INVESTIGATION OF THE REAL TIME FUZZY CONTROL SYSTEM OF A TWO-VARIABLE PLANT

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Abstract: Temperature and humidity are the basic variables in the energy efficient control of indoor comfort in laboratory premises. Their interconnection, the many disturbances – outdoor ambient influences, people and equipment impact, etc. and the inertia make difficult the modelling of the processes and the design of the control using classical approaches. The model free fuzzy logic control has proven its advanges in such cases. The aim of the present paper is to study designed and tested by simulation different two-variable fuzzy logic controllers (FLCs) in the real time control of a pilot plant and to assess the system performance and the energy consumption. The pilot plant is built on operational amplifiers to model the temperature-humidity relationship. In real time control a more realistic system is considered, subjected to real world noises, disturbances, inertia, nonlinearities due to insensitivity and saturation of signals, etc. The main results are development of the pilot plant and the real time fuzzy logic algorithms, experimentation and comparison of systems performances and selection of the most energy efficient FLC.

Key words: energy efficiency, fuzzy logic two-variable PI controllers, MATLAB^{TM}, pilot plant for indoor climate, real time experimentation

1. Introduction and Aim of Investigation

Indoor comfort is of cruicial importance for the modern high standards of living. However, it is high energy consuming and a proper control should account for energy efficiency [1, 2]. The plant is characterised by several basic interconnected variables – temperature, humdity, emissions of carbon doxide, etc., so, it is multivariable. Besides, it is subjected to many disturbances - outdoor ambient influences (air temperature, humidity, wind, etc.), people and equipment impact, etc. The processes are also nonlinear, very inertial, with variable parameters and model uncertainties [1]. The application of the classcal control approach requires a working -simple and precise, plant model, which is hard to derive, considering all above mentioned plant peculiarities. The fuzzy logic controllers (FLCs) are proper candidates for control in air-condition systems as they are model free, based only on expert information about the process, and also ensure system robustness [3]. Most of the FLCs, however, are complex in structure in order to respond to the high demands for the control of such compex plants. They are designed as evolving, adaptive or with tuning rules, employing advanced techniques such as genetic algorithms [4-7]. In [8, 9] a simple and practical design is developed for multivariable, mainly two-variable PI/PID FLCs that accounts for plant variables interconnection, nonlinearity, inertia, model uncertainty and system stabilty demands. Besides, the controllers ensure smooth and economic control action.

Three types of PI FLCs for a two-variable linear plant that describes processes similar to those in indoor climate, are designed in [9]. The systems performances are compared by simulation.

The aim of the present investigation is to experimentally study the designed in [9] three types of FLCs in a more realistic environment, using pilot plant model and MATLAB^{TM} real time in order to better assess the performances of the closed loop systems and to select the most energy efficient FLC. The main tasks in fulfillment of the aim are: 1) to develop a pilot two-variable plant to model premise‘s temperature and humidity characteristics; 2) to modify the FLCs in [9] for real time implementation and 3) to design and carry out MATLAB^{TM} real time experimentation and to assess systems performance and energy efficiency.

In real time control of a pilot plant a more realistic system is considered, subjected to real world noises, disturbances, inertia, nonlinearities due to insensitivity and saturation of signals, etc.

2. Development of Plant Pilot Model

The plant pilot model uses experimental step responses, described in litarature [2-6]. It is built on a developed trainer, based on operational amplifiers in the schemes of functional generators to perform time lags, integrators, inverters, summing elements, gains, etc. – all with tunable parameters by the means of potentiometers. A data aquisition board (DAQ) with an ADC with multiplexer and DACs make the interface between the computer and the trainer. A Simulink model of MATLAB^{TM} performs: 1) exchange of signals between plant on trainer and controller on computer via the DAQ in accepted standard range [-10, 10],V and the corresponding drivers; 2) control algorithm and 3) visualisation. In investigation of the plant this Simulink model consists of the necessary generators of the inputs to the plant and the recorder of the plant outputs, the blocks Analog Inputs, Analog Outputs for addressing DAQ. In Fig.1 is shown the experimental setup, which consists of the configured on the trainer two-variable pilot model of the plant with outputs y_1,V and y_2,V for the indoor air temperature and humidity respectively, computer with the Simulink model and DAQ.

In Fig. 2 are presented the experimentally recorded pilot plant step responses in MATLAB^{TM} real time for different inputs applied, which are similar to the given in [2-6].

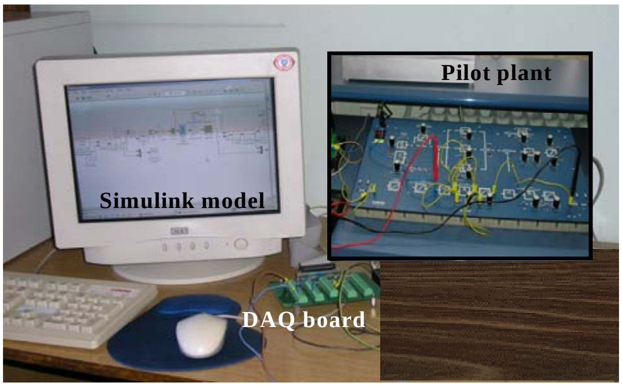

Figure 1 Plant pilot model for indoor temperature and humidity with DAQ interface to MATLAB^{TM}

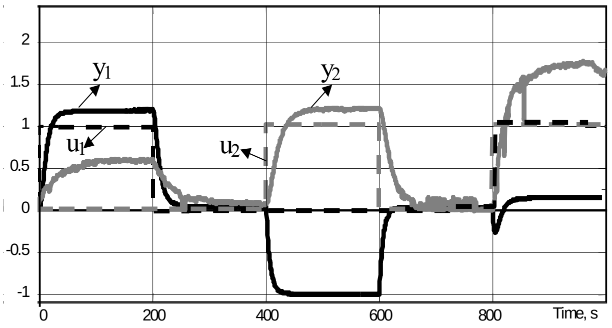

Figure 2 Step responses in real time investigation of the pilot plant model outputs y_1 and y_2

3. Design of Two-variable Fuzzy PI Controllers for Real Time Application

The general matrix block diagram of the designed two-variable PI FLC is given in Fig.3. It consists of two identical in structure channels. Each channel includes: 1) a preprocessing unit for computation of the derivative of error $\dot{e}(t)$ and of the signed distance d_s and for signal normalisation in the range [-1, 1]; 2) a signal commutation unit to determine the fuzzy unit (FU) inputs; 3) a fuzzy unit with two inputs; 4) a cross control unit CC, and 5) a post-processing unit, generally expressed as a PID algorithm. The cross connection in the two-variable FLC is accomplished via: 1) the inputs to the FUs for variant 1 and 2, which are the main and cross channel error or signed distance respectively; 2) the outputs of the FUs for variant 3, the inputs then are the main channel error and derivative of error. The cross connections are described by the matrices $\mathbf{C}_e$, $\mathbf{C}_{de}$, $\mathbf{C}_{ds}$ and CC, given for the three variants in Table 1 together with the determined by them inputs to each FU and the post-processing, where $\mathbf{I}=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$, $\varnothing$ - the zero matrix and $\mathbf{E}=\begin{bmatrix}1 & 1\\ 1 & 1\end{bmatrix}$, $\mathbf{E}1=\begin{bmatrix}1 & 1\\ 1 & -1\end{bmatrix}$.

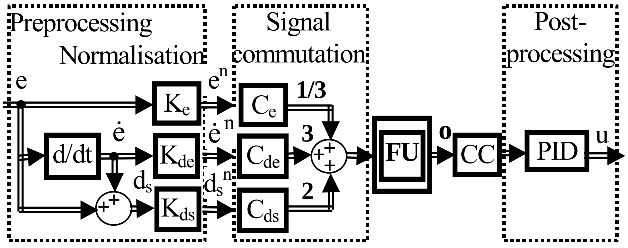

Figure 3 General matrix block diagram of two-variable fuzzy PI/PID controller

Table 1 Two-variable FLC channel connection

Vari-ant	C_e	C_{de}	C_{ds}	CC	FU_i input	Post processing
1	**E**	∅	∅	**I**	$[e_i^n, e_j^n]$	**PI**
2	∅	∅	**E**	**I**	$[d_{si}^n, d_{sj}^n]$	**Integrator**
3	**I**	**I**	∅	**E1**	$[e_i^n, \dot{e}_i^n]$	**Integrator**

The FUs for the main and the cross channel input variable for variant 1 and 2 use the membership functions (MFs), shown in Fig.4. The rule bases of the two FUs, given as Fuzzy Associate Memories (FAM) in Table 2, are derived, considering estimates of the sign and the magnitude of the gains across the main and the cross channels of the plant. Variant 3 uses identical for the two FUs standard 5x5x5 MFs and FAM, shown in Fig. 5 and Table 3 respectively.

The scaling factors K_e, K_{ds} and K_{de} that normalise the FUs inputs in the range [-1 1] are determined from the maximal expected system errors $|e_{max}|$. The derivative of error is computed by a noise filtering differentiator with transfer function $K_{ds}(T_d s+1)^{-1}$. The parameters of the differentiators and the post-processing units are tuned from fuzzy system robust performance criterion according to the procedure, developed in [8]. Their values are shown in Table 4.

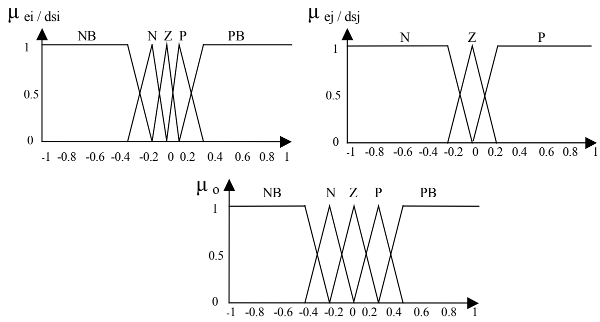

Figure 4 Membership functions for inputs and outputs in variants 1 and 2

Table 2 FAM of two-variable FLC in variants 1 and 2

o_1		e_1 or d_{s1}				
		NB	**N**	**Z**	**P**	**PB**
e_2 or d_{s2}	**N**	NB	N	Z	Z	P
	Z	N	N	Z	P	PB
	P	Z	Z	P	PB	PB
o_2		e_2 or d_{s2}				
		NB	**N**	**Z**	**P**	**PB**
e_1 or d_{s1}	**N**	N	Z	P	PB	PB
	Z	N	N	Z	P	P
	P	NB	N	N	Z	P

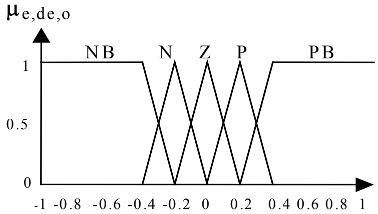

Figure 5 Membership functions for inputs and outputs in variants 3

Table 3 FAM of two-variable FLC in variant 3

o		*e*				
		NB	**N**	**Z**	**P**	**PB**
$\dot{e}$	**NB**	NB	NB	NB	N	Z
	N	NB	NB	N	Z	P
	Z	NB	N	Z	P	PB
	P	N	Z	P	PB	PB
	PB	Z	P	PB	PB	PB

Table 4 Parameters of two-variable FLC and classical decoupling PI

Type of two-variable controller	**PI FLC** (identical parameters for the FLCs in the two channels)			**PI standard decoupling** Main PI controllers Feedback cross controllers differentiators	
Parameters	Variant 1	Variant 2	Variant 3	Channel 1	Channel 2
K_d	-	5	5	1.4	4.65
T_d	-	1	1	8	5
K_p	0.2			1.63	2.72
T_i	2	5	3.33	11.7	18

4. A Real Time Experimentation and Assessment of Systems Performance and Energy Efficiency

The following experiments are designed:

➢ With respect to the closed loop systems investigated

- with the designed two-variable FLCs in variants 1, 2 and 3;

- with a designed classic PI decoupling controller [9] with parameters, given in Table 4, where the cross controllers are differentiators, connected in cross-feedback to the main controllers;

- With respect to the input reference signals

Number of experiments N	**$y_{1r}(t)$ V**	**$y_{2r}(t)$ V**
1	0→1	0
2	1→0	0
3	0	0→1
4	0	1→0
5	0→1	0→1

- With respect to outputs of interest - plant output $y_1(t)$ and $y_2(t)$, control action $u_1(t)$ and $u_2(t)$, global energy consumption of each of the investigated fuzzy and classic systems, k=1÷4, estimated by the following introduced measure

$$U^{k} = \sum_{i} U_{i}^{k} = \int_{0}^{t_f} \left| u_{i}^{k}(t) \right| dt , \qquad (1)$$

where $\left| u_{i}^{k}(t) \right| = \sum_{N=1}^{5} \left| u_{iN}^{k}(t) \right|$ is computed from all step responses to reference signals, N=1÷5, for the time of the investigations t_f =2000s and for the two channels i=1, 2. In (1) $|u_{i}^{k}(t)|$ is the magnitude of the voltage input to the plant, elaborated by the controller, $u_{i}^{k} \in [-10, 10]$V. The most energy efficient FLC is the one with the smallest U^k.

Thus (1) can be included in the suggested bellow a general compound criterion for selection of the FLC that ensures the best system performance, expressed in the least energy consumption, sum for all step responses and channels of the settling times $t_{s}^{k} = \sum_{i=1}^{2} \sum_{N=1}^{5} t_{siN}^{k}$, and the absolute maximal deviations from reference $| y_{m}^{k} | = \sum_{i=1}^{2} \sum_{N=1}^{5} | y_{miN}^{k} |$.

$$I^{k} = a \frac{U^{k}}{\sum_{k=1}^{4} U^{k}} + b \frac{t_{s}^{k}}{\sum_{k=1}^{4} t_{s}^{k}} + c \frac{| y_{m}^{k} |}{\sum_{k=1}^{4} | y_{m}^{k} |} \qquad (2)$$

The FLC that leads to I^k=min will be further completed in an industrial programmable logic controller [10].

The step responses from the real time operation of the three FLC systems and the classical two-variable system are shown in Fig.6. There are given for comparison the step responses from simulation in [9]. The corresponding control actions are depicted in Fig.7. The estimated $t_{s_i}^{k}$, $|y_{m_i}^{k}|$, U^k, and I^k for a=b=c=1 in (2) are presented in Table 5.

The system with FLC – variant 1 is the most economic (U^1=min), but with worse performance indices. The best is the system with FLC – variant 2 according to the complex criterion (2) (I^2=min) – both economic and with good performance estimates.

5. Conclusion

The main contributions, described in this paper, are the following.

A pilot model of a two-variable plant is developed on a trainer, based on operational amplifiers to be controlled via a DAQ by a Simulink controller in MATLAB$^{\text{TM}}$ real time. It models processes in climate comfort control – indoor temperature and humidity.

Three variants of designed and tested via simulation fuzzy two-variable controllers are modified for real time control of the pilot plant.

Then experimentation of the closed loop systems in more realistic environment is carried out in order to assess the most energy efficient FLC that ensures also small settling time and maximal dynamic deviation from reference. Two criteria are suggested – one for energy efficiency and another for overall performance that combines relative performance measures and relative energy efficiency. Applying these criteria the best FLC is selected for further completion by industrial programmable logic controllers for the control of the temperature and the humidity in a laboratory, which is the goal of a future work. For comparison the designed classical two-variable control system has shorter settling times, but greater absolute maximal deviations and energy consumption estimate U^4.

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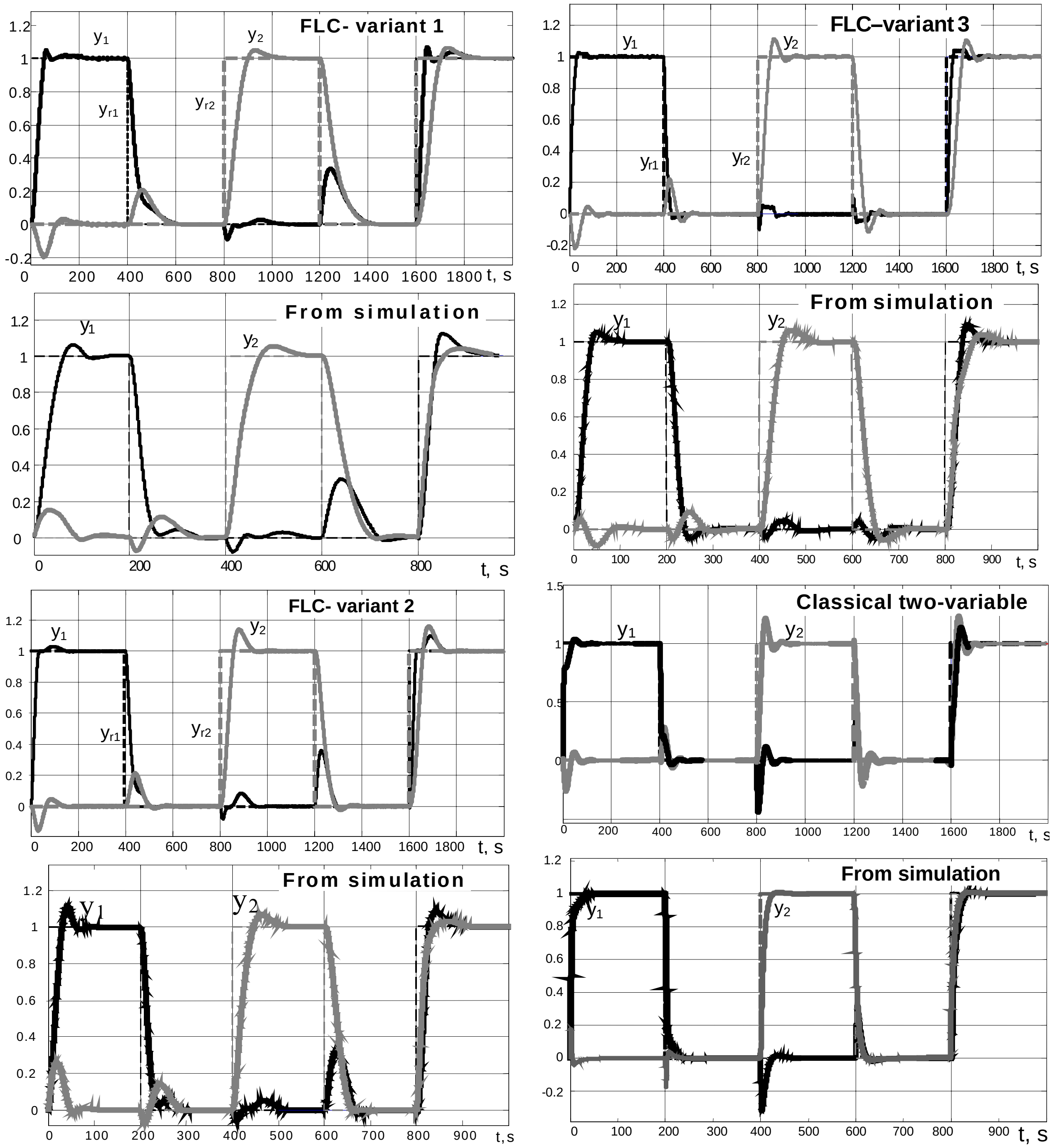

Figure 6 Step responses from MATLAB^{TM} real time operation and simulation of investigated systems

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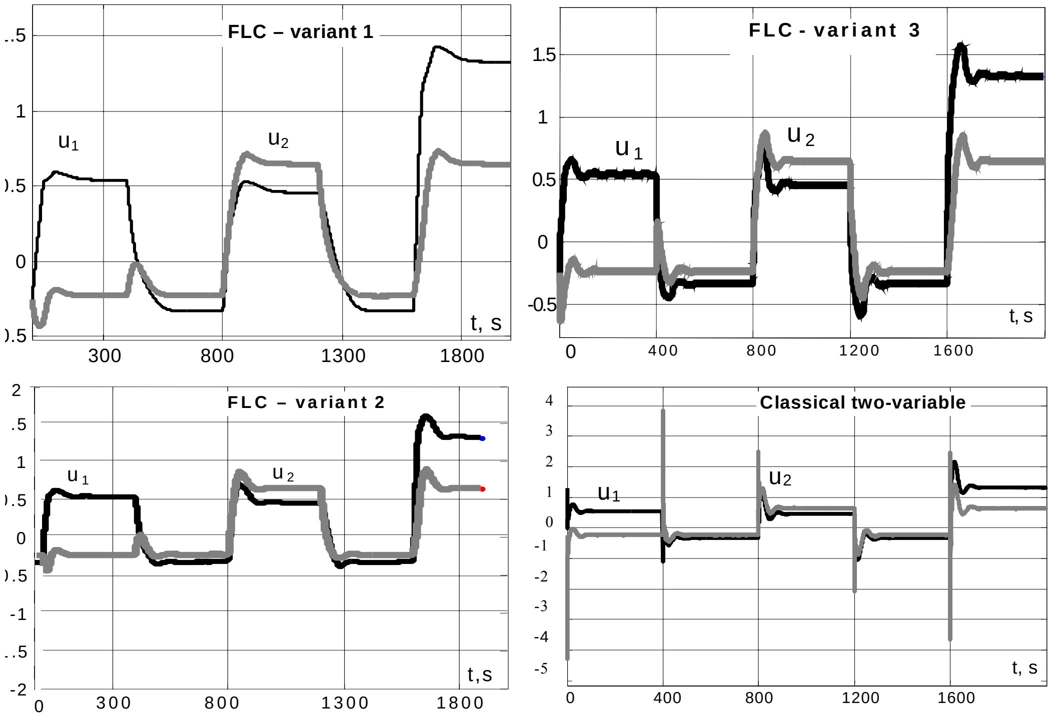

Figure 7 Control actions from MATLAB™ real time operation of investigated system

Table 5 Systems performance assessment

Reference steps	**Systems**	**FLC variant 1**		**FLC variant 2**		**FLC variant 3**		**Classic**	
		t_s, **s**	$\|y_m\|$	t_s, **s**	$\|y_m\|$	t_s, **s**	$\|y_m\|$	t_s, **s**	$\|y_m\|$
$u_{1r}=0\to1$ $u_{2r}=0$	$\mathbf{y_1}$	250	0.05	150	0.03	100	0.02	120	0.04
	$\mathbf{y_2}$	230	0.19	150	0.16	200	0.22	130	0.26
$u_{1r}=1\to0$ $u_{2r}=0$	$\mathbf{y_1}$	250	0	110	0	130	0.02	120	0.03
	$\mathbf{y_2}$	250	0.21	180	0.01	160	0.05	130	0.07
$u_{1r}=0$ $u_{2r}=0\to1$	$\mathbf{y_1}$	250	0.09	150	0.09	140	0.1	130	0.44
	$\mathbf{y_2}$	230	0.05	200	0.14	200	0.11	150	0.21
$u_{1r}=0$ $u_{2r}=1\to0$	$\mathbf{y_1}$	230	0.35	100	0	150	0.05	150	0.12
	$\mathbf{y_2}$	250	0	180	0.02	200	0.11	150	0.21
$u_{1r}=0\to1$ $u_{2r}=0\to1$	$\mathbf{y_1}$	250	0.07	150	0.1	150	0.04	130	0.14
	$\mathbf{y_2}$	250	0.065	200	0.16	200	0.1	150	0.25
Σ		**2440**	**1.075**	**1570**	**0.71**	**1630**	**0.82**	**1360**	**1.77**
Total measures		$U^1= 1940$ $I^1= 0.828$		$U^2= 2093$ $I^2= 0.636$		$U^3= 2104$ $I^3= 0.672$		$U^4= 2197$ $I^4= 1.863$	