

EVALUATION OF THE IMPACT OF NETWORKING ACTIVITIES ON THE QUALITY OF RESULTS OBTAINED WHEN APPLYING SYSTEM IDENTIFICATION TECHNIQUES TO IN-SITU MEASUREMENTS FOR ASSESSING ENERGY PERFORMANCE OF BUILDING COMPONENTS

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ABSTRACT

The application of system identification techniques to the energy performance of buildings and building components requires a very high level of knowledge of physical and mathematical processes. This factor, combined with the quality of the data, the description of the monitoring environment and procedure, together with the experience of the user of the analysis software itself, can end up in varying results from different users when applying different models and software packages. The objective of a number of activities in recent years has been to develop benchmark test data sets for assessing user performance. Past international system identification competitions ('94 & '96), demonstrated the spread in results that can be expected with regards to application of different models and techniques to the same data. Furthermore, activities of the PASLINK EEIG have tried to consolidate and strengthen the level of knowledge in system identification techniques when applied to the energy and environmental performance of buildings and building components. Workshops have been implemented to assist in the development and application of training instruments which aim to promote the levels of expertise within the grouping and to ensure that data analysis meets the minimum required quality levels. This paper compares the spread in results obtained during the previous competitions to that obtained during the workshops carried out by the PASLINK EEIG following ten years of networking activities in the field. The objective is to identify the extent to which the networking activities have strengthened the position of the individual teams working in the field and to identify the areas where quality assurance is met and, furthermore, where further improvements can be made. A direct comparison of the quality of results obtained on test results from the previous decade is made with the recent results of data analyzed by following the networking is given and account is taken for changes in software and tools as well as the composition of the individual teams.

Keywords: Dynamical analysis, energy performance, buildings, building components

1. INTRODUCTION

During the last decade, system identification techniques have been developed in order to facilitate the need of researchers for a better and more accurate knowledge of the thermal characteristics of building components. Many software packages have been developed, like LADY, CTLSM, MRQT351, MATLAB, and extensive use has been performed. In order to evaluate to an extent the different software capabilities and the experience of the software user, two system identification competitions have been organized, one in 1994 and another in 1996. Apart from that, in the framework of the IQ-TEST project (ERK6-CT1999-2003), a European Community project under the EESD programme, three training exercises have been carried out, aiming to the improvement of expertise of the participating teams. This paper briefly presents the results obtained during the previous competitions, and that obtained during the

workshops carried out during the IQ-TEST project, and tries to identify the level of skill gained over the last years by the participants.

2. 1ST SYSTEM IDENTIFICATION COMPETITION

In the 1st System Identification Competition (1994), the participants were asked to work with some of the 5 case studies prepared by using their preferable software program and present their results [1]. Twenty people participated in this competition and the methods used for the data analysis can be found in Table 1. The case studies comprised: Case 1, a homogenous wall for the estimation of R (thermal resistance) and C (thermal capacitance). Case 2 referred to a three layer symmetric wall for the estimation of R and C. Case 3 was concerning the estimation of five specially defined parameters (H1, H2, H3, G1, and G2) of a lumped parameter system. Case 4 was concerning with the predictions of the heat flow density at the internal surface of a two layer wall for the estimation of R. Case 5 was concerning with the predictions of the heat flow density at the internal surface of a homogenous wall for the estimation of R and C [2].

Table 1. Applied methods used for the 1st System Identification Competition [1].

Identity Nr.	Method name	Method description
1001	MRQT	Thermal network
1002	CTLSM	Thermal network, CT
1003	Pentaur	Mult. Regression, QBasic
1004	IDENT	Thermal network
1005	LabView	Thermal network, FFT
1006	MRQT	Thermal network
1007	MRQT	Thermal network
1008	NN	MATLAB, NN
1009	XPrisma	Sing. Value decomposition
1010	SIMPLEX	MATLAB
1011	PEM	MATLAB, SIT
1012	CT	MATLAB
1013	NN	QBasic
1014	PEM	MATLAB, SIT
1015	HC, own heat cond. eq.	T Pascal
1016	LADY	Mode reduction
1017	PEM	MATLAB, SIT
1020	CTLSM	Thermal network, CT
1021	CTLSM	Thermal network, CT
1022	PEM	MATLAB, SIT

Full instructions concerning the cases and their data sets were provided to the participants. The submitted were evaluated using the same software program. A ranking of performance was made based on standard statistical measures for each individual case. The estimation and prediction results were separately evaluated. For all cases an overall check has been performed by comparing the estimated result of the overall values for R and C with the values used for the creation of the data. Statistical tests were also applied, like t-test, F-test, and χ^2 test for a more complete comparison between results. The results obtained for Case 1 can be seen in Table 2.

Table 2. Overview of results for Case 1.

Identity Nr.	Thermal Resistance		Thermal Capacitance	
	Estimated R	Difference %	Estimated C	Difference %
1001	8.658	0.08	52.99	0.901
1002	9.356	8.15	32.40	39.41
1003	8.636	0.17	53.778	0.57
1004	9.171	6.01	50.05	6.40
1005	9.138	5.63	54.17	1.31
1006	8.945	3.4	34.39	35.69
1007	8.726	0.87	0.125	99.77
1009	8.775	1.43	3.043	94.31

1010	0.0078	99.91	3.67	93.14
1011	13.2	52.58	13.97	73.87
1015	8.8	1.72	57.00	6.60
1016	8.666	0.18	60.49	13.13
1020	9.841	13.76	43.07	19.45
1021	8.655	0.05	55.89	4.52
1022	12.936	49.54	17.19	67.85
	"Real" R value = 8.651 (m ² K)/W		"Real" C value = 53.472 Wh/(m ² K)	

The results of all Cases in terms of percentage differences from the "real" value are summarized in Table 3. It was found that large discrepancies were observed between results, a fact which was depending on the ability of the participants to model each individual case, the software program limitations, and the right treatment of data sets.

Table 3. Overview of results from the 1st System Identification Competition Cases.

Cases	Parameter	"Real" Value	Minimum Difference %	Maximum Difference %
Case 1	R	8.651	0.05	99.91
	C	53.472	0.57	99.77
Case 2	R	3.229	0.09	99.83
	C	81.00	0.92	833.77
Case 3	H1	1000	0.77	99900
	H2	10.00	0.33	73379
	H3	0.100	0.00	155851
	G1	100.00	0.20	245750
	G2	50.00	0.00	22200
Case 4	R	3.140	0.06	99.91
	C	26.778	1.10	100
Case 5	R	2.268	0.08	99.85
	C	22.00	1.41	99.27

The differences appear in percentages which makes a direct comparison possible among participants. The competition showed that a number of methods and techniques exist and how inventive researchers can be to solve a relatively simple physical problem. The competition concluded with the remark that the applied identification technique can be known, but the applicant needs a certain level of skill to apply the method successfully in order to perform well. Furthermore the competition has shown that the estimation of the uncertainty of the parameter estimates was a difficult task and it was not looked into great extent.

3. 2nd SYSTEM IDENTIFICATION COMPETITION

In 1996, a second System Identification Competition was organized, involving practical problems, such as solar radiation and experimental data. The objective of this competition was to set up a comparison between alternative techniques and to clarify particular problems of system identification applied to the thermal performance of buildings. The competition was mainly concerned with wall components and solar radiation. Four different cases were provided for estimation and prediction [3]. Three of these cases have been designed with wall components in order to test parameter estimation methods and include different degrees of difficulty. Prediction tests were also included on experimental data. The evaluation of the results from this competition is in its final stage, and the outcomes will be published in the near future. Eighteen people participated in this competition and a variety of simulation methods for the data analysis was used. The results of Cases B and D in terms of percentage differences from the "real" value are summarized in Table 4. It was found that good agreement was achieved in mainly the estimation of the thermal resistance, R, with differences between the estimated results and the "real" value ranging from 0.08 to 2.99 % for Case B, and 0.1 to 3.7 % for Case D, respectively. In terms of the thermal capacitance, C, the differences between the estimated results and the "real" value ranging from 1.37 to 344 % for Case B, and 0.86 to 129 % for Case D, respectively depicting the greater difficulty to estimate this parameter. Quality aspects regarding data treatment were taken into account.

Table 4. Overview of results from two of the 2nd System Identification Competition Cases.

Id. Nr.	Case B				Case D			
	Thermal Resistance		Thermal Capacitance		Thermal Resistance		Thermal Capacitance	
	Estimated R	Difference %	Estimated C	Difference %	Estimated R	Difference %	Estimated C	Difference %
2001	2.546	0.24	73.46	344	3.024	1.44	54.47	129
2002	2.542	0.08	18.6	12.50	2.985	0.13	21.2	10.62
2003	x	x	x	x	2.992	0.37	17.15	27.70
2004	2.545	0.18	18.15	9.78	2.984	0.10	21.05	11.25
2005	2.545	0.18	17.65	6.76	2.974	0.23	21.77	8.22
2006	2.544	0.16	17.5	5.85	2.979	0.07	21.12	10.96
2007	x	x	x	x	2.977	0.13	21.656	8.70
2008	2.543	0.12	17.27	4.46	2.978	0.10	21.46	9.52
2102	2.616	2.99	23.5	42.14	2.953	0.94	23.514	0.86
2103	x	x	x	x	2.998	0.57	19.13	19.35
2104	x	x	x	x	3.091	3.70	27.339	15.26
2201	2.544	0.16	16.99	2.76	2.974	0.23	25.41	7.13
2202	2.545	0.2	16.99	2.76	2.974	0.23	25.354	6.89
2301	2.545	0.2	15.63	5.46	2.974	0.23	21.35	9.99
2401	2.543	0.12	16.76	1.37	2.960	0.69	35.569	49.96
2601	2.544	0.16	17.09	3.37	2.974	0.25	21.492	9.39
	“Real” R value = 2.54 (m ² K)/W		“Real” C value = 16.533 Wh/(m ² K)		“Real” R value = 2.981 (m ² K)/W		“Real” C value = 23.919 Wh/(m ² K)	

4. TRAINING PACKAGES FROM IQ-TEST PROJECT

In the framework of IQ-Test (Improving Quality in Test and Evaluation procedures of Solar and Thermal performances of building components) project [4], under the coordination of the PASLINK EEIG network, a work package for the training of test site personnel and data analysis was carried out. The objective of this package was to develop and apply a set of training instruments, aiming to promote that at each member’s outdoor test site the expertise in the design, preparation and execution of tests and the analysis of test data comply with the required minimum quality level. Having in mind the difficulties with which test site teams are faced with, regarding the data modeling and analysis of an experiment, together with accuracy of results, three training sessions were organized whose aims were the following:

- 1) To train people in system identification, parameter estimation and model validation using statistical methods.
- 2) To transfer the know-how on non-linear and non-stationary modelling of thermal dynamics of complex building components.
- 3) To train people to use and implement methods for automatic detection of errors in on-line measurements. Methods for both systematic and random errors were considered.
- 4) To train people to implement methods for correction of errors and for filling in missing observations in time series.
- 5) To assist people and test teams in signal processing, error detection, statistics, system identification, model verification and in modeling dynamical systems in general.
- 6) To train on the design of experiments. The motivation for this subject was the fact that by designing the experiment in an optimal way, the number of test, or the needed time period, can be reduced.

The training sessions - workshops organised, consisted of:

- Workshops with presentations concerning system identification, data processing and error analysis.
- Training sessions with hands-on analysis of simulated or real dynamic tests sequences and/or discussion of home work.

Material from these sessions included: Presentations at the workshops, specifications of the calculation cases, and individual homework reports. Approximately twenty people participated in each of the workshops and apart from attending lectures from specialists on system identification and data modelling, were asked to analyse data sets by using the software program of their choice. However, in these training sessions, the identification software LORD [5], the ancestor of MRQT, was widely used and some teams

used the MATLAB – IDENT software [6]. The outcomes of these sessions were: Workshop presentations, training package which includes all the case studies instructions and data sets, a list of frequently made mistakes during dynamic analysis of test results and tips on how to overcome them, guidance on an experiment set up and error analysis procedures, and a complete example of test evaluation report.

In the 1st training session, three exercises were studied by the participants concerning sets of data from different sources. The main objectives of this session was to gain a thorough knowledge on data analysis and the application of System Identification Techniques, and to get familiarised with the dynamic analysis of thermal data software tool LORD. The outcomes of this training session were important because they set up a platform on how a complete data analysis procedure should be performed.

In the 2nd training session, two data sets were analysed by the participants taken from a specimen test carried out in the frame of IQ-Test project by one of the participating teams. The results, which included the determination of the UA, U and g-values of a wall and window components were satisfactory with small variations in each parameter estimation. A template on how to perform error analysis was also implemented, taking into account all possible parameters which could affect the accuracy of the result. The workshop was enriched with lectures on dynamic analysis and modelling techniques for the assessment of unknown parameters in physical systems and in particular systems that have dynamic or non-linear behaviour, like i.e. photovoltaic and ventilated facades together with a comparison of Output Error (OE) and Prediction Error (PEM) methods.

In the 3rd training session, two data sets were analyzed by the participants taken from a specimen test constituting of an opaque wall component and an “unknown” component [7]. The objective of the exercise was to determine the UA-value of the opaque wall, the U-value of the wall’s central part, the UA-value of the wall with the unknown component installed in the central part of the wall, the UA and gA-values of the unknown component. For the data analysis, the software programs LORD and MATLAB were used. The results showed good agreement between the teams for achieving the UA- and gA-values of the unknown component: The UA range = 2.9-3.1 W/K, gA range = 0.65-0.68 m² and excellent agreement was achieved for the UA-value of the opaque wall with the unknown component, with a range of values between 3.97 and 4.04 W/K [1], [8]. The identification of the whole wall UA-value of the opaque wall (range 1.24-1.41 W/K) provided the largest contribution to variation in the estimates of the UA-value of the component. Table 5 presents the results of this training exercise.

Table 5. Overview of the results from the 3rd training workshop.

Team ID.	Opaque Wall Test				Component X Test					
	Whole Wall UA (W/K)	Diff. %	Profile A U-value (W/m ² K)	Diff. %	Wall + component UA (W/K)	Diff. %	UAcomponent (W/K)	Diff. %	gA _{component} (m ²)	Diff. %
A	1.33	0.76	0.17	5.56	3.99	0.00	2.99	0.40	0.67	1.52
B	1.37	3.79	0.18	0.00	4	0.25	2.96	1.40	0.67	1.52
C	1.28	3.03	0.18	0.00	4	0.25	3.06	1.93	0.67	1.52
D	1.37	3.79	0.18	0.00	4	0.25	2.96	1.40	0.67	1.52
E	1.28	3.03	0.18	0.00	3.98	0.25	3.04	1.27	0.67	1.52
F	1.41	6.82	0.18	0.00	3.98	0.25	2.91	3.06	0.67	1.52
G	1.36	3.03	0.18	0.00	4	0.25	2.99	0.40	0.65	1.52
H	1.35	2.27	0.18	0.00	3.97	0.50	2.96	1.40	0.66	0.00
J	1.26	4.55	0.18	0.00	4.04	1.25	3.1	3.26	0.68	2.27
K	1.24	6.06	0.18	0.00	3.98	0.25	3.08	2.60	0.67	1.52
Average UA= 1.32		Average U= 0.18			Average UA _{wall+component} = 3.99		Average UA _{component} = 3.002		Average gA _{component} = 0.66	

The deviations between the estimated results ranged: for the UA-value of the opaque wall between 0.76 and 6.8 %, for the central part of the opaque wall between 0.0 and 5.6 %, for the UA-value of the wall component with the unknown component installed between 0.0 and 1.25 %, for the UA-value of the unknown component between 0.4 and 3.26 %, and for the gA-value of the unknown component between 0.0 and 2.27 %.

Quality aspects regarding the data and error analysis have also been dealt with by the development of a spreadsheet for the estimation of the uncertainty of the measurement results.

5. COMPARISON OF RESULTS

System Identification techniques have been applied to assess the energy performance of building components for many years. During this period, successful steps have been realized to assist the researcher to better understand the physical and mathematical processes that can be applied in the estimation of the thermal properties of buildings and building components. The three above mentioned events have contributed to this objective by clarifying particular problems of system identification and providing quality procedures regarding data modeling and analysis to improve the researcher's performance in achieving reliable results. In an attempt to quantify this, an inter-comparison of results acquired from the three events has been performed. In Figure 1 all the results from the cases and exercises mentioned above are presented in terms of the minimum and maximum deviations from the "real" value. By this way, a comparison of the obtained results can be made (note that the chart is in logarithmic scale). It can be seen that the deviation range for the results of the 1st System Identification Competition are very large depicting the problems that arose during the data modeling and analysis process.

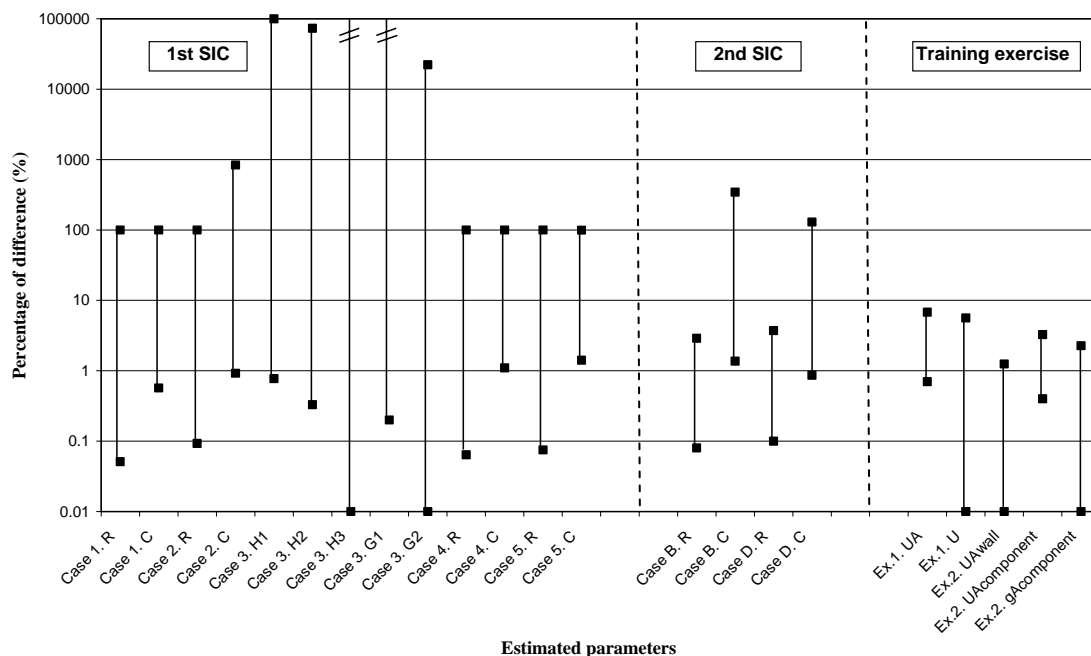


Figure 1. Comparison of the spread of results from the cases of the three events.

Concerning the 2nd System Identification Competition it can be seen that the spread of results in same cases is small and in some others large. Finally, in the last training session, through the IQ-Test project, the spread of results for all cases studied is small.

It should also be noted that in all events the case studies – exercises were of ranging difficulty: from simple cases to more complicated ones.

In Figures 2 to 4 the best and worse results of the three events are presented, taking into account the performance of all participants. It can be seen that in the 1st System Identification Competition (refer to Figure 2), even in the best case (R-value estimation from case 1) in terms of the deviation of results from the "real" value, the results are quite scattered. The worse case depicts the inefficiency of the participants to correctly identify the unknown parameter (case 3 – thermal conductance). Regarding the best and worse case results of the 2nd System Identification Competition (refer to Figure 3) it can be seen that the thermal resistance, R, of case B has been estimated satisfactory. However, the thermal capacitance of the same case has not been determined accurately. Finally, in the 3rd IQ-Test Workshop, both best and worse cases showed a good consistency in the estimation of the unknown parameters (see Figure 4), with small deviation of results pointing out the good performance of all participants.

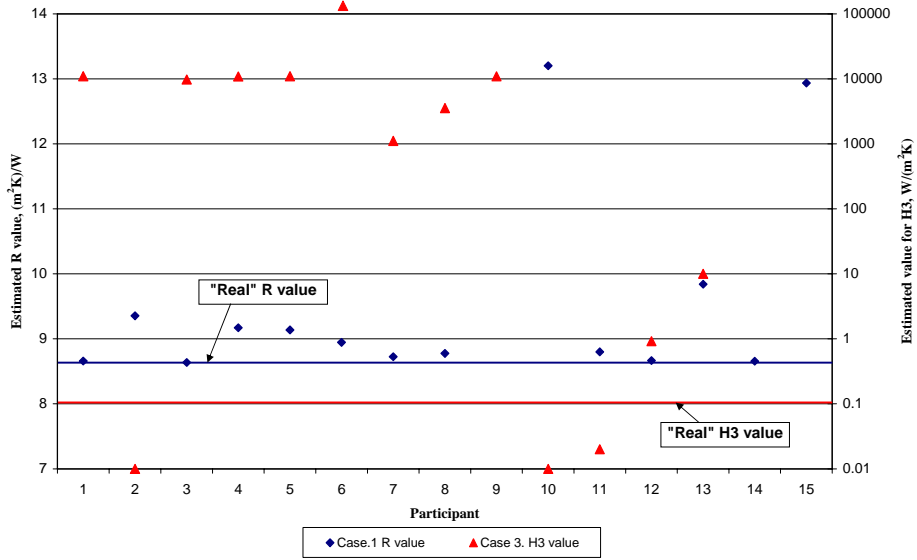


Figure 2. Best and worst Case results from 1st System Identification Competition.

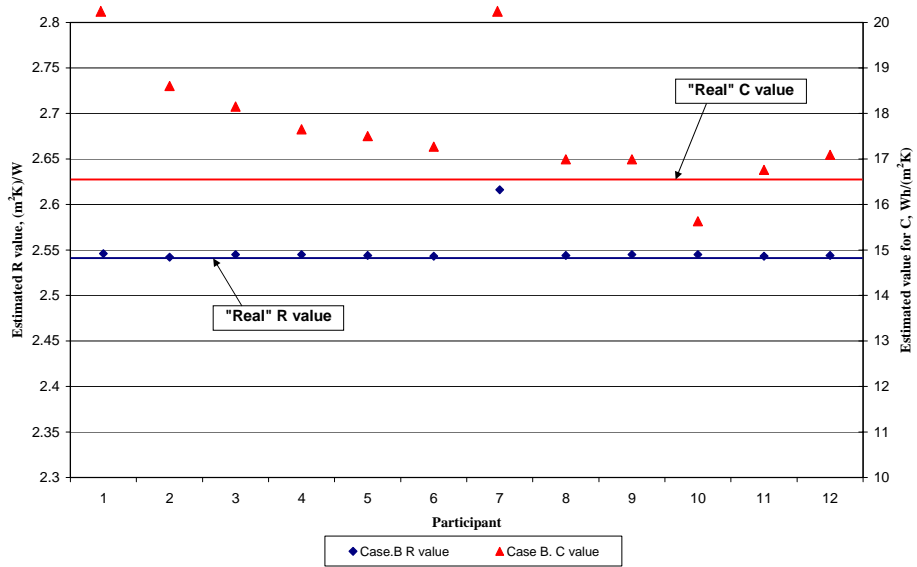


Figure 3. Best and worst Case results from 2nd System Identification Competition.

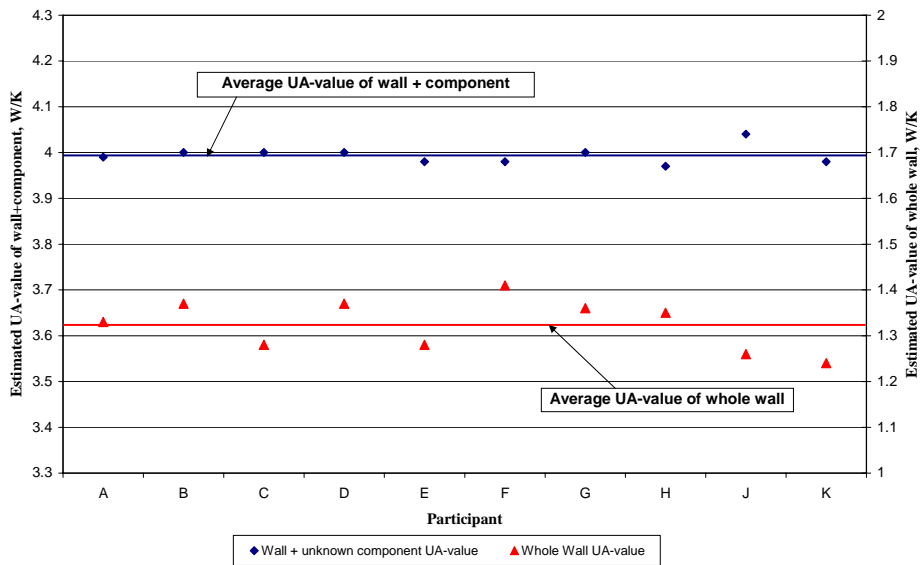


Figure 4. Best and worst Case results from 3rd Workshop.

The above findings can serve as an indication on how the level of skill on applying data analysis methods and techniques has been improved over the years. This has been achieved by the development of quality procedures regarding the following aspects: building components testing, data collection and processing, data modeling and analysis, validation of results, and error analysis.

In Figure 5, a breakdown of the three events has been done, by means of new participants and people that have participated in both the last event and either of the two prior events. It is considered that in the 1st System Identification Competition all participants were new, in the 2nd System Identification Competition 7 persons were new while 9 persons had participated in SIC 1, and in the third event only 3 persons had participated in SIC 1 and/or in SIC 2. It can be seen that, regarding the 3rd training workshop, although 70 % of the participants were new, through the knowledge gained during the IQ-Test project, and the development of new, user friendly software tools, they performed effectively and provided good results.

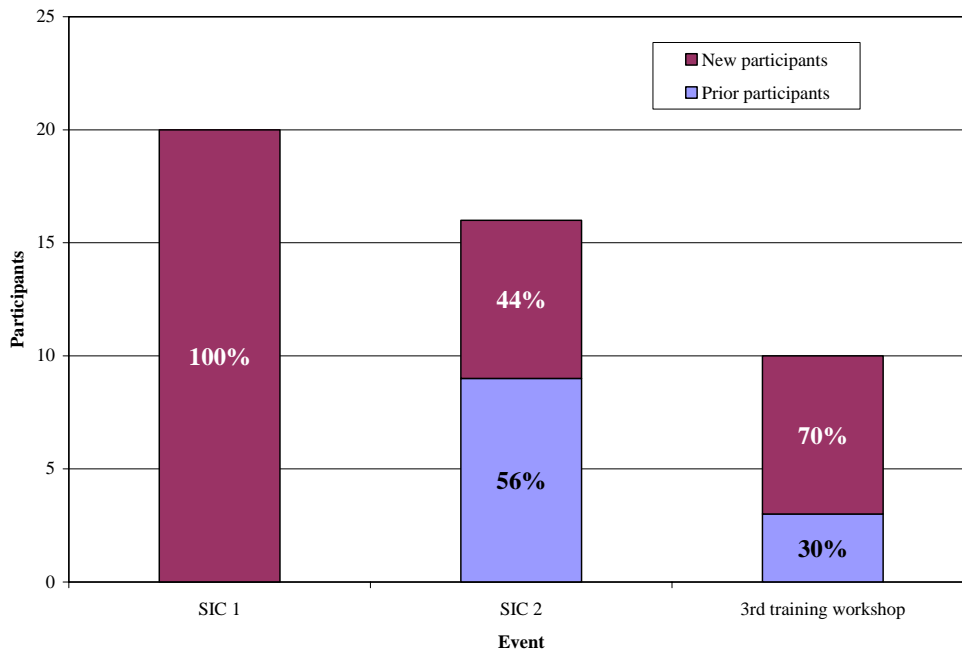


Figure 5. Composition of participants in the three events.

It should be stressed here that the application of System Identification techniques implies a thorough knowledge of the experiment set up, the control strategy and data acquisition, the data processing, instruments used together with their accuracy, and factors which can dynamically affect the test (i.e. ambient conditions). Taking also into consideration the different background of the researchers, and the fact that changes in personnel involved with data analysis often occur, the objectives of the IQ-Test Thematic network (refer also to section 4) to establish a quality level in data analysis and confidence of results have been met and it can be regarded as a success of this Thematic network.

6. CONCLUSIONS

The general conclusions that can be drawn are the following:

- Competitions, workshops and training courses can serve as a tool to clarify and solve particular problems regarding the application of dynamical analysis methods and establish the co-operation and exchange of ideas between researchers.
- The level of expertise of the person involved in data modeling and analysis procedures plays an important role.
- The level of skill can be improved by the constant involvement with experimental data treatment, self experimentation on data analysis and modeling procedures, and by participating to system identification competition and related Conferences-workshops.
- Special step to step procedures have been prepared and can be used to help the researcher to check parameter identification results and prepare better initial parameters and/or model.
- New software tools have been developed (LORD, MATLAB-IDENT), in a user friendly environment, to help the researcher to perform a data analysis more easily and in less time.

- Quality aspects regarding the uncertainty of measurement results have been dealt with by incorporating both the OEM and PEM error analyses in the latest LORD version, and by the development of a software guidance tool which informs the researcher and the potential client on the expected accuracy of a dynamic thermal/solar test on a building component.

The IQ-Test project has provided valuable information through workshops, guidance tools, knowledge transfer, in order to help researchers to get familiarized with identification techniques and dynamical analysis and modeling methods mainly applied to the energy performance assessment of buildings.

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