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445 - Application of Sensitivity Analysis to Parameters of Large Solar Water Heating Systems

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Abstract

In this paper the application of sensitivity analysis to the investigation of solar water heating systems is considered. Two global sensitivity analysis methods are described and applied to different solar heating systems. The first one is the Morris method that only ranks parameters by importance and the second one is the Fourier amplitude sensitivity test (FAST) that quantifies the influence of the parameters on the target functions. The both methods were implemented into the GenOpt (Generic Optimization) software and coupled with the TRNSYS simulation program.

Keywords: Sensitivity analysis, Fourier amplitude sensitivity test, Morris method

1. Introduction

In recent years, many middle to large solar heating systems were installed all around Europe and especially in Germany. A proper design of such systems is decisive for their functionality. Underdimensioning or poor selection of design parameters as well as the control strategy could lead to an overall poor efficiency of the systems. During the designing process, the advanced numerical optimization methods should be used in order to find the optimal parameter values that provide the best efficiency of the system. Considering that the target functions depend on a high number of optimization parameters and that the global optimization algorithms require large number of system simulations, the task of optimization turns to be very computationally expensive. In order to decrease the number of optimization parameters and, thus, make the optimization faster, the sensitivity analysis of parameters could be used prior to optimization. Only the most influential parameters are then selected for optimization. Another straightforward application of the sensitivity analysis is analysis of uncertainties, that is, how uncertainties in parameters influence the uncertainty of the target function. Here two sensitivity analysis methods are described and applied to the analysis of two solar heating systems. For the first system the influence of the operation parameters on the cost function is investigated by the qualitative Morris method. A more comprehensive Fourier amplitude sensitivity test is applied to the investigation of the influence of the design parameters on the solar fractional savings function of the second system. In this paper only the exemplary examples of applications of the both methods are considered. The methodological application of the methods is planned but not yet realized.

2. Description of global sensitivity analysis methods

The sensitivity analysis methods are divided in local and global ones. With local sensitivity analysis, the influence of parameters could be estimated only around a certain point in the parameters space. In the case of solar heating system, such an estimation is needed in a wider range of parameters variations, in a certain volume of space. For this, two representatives of global sensitivity analysis are applied, namely the Morris method and the Fourier amplitude sensitivity test (FAST).

2.1. Morris method

This method is qualitative and only ranks parameters by its importance which means influence on the target function [2]. However, it also allows to determine whether the parameters have linear or non-linear effects on the target function or if they are involved in interactions with other parameters. The Morris method is based on the so-called elementary effects, defined for the *i*th parameter as follows:

$$d_i(x) = \frac{[y(x_1,...x_{i-1}, x_i + \Delta, x_{i+1},..., x_k) - y(x)]}{\Delta} \qquad (1)$$

The elementary effects $d_i(x_m)$ are calculated at different parameter configurations x_m, $m = 1,...,M$ and then the distribution F_i of the elementary effects d_i or the distribution G_i of their absolute values is examined. The most informative sensitivity measures are the mean μ of the distribution G_i and the standard deviation σ of the distribution F_i. The mean μ is used to detect overall influence of the *i*th parameter on the target function y. The deviation σ is used to detect the parameters involved in interaction with other parameters or those, whose influence on y is non-linear.

2.2. Fourier amplitude sensitivity test

The Fourier amplitude sensitivity test (FAST) is a quantitative method [3]. It computes the contribution of each parameter to variations of the target function. It is called the "main effect" and defined as

$$S_i = \frac{\mathrm{var}_{x_i} \, | E(y \mid x_i) |}{\mathrm{var}(y)} \qquad (2)$$

Variations in numerator and denominator of (2) are multidimensional integrals over appropriate spaces. Their computation is very expensive. In the FAST, they are replaced by the one-dimensional integrals over the some curve exploring the space

$$x_i(s) = K_i(\sin \omega_i s) \qquad (3)$$

In the next stage of the method, the target function $y(s) = y(x_1(s), x_2(s),..., x_n(s))$ is expanded in the Fourier series $y(s) = \sum_{j=-\infty}^{+\infty} \{A_j \cos js + B_j \sin js\}$, and then the spectrum $\Lambda_j^2 = A_j^2 + B_j^2$ of the Fourier series expansion is used for calculation of the main effects.

The FAST algorithm can quantify influence of the parameters but for this it requires more calculations of the target function than the Morris method. If the system depends on very large number of parameters then it would be reasonable first to apply the Morris method and then to quantify the influence of only the most important parameters by the FAST algorithm.

3. Description of the investigated systems

The sensitivity analysis methods briefly described above are applied to analysis of two solar heating systems.

Fig. 1 shows the design of the system installed at a hospital in Frankfurt (Germany) [3]. It is designed as a preheating system. Depending on the temperatures in the collector loop and in the solar buffer storages, different inlets are used for charging the solar storage. For this system the design parameters are fixed at the values given in the figure, and only the influence of the operational parameters is investigated. The time resolution for simulating the system in TRNSYS was set to 10 minutes.

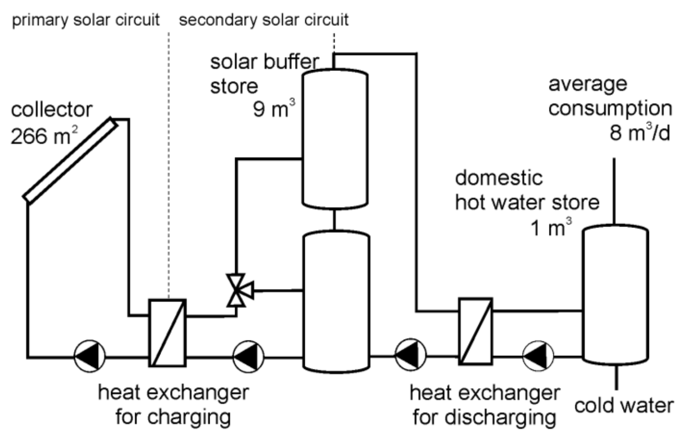

Fig. 1. Scheme of solar preheating system

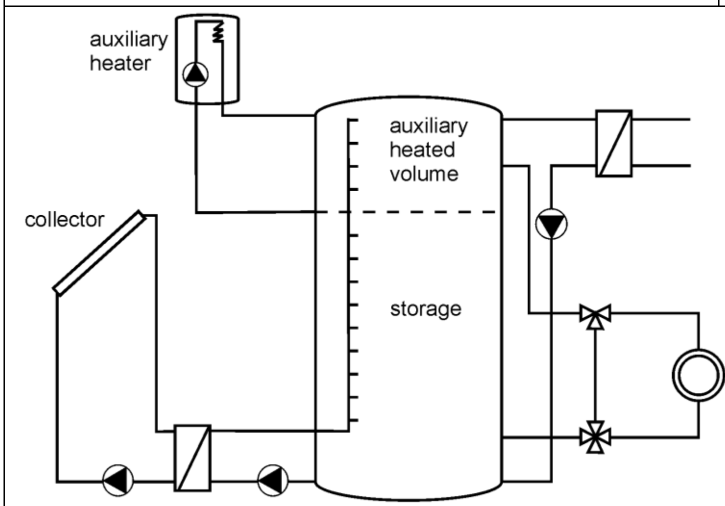

Fig. 2. Scheme of reference solar combisystem with auxiliary heating loop

In Fig. 2, a schematic layout is shown of the reference solar combisystem of Task 32. Besides the collector and storage tank, it has also an auxiliary heating loop with heated volume inside the tank. The weather data for Zurich (Switzerland) were taken for simulation and the time resolution was 3 minutes. The influence of a few design and operation parameters is investigated by the FAST algorithm.

This system is an example of planning case, when all design and operational parameters can be chosen for sensitive analysis and consequent optimization. The methodological approach would be first to apply the Morris method and then FAST for more accurate estimation of the parameters influence.

4. Numerical results

The described sensitivity analysis methods are implemented into the Genopt (Generic optimization program) [4] and coupled with the simulation program TRNSYS. For the first system, the influence of 16 parameters on the target function, describing the overall cost of the system in ct/kWh_{solar}, was investigated by the Morris method. Results of the analysis are presented in the Table 1.

Table 1. Ranking of the parameters by their influence on the cost target function by the Moris method. The value of the mean μ estimates the overall influence of the parameter and the deviation σ shows its non-linear effect.

N	Parameter		Variation range	μ	δ
1	$\dot{v}_{\mathrm{dis,max}}$	Max. discharge spec. volume flow	[10; 15] in L/m^{2}h	4.54	7.44
2	$\dot{v}_{\mathrm{sol,p}}$	Specific volume flow	[6; 10] in L/m^{2}h	2.29	2.92
3	D_{pipe}	Pipe deameter	[20; 30] in mm	1.85	4.75
4	V_{store}	Volume of solar storage	[4000; 8000] in Liter	0.46	0.58
5	β_{coll}	Collector slope	[30; 46] in ^{o}	0.70	0.51
6	ΔT_{hyst}	Hyst. for contr. pump in sec. circ	[1; 7] in K	0.41	0.29
7	H_{ch1}	Rel. pos. of inlet 1	[0.6; 1]	0.30	0.77
8	H_{ch2}	Rel. pos. of inlet 2	[0.1; 0.6]	0.24	0.21
9	S_{h1}	Rel. pos. of temp. sensor 1	[0.1; 0.5]	0.23	0.41
10	ΔT_{u}	Temp. diff. to switch off the pump	[0; 7] in K	0.16	0.23
11	S_{h2}	Rel. pos. of temp. sensor 2	[0.55; 0.75]	0.18	0.26
12	UA_{SHE}	UA value of the sol. heat exch.	[70; 130] in W/m^{2}K	0.08	0.09
13	γ_{coll}	Scaling factor	[-5; 6] in ^{o}	0.03	0.02
14	G_{hyst}	Hyst. for contr. pump in sol. circ.	[2; 50] in W/m^2	0.02	0.02
15	G_{min}	Switch-off threshold for pump	[40; 200] in W/m^2	0.01	0.02
16	S_{h3}	Rel. pos. of temp. sensor 3	[0.8; 1]	0.00	0.00

In Fig. 3 the mean μ of the distribution G_i versus the standard deviation σ of the distribution F_i is given. The larger the value of the mean μ. the larger the overall influence of the parameter. Large values of the standard deviation σ mean strong non-linear effect of the parameter or its interaction with other parameters. It is seen that parameters 1-3 (the maximal power of two pumps in charging and discharging circuits and the diameter of pipes) are the most important and influence the target function both linearly and non-linearly. Parameters 4-7 could be considered as average important and the other 9 parameters as not important.

The second system has been investigated with the FAST. The target function is chosen as the fractional thermal energy savings $f_{\text{sav,therm}}$:

$$f_{\text{sav,therm}} = 1 - \frac{E_{\text{aux}}}{E_{\text{ref}}}. \tag{4}$$

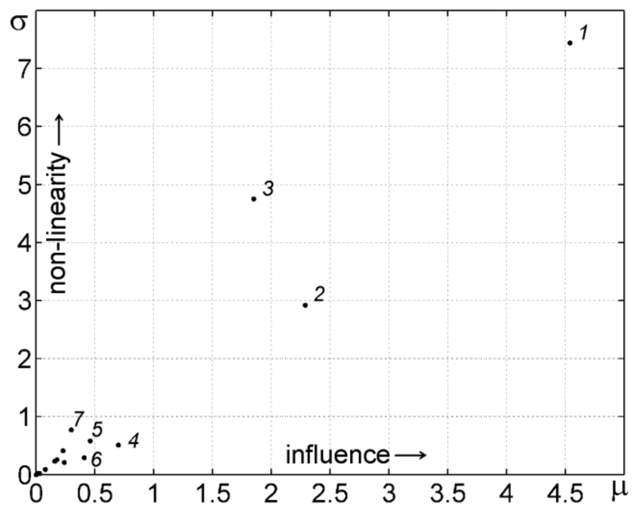

Fig. 3. Ranking of parameters of solar preheating system (Fig. 1) by the Morris method. The value of the mean μ estimates the overall influence of the parameter and the deviation σ shows its non-linear effect.

Table 2 shows the main effects on $f_{\text{sav,therm}}$ of six parameters that were chosen by hand. The parameters have been changed in the given ranges. As the first test shows. the most influential parameter is the collector area (around 80% of all variation of $f_{\text{sav,therm}}$). In tests 2-4 the collector area is fixed at corresponding values and the importance of the other parameters is investigated. It is seen that the influence of the store volume and the mass flow grows with increasing the collector area.

Table 2. Sensitivity of parameters of the reference system determined with the FAST algorithm.

Parameter	Variation range	Sensitivity indices (main effect)			
		Test 1	Test 2	Test 3	Test 4
Collector area	[20; 100] in m^2	0.8144	Fixed at 30 m^2	Fixed at 50 m^2	Fixed at 100 m^2
Store volume	[3; 20] in m^3	0.0776	0.2780	0.3823	0.5655
Store UA value	[0; 50] in $W/K/m^2$	0.0732	0.5856	0.4370	0.2630
Set temperature of DHW	[40; 65] in °C	0.0012	0.0215	0.0140	0.0083
Mass flow in solar loop	[10; 70] in $kg/h{\cdot}m^2$	0.0272	0.1136	0.1328	0.1353
Auxiliary volume	[0.2; 1.0] in m^3	0.0029	0.0100	0.0090	0.0094

5. Conclusion

The sensitivity analysis methods applied to the solar heating systems show that only some parameters have significant influence on the corresponding target functions. If the target function depends on many system parameters and only the most influential parameters should be identified then it seems to be computationally more efficient first to apply the Morris method and then the FAST algorithm.

Nomenclature

D_{pipe}	mm	diameter of pipes
d_i	-	Elementary effect
E_{aux}	kWh	Auxiliary final energy consumption of the solar combisystem
E_{ref}	kWh	Final energy consumption of the reference system
$E(y \mid x_i)$	-	expectation of the target function y conditional on a fixed value of parameter x_i
F_i	-	Distribution of elementary effects
$f_{\mathrm{sav,therm}}$	-	Fractional thermal energy savings
G_i	-	Distribution of absolute values of elementary effects
G_{min}	W/m^2	Switch-off threshold for controlling the pump in the solar circuit
G_{hyst}	W/m^2	Hysteresis for controlling the pump in the solar circuit
H_{ch1}	-	Relative position of the inlet charging the hot store.
H_{ch2}	-	Relative position of the inlet charging the cold store.
K_i	-	transformation functions
S_i	-	Main effects
s	-	Scalar variable
S_{h1}-S_{h3}	-	Relative positions of the temperature sensors for switching on the solar circuit.
UA_{SHE}	W/m^{2}K	UA value of the heat exchanger in the solar circuit
var_{x_i}	-	variation taken over all possible values of x_i
$\dot{v}_{\mathrm{dis,max}}$	L/m^{2}h	Maximal discharge specific volume flow
$\dot{v}_{\mathrm{sol,p}}$	L/m^{2}h	Specific volume flow in the primary solar circuit
V_{store}	Liter	Volume of solar storage
x	-	Parameters vector
y	-	Target function
β_{coll}	^{o}	Collector slope
γ_{coll}	^{o}	Scaling factor
Δ	-	Displacement
ΔT_{u}	K	Temperature difference for switching off the pump in the secondary solar circuit
ΔT_{hyst}	K	Hysteresis for controlling the pump in secondary solar circuit
μ	-	mean of the distribution G_i

σ - deviation of the distribution F_i

ω_i - Angular frequency

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