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Analyzing shocks on the interest rate structure with Kohonen map

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1. Introduction

Modeling the relationship between zero-coupon rates of different maturity - the term structure of interest rates - is considered as an important issue, both by academics and practitioners. This problem has many implications for the valuation of interest rate contingent claims, for the management of financial institutions and, in another area, for monetary policy. Although there are many approaches to describe the term structure, the most widely used models are the continuous-time, general equilibrium models, pioneered by Cox, Ingersoll and Ross (CIR) (1985a). This framework is fully consistent with the no-arbitrage hypothesis and has been used by CIR (1985b), Longstaff (1989,1992), Longstaff-Schwartz (1992) and Platten (1994).

Another important feature is to model the process that describes the evolution of the interest rate term structure. Processes have been proposed by Ho and Lee (1986), Heath, Jarrow, Morton (1990, 1992) to price interest rate contingent claims. An important characteristic of these processes is that they are all arbitrage-free.

More recently, as the Basle Committee on Banking Supervision (1995) recommends the banks to develop their own risk management model to calculate the capital adequacy for their commercial and trading activities, it has become crucial to refine the measure of the risk undertaken by the banks. One popular way to achieve this aim is the Value at Risk (VaR) methodology. VaR describes the profit and loss profile under different scenarios. A solution to generate scenarios is given by the Monte Carlo simulation which assumes that the data are normally distributed. JP Morgan has proposed in 1994 to measure VaR, related to interest rates contingent claims, by using a Monte Carlo simulation. Although JP Morgan has refined its methodology to incorporate non normality of the data, one should remark that the results of the simulation procedure lead to interest rate structures that are not arbitrage free.

The goal of this paper is to classify the observed shocks on the interest rate term structure and to verify that these classes of shocks are compatible with the theoretical shocks predicted by the general equilibrium models and, consequently, respect the no-arbitrage condition.

2. Data description

To classify the observed shocks on the interest rate structure, we use data of the US bonds market. Our data are daily interest rate structures for maturity from 1 to 15 years. The interest rate for each maturity has been calculated by JP Morgan from the prices of US T-Bills and T-Bonds. The sample covers the period from 5/1/1987 to 10/5/1995, altogether 2088 entries. Using these data, we calculate the shocks which are the differences between the observed term structure at time t (given that we only have 15 rates corresponding to maturity ranging from 1 year to 15 years) and time t-10 working days (time delay recommended by the Basle Committee on Banking Supervision).

3. Methods

3.1 Preprocessing of the data

As we seek to put into light the shape of the interest rate structure deformation, we have to normalize our data. Our problem is not the classical one which consists in a homogenization of the metrics of each used variable. Indeed, they are all interest rates (at different maturity). But, to analyze the shape of the shocks, we have to neutralize the level factor. After several trials, we decided to normalize each interest rate deformation by subtracting its mean and dividing the result by its standard deviation. Fig. 1 and 2 show the effect of this preprocessing on two hypothetical series characterized by the same shape but at a different level.

3.2. The Kohonen Algorithm

The Kohonen algorithm (Kohonen, 1982, 1989, 1995; Cottrell, Fort, 1987; Cottrell, Fort, Pagès, 1994) is a well-known unsupervised learning algorithm which produces a map composed by a fixed number of units. A physical neighborhood relation between the units is defined and for each unit i, $V_r(i)$ represents the neigborhood with radius r centered at i.

Each unit is characterized by a parameter vector W_i of the same dimension as the input space.

After learning, each unit represents a group of individuals with similar features. The correspondence between the features and the units respects (more or less) the input space topology : similar features correspond to the same unit or to neighbor units. The final map is said to be a self organized map which preserves the topology of the input space.

The learning algorithm takes the following form :

- at time 0, $W_i(0)$ is randomly defined for each unit i;
- at time t, we present a vector x(t) randomly chosen among the rows of the data matrix and we determine the winning unit *i**, which minimizes the distance between x(t) and $W_i(t)$;
- we then modify the W_i in order to move the weights of the winning unit *i** and its physical neighbors towards x(t), using the following relations :

$$W_i(t+1)=W_i(t) + \varepsilon(t)\,(x(t)-W_i(t)), \text{ for } i \in V_{r(t)}(i^*).$$

$$W_i(t+1)=W_i(t), \text{ for } i \notin V_{r(t)}(i^*).$$

$\varepsilon(t)$ is a small positive adaptation parameter, r(t) is the radius of $V_{r(t)}$ and $\varepsilon(t)$ and r(t) are progressively decreased during the learning.

The results have been obtained after 100 learning cycles (at each one, we present all the individuals composing the data set). The input space dimension is 15. We have used a one-dimension map. In section 4, we present results with 3, 6, 9, 12, and 15 units.

3.3. Hierarchical classification algorithm (HCA)

Based on a coordinate matrix, in which the rows are observations and the columns are variables, the hierarchical classification algorithm computes distances and is based on an usual clustering technique. One interesting feature of this algorithm is the fact that it finds clusters in the data set that are organized so that one cluster at step t will be entirely contained within another cluster at a future step and no kind of overlap between clusters is allowed. The result of the HCA is an output data set with the number of clusters desired and showing the cluster membership of each observation.

We have used the SAS Software implementation of this algorithm (proc CLUSTER with Ward method followed by proc TREE) to produce the results. In section 4, we limit ourselves to the case of 9 clusters but we have verified that the reached conclusions hold true with 3, 6, 12 and 15 clusters.

3.4. Comparison criteria

The classifications that we got with the two algorithms are compared using several statistics. First, for each dimension (maturity), we compare the ratio intra classes sum of squares on total sum of squares (SSI/SST) and the classical Fisher statistic. Then, to compare the classification power of each approach on all set of maturities, we have used four multidimensional extension of the Fisher test : Wilk's Lambda, Pillai's Trace, Hotelling-Lawley Trace and Roy's Greatest Root. Complete description of these tests can be found in Mardia, Kent, and Bibby (1979) or in Morrison, (1976).

4. Results

From the statistical point of view, table 1 and fig. 3 present the evolution of the ratio SSI/SST as the number of units in the one-dimensional Kohonen map increases. As expected, we see that, as the number of units increases, the ratio decreases. We concentrate our analysis on the results get with a 9-units network. We see indeed at fig. 3 that the gain in term of SSI/SST ratio slows significantly down behind this level. Table 2 shows the SSI/SST ratio and Fisher test for each dimension and for the two algorithms. As expected, results clearly allow to reject, for each dimension, the null hypothesis (the classification would been considered as not statistically significant) for both approaches. But both the SSI/SST ratio and the Fisher statistics show that for 13 of the 15 dimensions, the Kohonen algorithm dominates the classical hierarchical approach. Table 3 presents results of the multidimensional tests. They confirm the more important classification power of the Kohonen approach. Figures 4 and 5 present the counts of observations by unit (Kohonen map) and cluster (Hierarchical classification). They highlight the different behavior of the two algorithms. Figures 6 and 7 confirm that the standard deviations by unit obtained with the Kohonen algorithm are lower than the one obtained for clusters formed by the hierarchical classification approach.

Fig. 8 to 16 present the mean profiles of the interest rate shocks attached to each unit (for which the unit is the winning one). The number of interest rate shocks and the standard deviation is also given. It is interesting to note that the Kohonen algorithm has classified the shocks on the interest rate structure and also that the obtained classification is ordered in the sense where the mean profile of unit 1 is "more similar" to the mean profile of unit 2 than to that of unit 3 (and so on).

From the financial point of view, the class of shocks that we have observed are compatible with the general equilibrium model of Cox, Ingersoll and Ross (1985b) and of Longstaff (1989,1992). Those models are fully described by the values of different parameters and the level of the short rate. A shock on the interest rate structure corresponds to changes in the parameters and the short rate. For example, Grégoire and Platten (1995) show that the parameters of Longstaff's model are highly correlated when they are estimated on contiguous sub-periods. As a consequence, shocks may be described by a variation of the spread, the difference between the long rate and the short rate, a change in the volatility and by the level of the short rate. If the spread widen, we have a positive and monotone increasing shock and inversely. If the level of the short rate decreases and the spread broaden, we observed a monotone increase shock which has a zero value for a given maturity. Finally, a change in the volatility affects the curvature of the yield curve. The results of our classification procedure show that the nine constructed classes correspond to the theoretical classes. We see that unit 3 (fig. 10) corresponds to an increase in the short rate level and a narrowing spread while unit 5 (fig. 12) is the result of an augmentation of the volatility and a narrowing spread.

Moreover, these results are compatible with the widely used study of Litterman and Scheikman (1988). The authors show that, on average 97% of the variance of the interest rate is explained by a three factors model for weekly observations from January 1984 through June 1988. The first factor is called the level factor and it is highly correlated with the level of the short rate. The second factor, the steep, corresponds to a variation of the slope. We found in our study that, for daily observations, in 50% of the total number of cases the main deformation is a variation of the slope (cfr fig. 11 and 15).

5. Future works

As the Basle Committee on Banking Supervision recommends the banks to use a internal model to measure market risk for capital adequacy purposes, it has become crucial to develop models that estimate correctly the risks undertaken by the bank. The widely used measure for market risks is the Value at Risk (VaR). VaR gives the profit and losses profile under different scenarios. The question is : how to generate scenarios that are compatible with observed data and that are arbitrage-free? Our study suggests that it may be possible to generate scenarios, in particular for interest rate risk measurement, by the use of general equilibrium models. In fact, we have shown that the classes of shocks correspond to the theory. It is then possible to generate scenarios that use the empirical probabilities of historical shocks. As these shocks are described by a change in the parameters of a general equilibrium model, the resulting scenarios respect the no-arbitrage condition, which is a fundamental property in finance.

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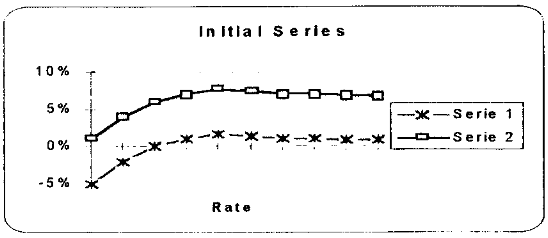


fig. 1

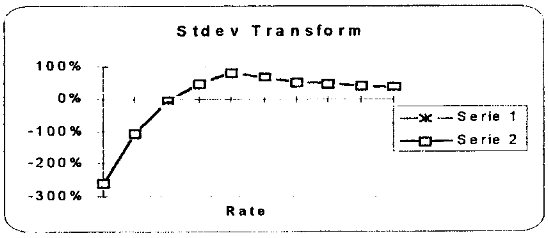


fig. 2

Classification statistics

Nbr Units	SSI	SST	SSI/SST
3	7707.99	31161	24.74%
6	4178.49	31161	13.41%
9	3217.16	31161	10.32%
12	2710.42	31161	8.70%
15	2350.4	31161	7.54%

tab. 1

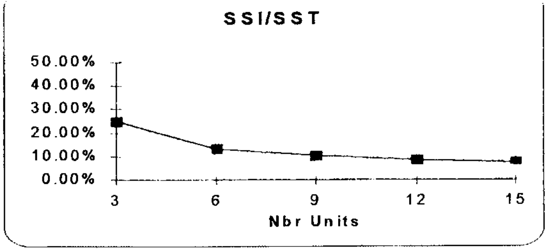


fig. 3

	Kohonen algorithm				*Hierarchical clustering algorithm*			
Dim	***SSI***	***SST***	***SSI/SST***	***Fisher***	***SSI***	***SST***	***SSI/SST***	***Fisher***
1	546,81	8388,67	6,52%	**3709,00**	553,72	8388,67	6,60%	3659,41
2	147,00	4000,57	3,67%	**6779,78**	167,22	4000,57	4,18%	5928,39
3	292,02	2689,42	10,86%	**2123,28**	295,58	2689,42	10,99%	2094,53
4	330,04	1809,89	18,24%	1159,65	298,46	1809,89	16,49%	**1309,69**
5	253,37	1144,95	22,13%	910,09	225,70	1144,95	19,71%	**1053,34**
6	126,36	690,95	18,29%	**1155,53**	135,46	690,95	19,60%	1060,49
7	210,44	707,72	29,73%	**611,15**	261,05	707,72	36,89%	442,51
8	282,92	830,65	34,06%	**500,70**	327,04	830,65	39,37%	398,23
9	203,96	794,79	25,66%	**749,17**	226,70	794,79	28,52%	648,05
10	94,74	685,25	13,83%	**1612,07**	100,45	685,25	14,66%	1505,55
11	79,85	915,90	8,72%	**2707,98**	83,01	915,90	9,06%	2594,74
12	63,97	1249,16	5,12%	**4791,67**	76,54	1249,16	6,13%	3961,71
13	74,19	1707,36	4,35%	**5693,22**	106,63	1707,36	6,25%	3882,47
14	151,31	2337,73	6,47%	**3737,21**	220,08	2337,73	9,41%	2488,44
15	360,21	3208,20	11,23%	**2044,80**	484,99	3208,20	15,12%	1542,15
Total	3217,17	31161,22	10,32%		3562,63	31161,22	11,43%	

tab. 2

	Kohonen algorithm	*Hierarchical clustering algorithm*
Wilk's Lambda	0,001661	0,002701
Pillai's Trace	2,373162	2,260267
Hotelling-Lawley Trace	49,044507	39,212269
Roy's Greatest Root	41,498329	32,977046

tab. 3

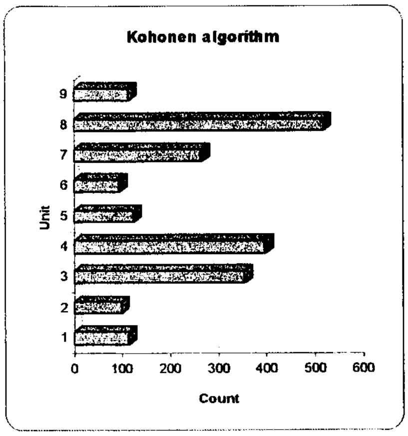


fig. 4 (Stdev : 149,31)

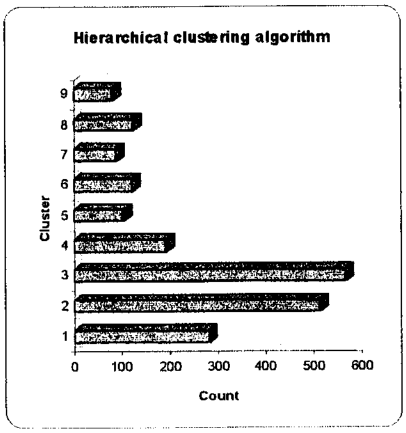


fig. 5 (Stdev : 175.36)

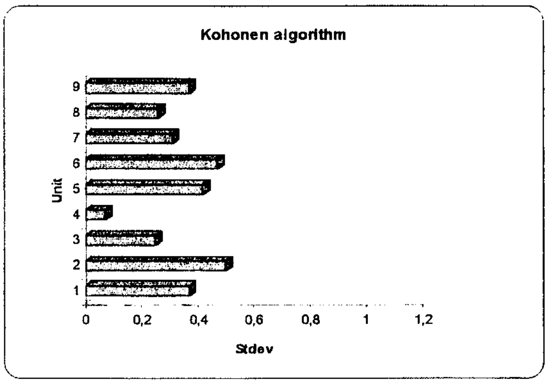


fig. 6

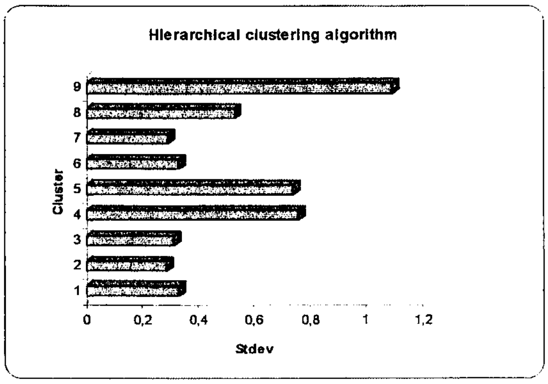


fig. 7

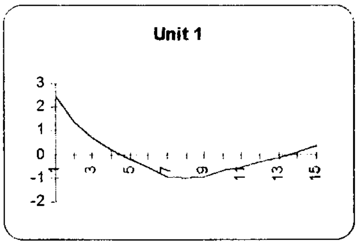
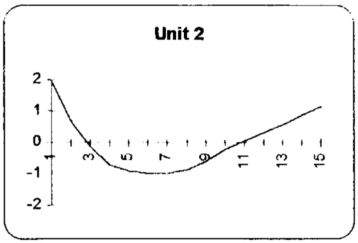


fig. 8 (count : 114 - StDev : 0.37)



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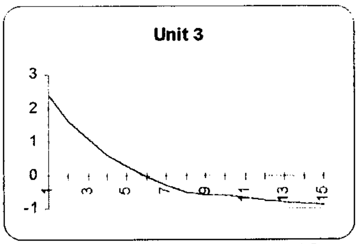

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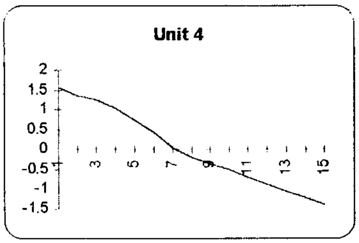

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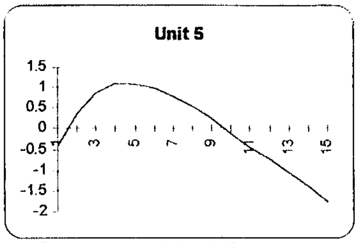

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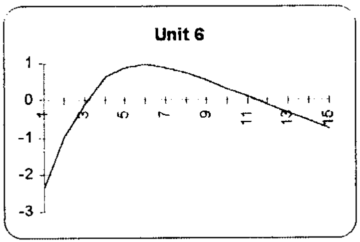

fig. 13 (count : 95 - StDev : 0.47)

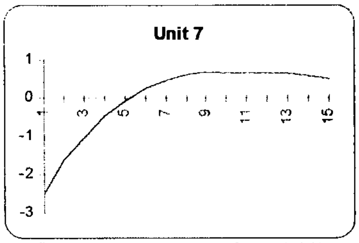

fig. 14 (count : 265 - StDev : 0.31)

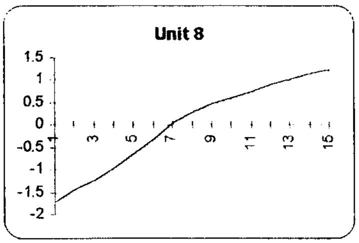

fig. 15 (count : 517 - StDev : 0.26)

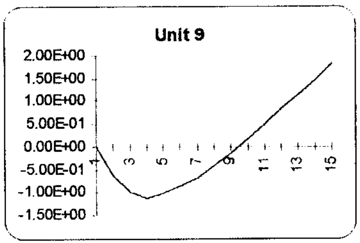

fig. 16 (count : 114 - StDev : 0.37)

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