000002	0.000000
Bad Point No.	11	12
Max Rel Error	0.00%	0.00%
BadRelPointNo.	11	12
Max Cook Dist.		
Suspicious point	0	0
No.ofActualExp	12	12
Filtered STD		

Fig. 7. **Approximation of response surface at 8 m·s^{-1}**

The final step is the validation of the optimal design through SolidWorks Flow Simulation to see how close the simulation and optimization results are. The value of Δ*P* obtained for the optimal design for the case of the wind velocity $v = 4$ m·s^{-1} is 5.39 Pa, which does not match exactly with the optimization results as there is a difference of 2.5 Pa. This difference is mainly due to the quality of approximation, improving the quality of approximation will provide more accurate optimization results.



Cross-sections of Criterion Surface: ELOp_8.prj

Set Range for Xj, Yi, Fi and Click ColorBox to Visualize Active Constraint!

Indices No	Opt	Min	Max	
1)X1: R60	0.361816	0.36	2	
2)X2: R90	0.01	0.01	2.5	
3)Y1: dP	2.01012	0	0	🟩
4)Y2: dT	8.55357	0	0	🟨
5) F1	0.361816	0	0	▨
6) F2	0.01	0	0	▨

No of Intervals= 30

Ribbons ○ On ● Off

Contours ○ On ● Off

Choose Xj to Variate
Axis x: 1
Axis y: 2

Optimal Value of Criterion=2.0101197 on axis Z

Fig. 8. **Optimization results for case of wind velocity 8 m·s^{-1} (red point indicates global minimum of Δ*P*)**

Conclusions

Considering the criteria of minimum pressure difference at different wind velocities of 4 m·s^{-1} and 8 m·s^{-1}, some specific optimum design points for the element ring were obtained. Very small difference was also observed in the obtained values of the optimum design points at 4 and 8 m·s^{-1}. This ensures reliability of the method as the difference is very small. Moreover, this difference can also be explained, as there will be obvious change in the interaction and reaction between the fluid flow and element with the change in the air velocity. The coordinate value for R90 is the same in both cases with minor difference for R60. However, the quality of the metamodel for the results at 8 m·s^{-1} was better according to the minimum Sigma Cross% criteria. It can be concluded from the obtained results that optimum design variables for the element ring can provide minimum pressure difference and ultimately better cooling. Practically the ring does not exist at the obtained optimum design points, which indicates that the element without the outer ring will provide the best result.

This study clearly indicates that incorporating the metamodeling approach instead of CFD simulation can drastically reduce the computational time for the optimization. Typically to complete CFD simulation for calculation of one criterion point for the discussed problem requires approximately 4 hours of multicore computer i9 processor time while using metamodels all optimization takes only few minutes. It allows in future to formulate a more realistic shape optimization problem of the ventilation elements taking into account uncertainty caused for example by changing the wind direction.

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Author contributions

Conceptualization, A.J. and S.R.V.; methodology, A.J. and S.R.V.; software, A.J. and S.R.V.; validation, S.R.V. and A.G.; formal analysis, A.G. and S.R.V.; investigation, S.R.V. and A.G.; data curation, S.R.V. and A.G.; writing – original draft preparation, S.R.V.; writing – review and editing, A.J. and S.R.V.; visualization, S.R.V. and A.G; project administration, S.R.V.; funding acquisition, A.J., S.R.V. and A.G. All authors have read and agreed to the published version of the manuscript.

References

[1] Jaeger K. Ventilation System for Clothing. US Patent No.: US 7,043,767 B2. May 16, 2006.

[2] Gulevskis A. An Element for Providing an Air Exchange between the Internal Microenvironment and the External Environment. International Publication No: WO 2021/246853 A1. International Application No: PCT/LV2021/050002. Dec. 09, 2021.

[3] Sacks J., Welch W.J., Mitchell T.J., Wynn H.P. Design and analysis of computer experiments. Statistical Science, 4(4), November 1989, pp. 409-423.

[4] Jones D.R., Schonlau M., Welch W.J. Efficient global optimization of expensive black-box functions. Journal of Global Optimization, 13(4), 1998, pp. 455-492.

[5] Jones D.R. A taxonomy of global optimization methods based on response surfaces. Journal of Global Optimization, 21, 2001, pp. 345-383.

[6] Sasena M.J. Flexibility and Efficiency Enhancements for Constrained Global Design Optimization with Kriging Approximations. PhD thesis, 2002.

[7] Janusevskis J., Riche R.L. Simultaneous kriging-based sampling for optimization and uncertainty propagation. Technical report, Equipe: Calcul de Risque, Optimisation et Calage par Utilisation de Simulateurs - CROCUS-ENSMSE - UR LSTI - Ecole Nationale Superieure des Mines de Saint-Etienne, July 2010. Deliverable no. 2.2.2-A of the ANR/OMD2 project. [online][11.03.2023] Available at: http://hal.archives-ouvertes.fr/hal-00506957.

[8] Carl E. Rasmussen and Christopher K. I. Williams. Gaussian Processes for Machine Learning (Adaptive Computation and Machine Learning). The MIT Press, December 2005.

[9] Auzins J., Janushevskis A. KEDRO User’s Manual. 2023. 50 p. [online][11.03.2023] Available at: http://www.mmd.rtu.lv/ProgramsA.htm

[10] Saxena A., Sahay B. Computer Aided Engineering Design, Springer, 2005, 394 p.

[11] Janushevskis A., Auzins J., Janushevskis J., Viba J. Optimization of Subsonic Aerodynamic Shape by Using Metamodeling Approach. Proc. 5th Int. DAAAM Conference “Industrial Engineering – Adding Innovation Capacity of Labour Force and Entrepreneurs”. Editor R.Kyttner. ISBN 9985-894-92-8. Tallinn University of Technology. 2006, pp. 41-46.

[12] Janushevskis A., Melnikovs A., Janusevskis J. Shape Optimization of a Lightweight Tetrapod Element Using CAD/CAE Tools and Metamodels. Proceedings IRF`2013. Editors: J.F.Silva Gomes, Shaker A. Meguid. ISBN: 978-972-8826-28-4. Fourth International Conference on Integrity, Reliability & Failure. Funchal, Portugal, 2013, 11 p.

[13] Janushevskis A., Vejanand S. R., Gulevskis, A. Analysis of Different Shape Ventilation Elements for Protective Clothing. WSEAS Transactions on Fluid Mechanics, Vol.17, ISSN: 1790-5087, 2022. pp. 140-146.

[14] Kumar R., Aggarwal R.K., Sharma J.D., Pathania S. Predicting Energy Requirement for Cooling the Building Using Artificial Network. Journal of Technology Innovations in Renewable Energy, 2012, 1, pp. 113-121.

[15] Janushevskis A., Vejanand S. R., Gulevskis A. Comparative Analysis of Different Shape Ventilation Elements for Protective Clothing. Engineering for Rural Development, Jelgava Conference, 25-27.05.2022, pp. 179-186. DOI: 10.22616/ERDev.2022.21.TF052

[16] Giering K., Lamprecht I., Minet O. Specific heat capacities of human and animal tissues. Proceedings of SPIE – The International Society for Optical Engineering, January 1996, 2624, pp. 188-197.

[17] Rugh J.P., Bharathan D. Predicting Human Thermal Comfort in Automobiles. Presented at the Vehicle Thermal Management Systems Conference and Exhibition, May 2005, Toronto, Canada.