Simplified ground-source heat pump models for predicting heat extraction

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Context

- The heat pump operation affects heat extraction from the ground, and the ground heat exchanger performance affects the heat pump performance.
- Simplified models of water-source heat pumps are needed for the design of ground heat exchangers
- Availability of data in manufacturers' catalogs often depends on local standards
- Calculation of heat extraction by means of simple equations (fast and easy to implement)

Method

Purpose

- GHE design
- Heat extraction
- Low computational time
- Acceptable accuracy
- Easy-to-use

Data availability review

- Type of heat pump
- Catalog data
  - North America
  - Northern Europe
  - Southern Europe

Model review

- Literature
- Standards
- Simulation software
  - Energy Plus
  - TRNSYS
  - Modelica

Catalog selection

- W-to-W
- Heating
- Area
- Data grouped by data availability

Method

Methodology development

- COP
- Heat extraction
- Evaluation through RMSE

Application of the models

- Matrix reduction
- Application of the existing models
- Improvement of the existing models
- Development of new models

Validation against catalog data

- Application of the selected models
- Evaluation of the results
- Recommendations

Validation against experimental data

- Application of the selected models
- Evaluation of the results
- Verification of the recommendations

Catalog data overview

Matrix of Data and Group identification → Model selection → Eq. coefficients calculation → Validation against catalog data → Recommendations

Example of data matrix – Southern Europe

SEFT [°C]	SExFT [°C]	LEFT [°C]	LExFT [°C]	HC [kW]	Pel [kW]	COP [kW/kW]
0	-3	30	35	18.5	4.75	3.80
3	0	30	35	20.0	4.90	4.08
0	-3	40	45	17.0	5.55	3.06
3	0	40	45	18.8	5.70	3.30

Possible Matrix reduction

- Different number of op. points
- Different variables

Group identification

Matrix of Data and Group identification → Model selection → Eq. coefficients calculation → Validation against catalog data → Recommendations

Water-to-water		Group 1	Group 2	Group 3	
		NA	NE	SE1	SE2
Source Ent. Fluid Temp.	SEFT	✓	✓	D	✓
Source Fluid flow rate	SFfr	✓	x	✓	D
Load Ent. Fluid Temp.	LEFT	✓	x	D	✓
Heating Capacity	HC	✓	✓	✓	✓
Electrical Power	Pel	✓	x	✓	D
Heat Extraction	HE	✓	D	✓	✓
Load Ex. Fluid Temp.	LExFT	✓	✓	✓	✓
COP_H	COP_H	✓	✓	✓	D
Load Fluid flow rate	LFfr	✓	x	✓	✓
Heating Capacity [kW]		14.7	7.57	8.3	18

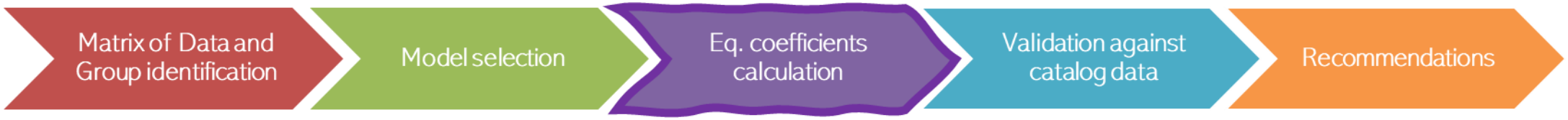
✓ Available
x Not available
D Derivable

The models

Matrix of Data and Group identification → Model selection → Eq. coefficients calculation → Validation against catalog data → Recommendations

	MODEL – Water-to-Water	Group 1 - NA	Group 2 - NE	Group 3 – SE1	Group 3 – SE2
wh01	$COP_H = c_0 + c_1 \cdot SEFT + c_2 \cdot SFfr + c_3 \cdot (LExFT - SEFT) + c_4 \cdot (LExFT - SEFT)^2$	✓		✓	
wh02	$COP_H = c_0 + c_1 \cdot (LExFT - SEFT) + c_2 \cdot (LExFT - SEFT)^2$	✓	✓	✓	✓
wh03	$COP_H = 8.77 - 0.15 \cdot (LExFT - SEFT) + 0.000734 \cdot (LExFT - SEFT)^2$	✓	✓	✓	✓
wh04	$COP_H = c_0 \cdot \exp(c_1 \cdot SFExT + c_2 \cdot LEFT) + c_3 \cdot \frac{SFExT}{LFET} + c_4$	✓		✓	✓
wh05	$COP_H = c_0 \cdot \exp(c_1 \cdot SEFT + c_2 \cdot LExFT) + c_3 \cdot \frac{SEFT}{LExFT} + c_4$	✓	✓	✓	✓
wh06	$COP_H = c_0 + c_1 \cdot SEFT + c_2 \cdot LEFT + c_3 (SEFT \cdot LEFT)$	✓		✓	✓
wh07	$COP_H = c_0 + c_1 \cdot SEFT + c_2 \cdot LExFT + c_3 (SEFT \cdot LExFT)$	✓	✓	✓	✓
wh08	$COP_H = COP_{Carnot} \cdot \eta_{carnot,0} \quad \rightarrow \quad COP_{Carnot} = \frac{LEFT+273}{LEFT-SEFT}$	✓	✓	✓	✓
wh09	$COP_H = c_0 + c_1 \cdot LExFT + c_2 \cdot (LExFT - SEFT) + c_3 \cdot (LExFT - SEFT)^2$	✓	✓	✓	✓
wh10	$COP_H = c_0 + c_1 \cdot (LExFT - SEFT) + c_2 \cdot (LExFT - SEFT)^2 \quad \rightarrow \quad STAND.$		✓		
wh11	$COP_H = c_0 + c_1 \cdot (LEFT - SEFT) + c_2 \cdot (LEFT - SEFT)^2 \quad \rightarrow \quad STAND.$	✓			

Calculation of heat extraction



$$COP_H = c_0 + c_1 \cdot (LExFT - SEFT) + c_2 \cdot (LExFT - SEFT)^2$$

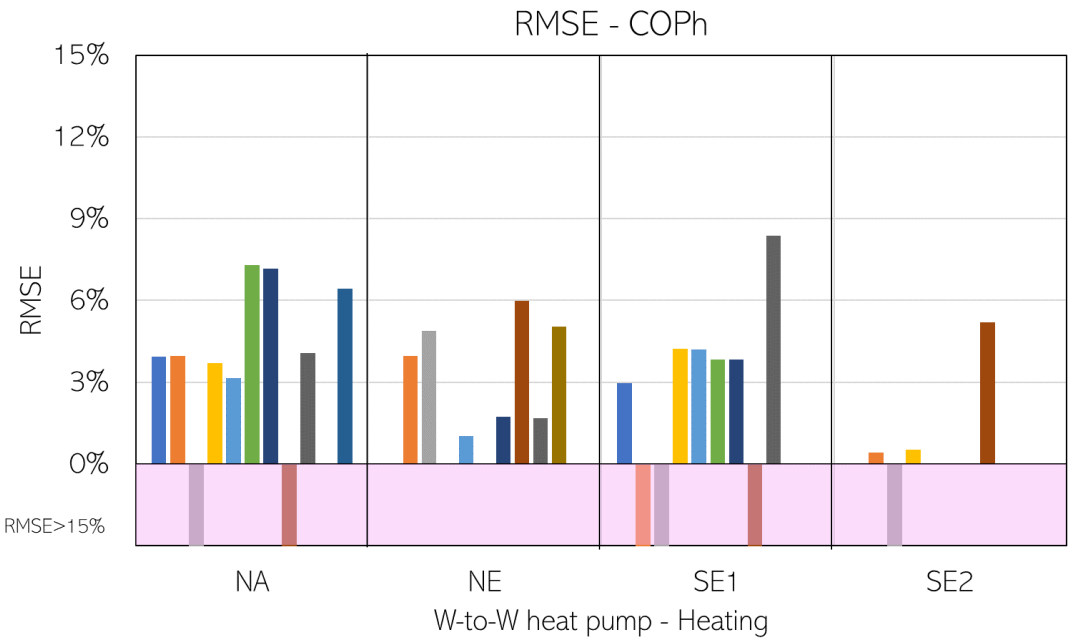
$$\dot{q}_{extraction} = \dot{q}_{heating} \cdot \left(1 - \frac{1}{COP_h}\right)$$

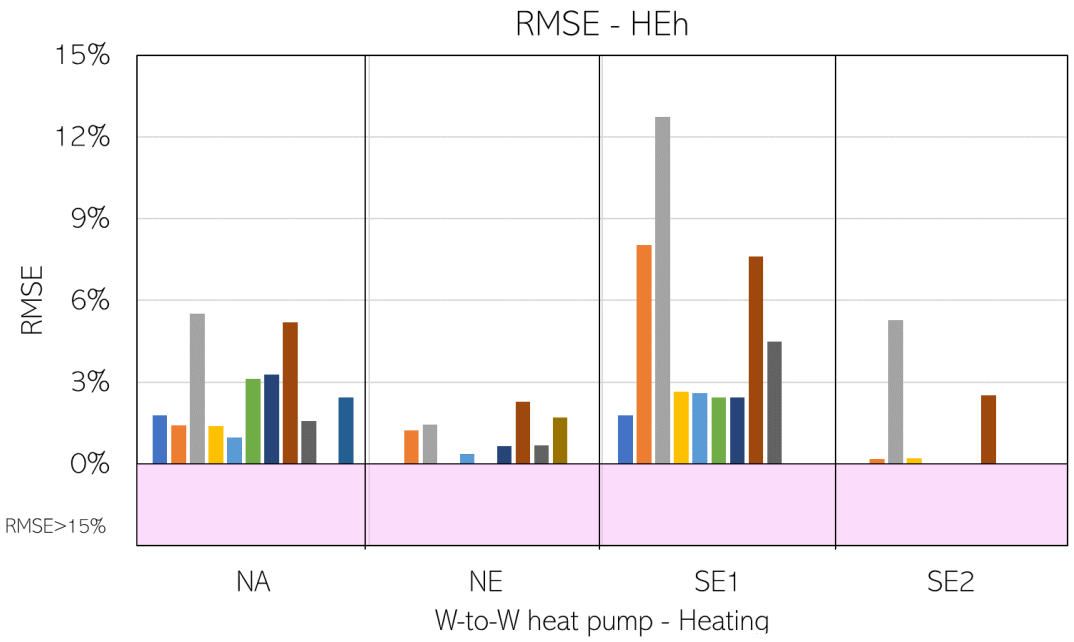
- Generalized least squares method or
- Generalized Reduced Gradient (non-linear solver implemented in Microsoft Excel)

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_{c,i} - y_{m,i}}{y_{c,i}}\right)^2}$$

Validation

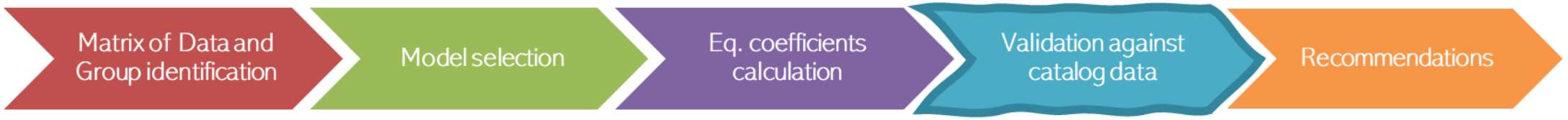
Matrix of Data and Group identification → Model selection → Eq. coefficients calculation → Validation against catalog data → Recommendations





wh1 wh2 wh3 wh4 wh5 wh6 wh7 wh8 wh9 wh10 wh11

Validation



- wh03 and wh08 leads to an average $RMSE_{COP}$ of 21% and 17%, and to an $RMSE_{HE}$ of 6% and 4%.
- wh03 and wh08 are likely to overestimate the COP and the HE, compared to catalog data
- wh01 leads to very good results when a wide range of data is available, but high $RMSE_{COP}$ and $RMSE_{HE}$ when operation conditions are limited
- The other models lead to an average maximum $RMSE_{COP}$ of 5% and an average maximum $RMSE_{HE}$ equal to 3%.

Recommendations

Matrix of Data and Group identification → Model selection → Eq. coefficients calculation → Validation against catalog data → Recommendations

	WtoW_H	wh01	wh02	wh03	wh04	wh05	wh06	wh07	wh08	wh09	wh10	wh11
$RMSE_{COPh}$	Group 1	3%	4%	19%	4%	4%	6%	6%	24%	5%	N/A	12%
	Group 2	N/A	3%	4%	N/A	1%	N/A	2%	6%	2%	5%	N/A
	Group 3	2%	5%	32%	2%	2%	2%	2%	12%	3%	N/A	N/A
$RMSE_{HE}$	Group 1	3%	3%	6%	3%	3%	4%	4%	5%	3%	N/A	4%
	Group 2	N/A	1%	1%	N/A	0%	N/A	1%	3%	1%	2%	N/A
	Group 3	2%	3%	10%	2%	2%	2%	2%	4%	2%	N/A	N/A
Recomm.	Group 1	x										
	Group 2					x		x		x		
	Group 3	x			x	x	x	x				

Conclusions

- Results of the models strongly affected by the accuracy and the level of detail of the manufacturer's catalog data
- Models might also be used to compute the COP of the heat pump
- The recommended models give acceptable accuracy in the calculation of the heat extraction, with no more than 3% RMSE when compared to catalog data.
- The recommended models presented in this paper are suitable for single-speed water-to-water heat pumps in heating mode and quasi-steady operation
- Further work is in progress to address water-to-air heat pumps and cooling mode
- Additional research is needed to treat multi-stage and variable-speed heat pumps
- Comparisons against field measurements are in progress: additional comparisons to field measurements would be welcome!

Thank you!

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