

# Project Description

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Project Title: New Methods and Theory for the Comparison of  
Nonparametric Trend Curves

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## 1 State of the art and preliminary work

The comparison of nonparametric curves is a classical topic in econometrics and statistics. Depending on the application context, the curves of interest are densities, distribution functions, time trends or regression curves. The problem of testing for equality of densities has been studied for example in ??, ?? and ??. Tests for equality of distribution functions can be found in ??, ?? or ??. Tests for equality of trend and regression curves have been developed in ??, ?? and ?? among many others. In the proposed project, we focus on the comparison of nonparametric trend curves.

The statistical problem of comparing trends has a wide range of applications in economics, finance and other fields such as climatology and biology. In economics, a common issue is to compare trends in real GDP across different countries. It is highly debated whether real GDP growth is faster in economies in transition (such as Brazil, China or India) than in developed countries (cp. ??). Another example concerns the dynamics of long-term interest rates. To better understand these dynamics, researchers aim to compare the yields of US Treasury bills at different maturities over time (cp. ??). In finance, it is also of interest to compare the volatility trends of different stocks (cp. ??). A final example comes from climatology. In recent years, large spatial data sets have been collected which comprise long temperature time series for many different locations. Climatologists are very much interested in analyzing the trending behaviour of these time series (cp. ??). In particular, they would like to know how the temperature trend varies across locations.

Classically, time trends are modelled stochastically in econometrics; see e.g. Stock and Watson (1988). Recently, however, there has been a growing interest in econometric models with deterministic time trends; see Cai (2007), Atak et al. (2011), Robinson (2012) and Chen et al. (2012) among others. Non- and semiparametric trend modelling has attracted particular interest in a panel data context. Li et al. (2010), Atak et al. (2011), Robinson (2012) and Chen et al. (2012) considered panel models where the observed time series have a common time trend. In many applications, however, the assumption of a common time trend is quite harsh. In particular

when the number of observed time series is large, it is quite natural to suppose that the time trend may differ across time series. More flexible panel settings with heterogeneous trends have been studied, for example, in Zhang et al. (2012) and Hidalgo and Lee (2014).

In what follows, we consider a general panel framework with heterogeneous trends which is useful for a number of economic and financial applications: Suppose we observe a panel of  $n$  time series  $\mathcal{Z}_i = \{(Y_{it}, X_{it}) : 1 \leq t \leq T\}$  for  $1 \leq i \leq n$ , where  $Y_{it}$  are real-valued random variables and  $X_{it} = (X_{it,1}, \dots, X_{it,d})^\top$  are  $d$ -dimensional random vectors. Each time series  $\mathcal{Z}_i$  is modelled by the equation

$$Y_{it} = m_i\left(\frac{t}{T}\right) + \beta_i^\top X_{it} + \alpha_i + \varepsilon_{it} \quad (1)$$

for  $1 \leq t \leq T$ , where  $m_i : [0, 1] \rightarrow \mathbb{R}$  is a nonparametric (deterministic) trend function,  $X_{it}$  is a vector of regressors or controls and  $\beta_i$  is the corresponding parameter vector. Moreover,  $\alpha_i$  are so-called fixed effect error terms and  $\varepsilon_{it}$  are standard regression errors with  $\mathbb{E}[\varepsilon_{it}|X_{it}] = 0$  for all  $t$ . Model (1) nests a number of panel settings which have recently been considered in the literature. Special cases of model (1) with a nonparametric trend specification are for example considered in Atak et al. (2011), Zhang et al. (2012) and Hidalgo and Lee (2014). Versions of model (1) with a parametric trend are studied in Vogelsang and Franses (2005), Sun (2011) and Xu (2012) among others.

As usual in nonparametric regression, the trend functions  $m_i$  in model (1) depend on rescaled time  $t/T$  rather than on real time  $t$ ; cp. ??, ?? and ?? for the use and some discussion of the rescaled time argument. The functions  $m_i$  are only identified up to an additive constant in model (1): One can reformulate the model as  $Y_{it} = [m_i(t/T) + c_i] + \beta_i^\top X_{it} + [\alpha_i - c_i] + \varepsilon_{it}$ , that is, one can freely shift additive constants between the trend  $m_i(t/T)$  and the error component  $\alpha_i$ . In order to obtain identification, one may impose different normalization constraints on the trends  $m_i$ . One possibility is to normalize them such that  $\int_0^1 m_i(u)du = 0$  for all  $i$ . In what follows, we take for granted that the trends  $m_i$  satisfy this constraint. Within the general framework of model (1), we can formulate a number of interesting statistical questions concerning the trend functions  $m_i$  for  $1 \leq i \leq n$ .

### (a) Testing for equality of nonparametric trend curves

Most of the current literature on deterministic trends in time series heavily relies on the critical assumption of the common trend structure. This assumption means that each individual in the panel exhibits the same trend behavior. The majority of the works in this topic can not be easily generalized to the setting where the trend

functions are not the same for different individuals. Therefore, it is vital to be able to test the assumption of the common trend before imposing it.

This question can formally be addressed by a statistical test of the null hypothesis

$$H_0 : \text{There exists a function } m : [0, 1] \rightarrow \mathbb{R} \text{ such that } m_i = m \text{ for all } 1 \leq i \leq n.$$

A closely related question is whether all time trends have the same parametric form. To formulate the corresponding null hypothesis, let  $m(\theta, \cdot) : [0, 1] \rightarrow \mathbb{R}$  be a function which is known up to the finite-dimensional parameter  $\theta \in \Theta$ , where  $\Theta$  denotes the parameter space. The null hypothesis of interest now reads as follows:

$$H_{0,\text{para}} : \text{There exists } \theta \in \Theta \text{ such that } m_i(\cdot) = m(\theta, \cdot) \text{ for all } 1 \leq i \leq n.$$

If  $m(\theta, w) = a + bw$  with  $\theta = (a, b)$ , for example, then  $H_0$  is the hypothesis that all trends  $m_i$  are linear with the same intercept  $a$  and slope  $b$ . A somewhat simpler but yet important hypothesis is given by

$$H_{0,\text{const}} : m_i \equiv 0 \text{ for all } 1 \leq i \leq n.$$

Under this hypothesis, there is no time trend at all in the observed time series. Put differently, all the time trends  $m_i$  are constant. (Note that under the normalization constraint  $\int_0^1 m_i(w)dw = 0$ ,  $m_i$  must be equal to zero if it is a constant function.) A major aim of our project is to develop new tests for the hypotheses  $H_0$ ,  $H_{0,\text{para}}$  and  $H_{0,\text{const}}$  in model (1). In order to keep the exposition as clear as possible, we focus attention to the hypothesis  $H_0$  in what follows. Tests of  $H_{0,\text{para}}$ ,  $H_{0,\text{const}}$  and related hypotheses were for example studied in Lyubchich and Gel (2016) and Chen and Wu (2018).

In recent years, a number of different approaches have been developed to test the hypothesis  $H_0$ . Degras et al. (2012) considered the problem of testing  $H_0$  within the model framework

$$Y_{it} = m_i\left(\frac{t}{T}\right) + \alpha_i + \varepsilon_{it} \quad (1 \leq t \leq T, 1 \leq i \leq n), \quad (2)$$

where  $\mathbb{E}[\varepsilon_{it}] = 0$  for all  $i$  and  $t$  and the terms  $\alpha_i$  are assumed to be deterministic. Obviously, (2) is a special case of (1) which does not include additional regressors. Degras et al. (2012) construct an  $L_2$ -type statistic to test  $H_0$ . The statistic is based on nonparametric kernel estimators  $\hat{m}_{i,h}$  and  $\hat{m}_h$  of the functions  $m_i$  and  $m$ , where  $h$  denotes the bandwidth parameter. With the help of these estimators, the authors

define the statistic

$$\Delta_{n,T} = \sum_{i=1}^n \int_0^1 (\hat{m}_i(u) - \hat{m}(u))^2 du,$$

which measures the  $L_2$ -distance between the estimators  $\hat{m}_i$  and  $\hat{m}$ . In the theoretical part of their paper, they derive the limit distribution of  $\Delta_{n,T}$ . Chen and Wu (2018) develop theory for test statistics closely related to those from Degras et al. (2012), however, under more general conditions on the error processes  $\mathcal{E}_i = \{\varepsilon_{it} : 1 \leq t \leq T\}$ .

Zhang et al. (2012) investigate the problem of testing the hypothesis  $H_0$  in a slightly restricted version of model (1), where  $\beta_i = \beta$  for all  $i$ . The regression coefficients  $\beta_i$  are thus assumed to be homogeneous in their setting. They construct a residual-based test of  $H_0$  as follows: First, the authors estimate the model under the null by profile least squares and obtain the estimates  $\hat{\beta}$  and  $\hat{m}_i(t/T) \equiv \hat{m}(t/T)$ . Then, they obtain the augmented residual  $\hat{u}_{it}$  under  $H_0$  by  $\hat{u}_{it} = Y_{it} - \hat{\beta}^T X_{it} - \hat{m}(t/T)$ , which consistently estimates  $u_{it} = \alpha_i + \varepsilon_{it}$ . Afterwards, they run the local linear regression of  $\hat{u}_{it}$  on  $t/T$  and from this regression, the authors calculate the non-parametric goodness-of-fit  $R_i^2$  for each  $i$ . The test statistic for testing  $H_0$  is then defined by averaging the non-parametric goodness-of-fit  $R_i^2$ , which is proved to be asymptotically normal both under the null hypothesis and under a sequence of local alternatives.

The tests of Zhang et al. (2012), Degras et al. (2012) and Chen and Wu (2018) are based on nonparametric estimators of the trend functions  $m_i$  or other parameters of the model. They thus depend on one or several bandwidth parameters. It is however far from clear how to choose these bandwidths in an appropriate way. This is a quite general problem which concerns essentially all tests that are based on nonparametric curve estimators. There are of course many theoretical results on the optimal choice of bandwidth for estimation purposes. However, the optimal bandwidth for curve estimation is usually not optimal for testing. Optimal bandwidth choice for tests is indeed a quite open problem, and only little theory for simple cases is available, cp. Gao and Gijbels (2008). Since tests based on nonparametric curve estimators are commonly quite sensitive to the choice of bandwidth and theory for optimal bandwidth selection is not available, it appears preferable to work with bandwidth-free tests.

A classical way to obtain a bandwidth-free test of the hypothesis  $H_0$  is to use CUSUM-type statistics which are based on partial sum processes. This approach is taken in Hidalgo and Lee (2014). The model considered by the authors is the same as in Zhang et al. (2012), which is a slightly restricted version of the model (1) with  $\beta_i = \beta$  for all  $i$ . The authors then proceed as follows. First they transform the model by adding and subtracting the averages of different levels from the covariates and the dependent variables, which removes the trend and the fixed effects under  $H_0$ ,

and calculate the estimator  $\widehat{\beta}$  of  $\beta$  from the augmented model by the least squares method. To test  $H_0$ , the authors then instead of  $Y_{it}$  consider

$$\widehat{v}_{it} := Y_{it} - \widehat{\beta}^T X_{it} = (\beta - \widehat{\beta})^T X_{it} + m_i(t/T) + \alpha_i + \varepsilon_{it}.$$

Afterwards, they construct the estimator  $\widehat{\sigma}^2$  of the error variance  $\sigma^2$  and the CUSUM test statistics based on the transformation of  $\widehat{v}_{it}$  by the same procedure of adding and subtracting the averages of different levels, and prove that the normalized supremum of these test statistics converges to a random variable with a known distribution. However, the theory derived in Hidalgo and Lee (2014) relies on the assumption that the errors  $\varepsilon_{it}$  are independent across  $t$ , which is usually not true in practice. Furthermore, their test statistic is only applicable in the case when the number of cross-sectional units grows, which is also a heavy restriction on the possible applications.

A more modern way to obtain a test statistic which is free of classical bandwidth parameters is to use multiscale methods. The general idea is as follows: Let  $S_h$  be a test statistic for the null hypothesis of interest, which depends on the bandwidth  $h$ . Rather than considering only a single statistic  $S_h$  for a specific bandwidth  $h$ , a multiscale approach simultaneously considers a whole family of statistics  $\{S_h : h \in \mathcal{H}\}$ , where  $\mathcal{H}$  is a set of bandwidth values. The multiscale test then proceeds as follows: For each bandwidth or scale  $h$ , one checks whether  $S_h > q_h(\alpha)$ , where  $q_h(\alpha)$  is a bandwidth-dependent critical value (for given significance level  $\alpha$ ). The multiscale test rejects if  $S_h > q_h(\alpha)$  for at least one scale  $h$ . The main theoretical difficulty in this approach is of course to derive appropriate critical values  $q_h(\alpha)$ .

One of the first multiscale methods proposed in the literature is the SiZer approach of Chaudhuri and Marron (1999, 2000). In recent years, this approach has been extended in various directions; see Hannig and Marron (2006) and ?? among others. Park et al. (2009) developed SiZer methods for the comparison of nonparametric trend curves in a simplified version of model (1). Their analysis, however, is mainly methodological and only partly backed up by theory. Indeed, theory is only derived for the special case  $n = 2$ , that is, for the case that only two time series are observed. Moreover, the theoretical results are only valid under very severe restrictions on the set of bandwidths  $\mathcal{H}$  that is taken into account. In particular, the bandwidths in the set  $\mathcal{H}$  are assumed to be bounded away from zero. Put differently, they are not allowed to converge to zero as the sample size grows, which is obviously a very severe limitation.

A major aim of our project is to develop new multiscale tests of the hypothesis  $H_0$  in the general model (1) which do not have the limitations of the SiZer methods discussed above. Importantly, we do not only intend to develop new test method-

ology but also to back up the methods by a general asymptotic distribution theory. To achieve this, we plan to build on a multiscale approach pioneered by Dümbgen and Spokoiny (2001). This general approach has been very influential in recent years and has been further developed in numerous directions; see for example Dümbgen (2002), Rohde (2008) and Proksch et al. (2018) for multiscale methods in the regression context and Dümbgen and Walther (2008), Rufibach and Walther (2010), Schmidt-Hieber et al. (2013) and Eckle et al. (2017) for methods in the context of density estimation. Importantly, all of these studies are limited to the case of independent data. It turns out that it is highly non-trivial to extend the methods to the case of dependent data. To do so, markedly different technical tools are needed. A first step to provide such tools has recently been made in Khismatullina and Vogt (2018). They developed multiscale methods for testing shape restrictions of the non-parametric trend function  $m$  in the univariate time series model  $Y_t = m(t/T) + \varepsilon_t$ . In our project, we aim to extend the techniques and methods from Khismatullina and Vogt (2018) to approach the problem of testing  $H_0$  in the panel model (1). Please see Section 2.2 on objectives for the details.

### (b) Clustering of nonparametric trend curves

Consider the general panel data model (1) and suppose that the null hypothesis  $H_0 : m_1 = \dots = m_n$  is violated in this model. Even though some of the trend functions  $m_i$  are different in this case, there may still be groups of time series with the same time trend. Formally, a group structure can be defined as follows within the framework of model (1): There exist sets or groups of time series  $G_1, \dots, G_{K_0}$  with  $\{1, \dots, n\} = \bigcup_{k=1}^{K_0} G_k$  such that for each  $1 \leq k \leq K_0$ ,

$$m_i = m_j \quad \text{for all } i, j \in G_k. \quad (3)$$

Hence, the time series of a given group  $G_k$  all have the same time trend. An interesting statistical problem is how to estimate the unknown groups  $G_1, \dots, G_{K_0}$  and their unknown number  $K_0$  from the data.

There are several approaches to this problem in the context of models closely related to (1). Degras et al. (2012) used a repeated testing procedure based on the methods described in part (a) of this section to estimate the unknown group structure in model (2). Zhang (2013) developed a clustering method within the same model framework which makes use of information criteria. Vogt and Linton (2017) constructed a thresholding method to estimate the unknown group structure in the panel model  $Y_{it} = m_i(X_{it}) + u_{it}$ , where  $X_{it}$  are random regressors and  $u_{it}$  are general error terms that may include fixed effects. Their approach can also be adapted

to the case of fixed regressors  $X_{it} = t/T$ . As an alternative to a group structure, factor-type structures may be imposed on the regression functions in panel models. Such factor-type structures have been studied in Kneip et al. (2012), Boneva et al. (2015) and Boneva et al. (2016) among others.

The problem of estimating the unknown groups  $G_1, \dots, G_{K_0}$  and their unknown number  $K_0$  in model (1) has close connections to functional data clustering. There, the aim is to cluster smooth random curves that are functions of (rescaled) time and that are observed with or without noise. A number of different clustering approaches have been proposed in the context of functional data models; see for example Abraham et al. (2003), Tarpey and Kinateder (2003) and Tarpey (2007) for procedures based on  $k$ -means clustering, James and Sugar (2003) and Chiou and Li (2007) for model-based clustering approaches and Jacques and Preda (2014) for a recent survey.

The problem of finding the unknown group structure in model (1) is also closely related to a developing literature in econometrics which aims to identify unknown group structures in parametric panel regression models. In its simplest form, the panel regression model under consideration is given by the equation  $Y_{it} = \beta_i^\top X_{it} + u_{it}$  for  $1 \leq t \leq T$  and  $1 \leq i \leq n$ , where the coefficient vectors  $\beta_i$  are allowed to vary across individuals  $i$ . Similar to the trend functions in model (1), the coefficients  $\beta_i$  are assumed to belong to a number of groups: there are  $K_0$  groups  $G_1, \dots, G_{K_0}$  such that  $\beta_i = \beta_j$  for all  $i, j \in G_k$  and all  $1 \leq k \leq K_0$ . The problem of estimating the unknown groups and their unknown number has been studied in different versions of this modelling framework; cp. Su et al. (2016), Su and Ju (2018) and Wang et al. (2018) among others. Bonhomme and Manresa (2015) considered a related model where the group structure is not imposed on the regression coefficients but rather on the unobserved time-varying fixed effects.

Virtually all of the proposed procedures to cluster nonparametric curves in panel and functional data models related to (1) have the following drawback: they depend on a number of bandwidths or smoothing parameters required to estimate the nonparametric functions  $m_i$ . In general, nonparametric curve estimators strongly depend on the chosen bandwidth parameters. A clustering procedure which is based on such estimators can be expected to be strongly influenced by the choice of bandwidths as well. Moreover, as in the context of statistical testing, there is no theory available on how to pick the bandwidths optimally for the clustering problem. Hence, as in the context of testing, it is desirable to construct a clustering procedure which is free of classical bandwidth parameters.

There are different ways to move into the direction of a bandwidth-free clustering algorithm. One possibility is to employ Wavelet methods. A Bayesian Wavelet-based method to cluster nonparametric curves has been developed in Ray and Mallick

(2006). There, the simple model  $Y_{it} = m_i(t/T) + \varepsilon_{it}$  is considered, where  $m_i$  are smooth functions of rescaled time  $t/T$  and the error terms  $\varepsilon_{it}$  are restricted to be i.i.d. Gaussian noise.

Another possibility is to use multiscale methods. This approach has recently been taken in Vogt and Linton (2018). They develop a clustering approach within the framework of the panel regression model  $Y_{it} = m_i(X_{it}) + u_{it}$ , where  $X_{it}$  are random regressors and  $u_{it}$  are general error terms that may include fixed effects. Imposing the same group structure as in (3) on their model, they construct estimators of the unknown groups and their unknown number as follows: In a first step, they develop a multiscale statistic  $\hat{d}_{ij}$  which measures the distance between any two functions  $m_i$  and  $m_j$ . In a second step, the distance measures  $\hat{d}_{ij}$  are used as the basis of a hierarchical clustering algorithm. In the theoretical part of their paper, they derive consistency results for their estimators. Letting  $\hat{K}_0$  be the estimator of  $K_0$  and  $\{\hat{G}_1, \dots, \hat{G}_{\hat{K}_0}\}$  the estimator of the group structure  $\{G_1, \dots, G_{K_0}\}$ , they in particular show that under appropriate regularity conditions,

$$\mathbb{P}(\hat{K}_0 = K_0) \rightarrow 1 \quad \text{and} \quad \mathbb{P}(\{\hat{G}_1, \dots, \hat{G}_{\hat{K}_0}\} = \{G_1, \dots, G_{K_0}\}) \rightarrow 1 \quad (4)$$

as the sample size goes to infinity. Even though promising, the consistency result (4) is only a first step into the direction of a complete asymptotic theory. A more refined theory would comprise results on convergence rates and confidence statements about the estimators.

Building on the work of Vogt and Linton (2018), we aim to develop multiscale clustering methods in model (1). We in particular aim to go beyond the basic theory derived in Vogt and Linton (2018) and to provide results on convergence rates and confidence statements. We give more details on these objectives in Section 2.2.

## 1.1 Project-related publications

### 1.1.1 Articles published by outlets with scientific quality assurance, book publications, and works accepted for publication but not yet published

BONEVA, L. and LINTON, O. and VOGT, M. (2015). A semiparametric model for heterogeneous panel data with fixed effects. *Journal of Econometrics*, **188** 327-345.

BONEVA, L. and LINTON, O. and VOGT, M. (2016). The effect of fragmentation in trading on market quality in the UK equity market. *Journal of Applied Econometrics*, **31** 192-213.

VOGT, M. and LINTON, O. (2017). Classification of non-parametric regression functions in longitudinal data models. *Journal of the Royal Statistical Society: Series B*, **79** 5-27.



### 1.1.2 Other publications

KHISMATULLINA, M. and VOGT, M. (2018). Multiscale inference and long-run variance estimation in nonparametric regression with time series errors. *Preprint*.

VOGT, M. and LINTON, O. (2018). Multiscale clustering of nonparametric regression curves. *Preprint*.

## 2 Objectives and work programme

### 2.1 Anticipated total duration of the project

2 years from October 1, 2019 to September 30, 2021.

### 2.2 Objectives

The main aim of the project is to develop new methods and theory for the comparison and clustering of nonparametric trend curves. As a modelling framework, we will consider the general panel setting (1) which was briefly introduced in Section 1: Suppose we observe a panel of  $n$  time series  $\mathcal{Z}_i = \{(Y_{it}, X_{it}) : 1 \leq t \leq T\}$  for  $1 \leq i \leq n$ . Each time series  $\mathcal{Z}_i$  is modelled by the equation

$$Y_{it} = m_i\left(\frac{t}{T}\right) + \beta_i^\top X_{it} + \alpha_i + \varepsilon_{it} \quad (5)$$

for  $1 \leq t \leq T$ , where  $m_i$  is a nonparametric time trend curve,  $X_{it}$  is a vector of regressor or control variables,  $\alpha_i$  are unobserved fixed effects and  $\varepsilon_{it}$  are idiosyncratic error terms with  $\mathbb{E}[\varepsilon_{it}|X_{it}] = 0$ . For each  $i$ ,  $\mathcal{P}_i = \{(X_{it}, \varepsilon_{it})\}$  is assumed to be a general time series process which fulfills some weak dependence conditions (e.g. conditions formulated in terms of strong mixing coefficients or in terms of the physical dependence measure introduced by Wu ??). We will not only allow for time series dependence in the data, but also for some forms of cross-sectional dependence. To derive our theoretical results, we will assume that the time series length  $T$  tends to infinity. The number of time series  $n$ , in contrast, may either be bounded or diverging.

#### (a) Contributions to statistical multiscale testing

The first main contribution of the project is to develop a novel multiscale test for the comparison of the trend curves  $m_i$  in model (5). More specifically, we aim to develop multiscale tests for the hypothesis  $H_0 : m_1 = \dots = m_n$  as well as for the related hypotheses discussed in part (b) of Section 1. To keep the exposition focused,

we restrict attention to  $H_0$  in what follows. For any interval  $[u - h, u + h] \subseteq [0, 1]$ , consider the hypothesis

$$H_0^{[i,j]}(u, h) : m_i(w) = m_j(w) \text{ for all } w \in [u - h, u + h].$$

Obviously, the hypothesis  $H_0$  can be reformulated as

$$H_0 : \text{The hypothesis } H_0^{[i,j]}(u, h) \text{ holds true for all intervals } [u - h, u + h] \subseteq [0, 1] \\ \text{and for all } 1 \leq i < j \leq n.$$

We aim to develop a multiscale method which simultaneously tests the hypothesis  $H_0^{[i,j]}(u, h)$  for all possible points  $(u, h)$  and all pairs  $(i, j)$  with  $i < j$ .<sup>1</sup> Our strategy to derive such a method can be outlined as follows:

*Step 1: Construction of the test statistic.*

- (i) Construct nonparametric estimators  $\hat{m}_{i,h}$  of the trend functions  $m_i$ , where  $h$  denotes the bandwidth parameter.
- (ii) Construct a test statistic  $\hat{S}_{ij}(u, h)$  for the hypothesis  $H_0^{[i,j]}(u, h)$ . A simple choice is a statistic of the form  $\hat{S}_{ij}(u, h) = \sqrt{Th}(\hat{m}_{i,h}(u) - \hat{m}_{j,h}(u))/\hat{\nu}_{ij,h}(u)$ , where  $\hat{\nu}_{ij,h}(u)$  is chosen to normalize the asymptotic variance of the statistic to 1.
- (iii) Aggregate the statistics  $\hat{S}_{ij}(u, h)$  into a multiscale statistic. As already discussed in Section 1, we will use the aggregation scheme of Dümbgen and Spokoiny (2001) to do so. The resulting multiscale statistic has the form

$$\hat{\Psi}_{n,T} = \max_{1 \leq i < j \leq n} \sup_{u,h} \{|\hat{S}_{ij}(u, h)| - \lambda(h)\},$$

where  $\lambda(h)$  are (appropriately chosen) additive correction terms. As one can see, the multiscale statistic  $\hat{\Psi}_{n,T}$  is not obtained by simply aggregating the individual statistics  $\hat{S}_{ij}(u, h)$ . We rather take the supremum of the additively corrected statistics  $|\hat{S}_{ij}(u, h)| - \lambda(h)$  as first suggested in Dümbgen and Spokoiny (2001).

*Step 2: Construction of test procedure.*

- (i) Suppose for a moment we could compute the  $(1 - \alpha)$ -quantile  $q_{n,T}^*(\alpha)$  of the multiscale statistic  $\hat{\Psi}_{n,T}$  under the null  $H_0$ . Then our multiscale test would be carried out as follows:

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<sup>1</sup>Obviously, in practice, we cannot consider all points  $u \in (0, 1)$  and all  $h > 0$  but have to restrict attention to a finite subset of points. We ignore this in our presentation for simplicity.

(T\*) Reject the overall null hypothesis  $H_0$  if  $\hat{\Psi}_{n,T} > q_{n,T}^*(\alpha)$ .

By construction, the decision rule (T\*) is a rigorous level- $\alpha$ -test, that is,  $\mathbb{P}(\hat{\Psi}_{n,T} > q_{n,T}^*(\alpha)) = 1 - \alpha$  under  $H_0$ .

- (ii) The quantile  $q_{n,T}^*(\alpha)$  is a highly complicated quantity which is not known in practice. Hence, it cannot be used to set up the test. The main theoretical challenge is to come up with an (asymptotic) approximation  $q_{n,T}(\alpha)$  of this quantile which is computable in practice. In particular,  $q_{n,T}(\alpha)$  should have the theoretical property that

$$\mathbb{P}(\hat{\Psi}_{n,T} > q_{n,T}(\alpha)) = (1 - \alpha) + o(1).$$

Once we have successfully derived the approximation  $q_{n,T}(\alpha)$ , the multiscale test can be carried out as follows:

(T) Reject the overall null hypothesis  $H_0$  if  $\hat{\Psi}_{n,T} > q_{n,T}(\alpha)$ .

- (iii) By using the decision rule (T), we regard the multiscale method as a test of the overall hypothesis  $H_0$ . Alternatively, one may view it as a simultaneous test of the family of hypotheses  $H_0^{[i,j]}(u, h)$  for all points  $(u, h)$  and pairs  $(i, j)$ . Looking at the method this way, we proceed as follows:

(T<sub>multi</sub>) For each interval  $[u-h, u+h]$ , reject the hypothesis  $H_0^{[i,j]}(u, h)$  if the corrected test statistic  $|\hat{S}_{ij}(u, h)| - \lambda(h)$  is above the critical value  $q_{n,T}(\alpha)$ , that is, if  $|\hat{S}_{ij}(u, h)| - \lambda(h) > q_{n,T}(\alpha)$ .

We conjecture that it is possible to prove the following theoretical result on the multiple testing procedure ( $T_{\text{multi}}$ ) under appropriate regularity conditions: With asymptotic probability at least  $1 - \alpha$ , the hypothesis  $H_0^{[i,j]}(u, h)$  is violated for all pairs  $(i, j)$  and for all intervals  $[u-h, u+h]$  for which  $|\hat{S}_{ij}(u, h)| - \lambda(h) > 0$ . According to this result, we can make the following simultaneous confidence statement: We can claim, with (asymptotic) confidence at least  $1 - \alpha$ , that the hypothesis  $H_0^{[i,j]}(u, h)$  is violated for all pairs of time series  $(i, j)$  and for all intervals  $[u-h, u+h]$  for which our test rejects. Hence, the multiscale test does not only give us information on whether the overall null hypothesis  $H_0$  is violated. It also allows us to make rigorous statistical confidence statements about (i) which pairs of time series  $(i, j)$  have different trends and (ii) in which time regions  $[u-h, u+h]$  these trends differ. This is valuable information in many applications.

In order to derive the multiscale methods outlined above, we will build on the methods and theory developed in Khismatullina and Vogt (2018). However, since

the data structure in the panel model (5) differs in various important respects from that of a univariate time series, the results from Khismatullina and Vogt (2018) do not carry over directly. Hence, a substantial amount of work is needed to develop the above multiscale methods and to derive theory for them.

Compared to existing test procedures, the multiscale test proposed above has the following main advantages:

- (i) Unlike many other methods, it does not depend on a specific bandwidth parameter  $h$ . It rather takes into account multiple scales or bandwidths  $h$  simultaneously. (Cp. Section 1 for a more detailed discussion of this advantage.)
- (ii) It is much more informative than non-multiscale tests: As explained above, it does not only allow to test whether the overall null hypothesis  $H_0$  is violated. It also allows to make rigorous statistical confidence statements about which time series have a different trend and in which time regions these trends differ.

## **(b) Contributions to curve clustering**

The second main contribution of the project is to develop a multiscale clustering approach which is based on the test methods from the first part of the project. To the best of our knowledge, the only multiscale clustering method available in the literature is due to Vogt and Linton (2018). Building on their approach, our strategy to construct a multiscale clustering algorithm in model (5) is as follows: (i) We use the multiscale test statistics from the first part of the project to construct distance measures between pairs of trends  $m_i$  and  $m_j$ . (ii) From these distance measures, we obtain so-called dissimilarity measures which form the basis of a hierarchical clustering algorithm.

As already discussed at the end of Section 1, Vogt and Linton (2018) derived some basic consistency statements for their clustering algorithm. The main challenge is to develop a refined theory which goes beyond these basic statements. To achieve this, we plan to make use of the theoretical results developed for the multiscale test in the first part of the project. We conjecture that with the help of these results, we should be able to derive much more precise theoretical statements than those in Vogt and Linton (2018). Let us consider the problem of estimating the unknown number of groups  $K_0$  to illustrate this point. The estimator of  $K_0$  in Vogt and Linton (2018) depends on a tuning parameter  $\pi_{n,T}$ . Only a heuristic rule is available for the choice of this parameter. In contrast to this, we plan to derive rigorous theory for the choice of this tuning parameter. In particular, we intend to choose  $\pi_{n,T}$  as an appropriate function of  $q_{n,T}(\alpha)$ , where  $q_{n,T}(\alpha)$  is the approximate quantile of the multiscale statistic introduced above. With this choice, our estimator  $\hat{K}_0$  of

$K_0$  implicitly depends on the significance level  $\alpha$ , that is,  $\hat{K}_0 = \hat{K}_0(\alpha)$ . For a given  $\alpha$ , we aim to prove that

$$\mathbb{P}(\hat{K}_0 = K_0) \geq (1 - \alpha) + O(r_{n,T}), \quad (6)$$

where  $r_{n,T}$  is the rate of the lower order terms. This statement can be interpreted as follows: For given  $\alpha$ ,  $\hat{K}_0$  is equal to the true number of groups  $K_0$  with (asymptotic) probability at least  $1 - \alpha$ . Hence, we can tune the clustering algorithm in such a way that the probability of misestimating the number of groups  $K_0$  is (asymptotically) controlled. (6) can thus be understood as an asymptotic confidence statement about the estimator  $\hat{K}_0$ .

### (c) Empirical applications

We intend to explore some empirical applications with the help of the new multiscale testing and clustering methods described above.

**Example 1.** *Short-term risk-free interest rates are one of the main topics of interest in the financial markets. For example, it is a key component of the capital asset pricing model, which describes the relationship between risk and return. Furthermore, the risk-free rate is also a required input in financial calculations regarding the pricing of bonds. There is an evergrowing amount of literature on the dynamics of interest rate. US Treasury bills are the real-world investment that serve as the proxy for these rates. Park et al. (2009) analyze the yields of the 3-month, 6-month, and 12-month Treasury bills in the context of comparing nonparametric curves. The authors assume that the yields come from the following model:*

$$Y_{it} = m_i(t) + \sigma_i \varepsilon_{it}, \quad i = 1, \dots, n, \quad t = 1, \dots, T, \quad (7)$$

*which is a simplification of our model (5). Park et al. (2009) apply SiZer method to the data and come to the conclusion that the underlying structure for different time periods is almost identical. They could not find any significant difference between any pair of the time periods, which concides with the results from applying other methods, see, for example, Fan and Yao (2008).*

**Example 2.** *Another example of comparison of time series with nonparametric trend functions described in Park et al. (2009) involves the long-term rates for US, Canada, and Japan from January 1980 to December 2000. The data is assumed to follow the same model (7). The authors perform pairwise comparison of the curves as well as comparison of the three time series at the same time using the proposed SiZer method. In both cases their method was able to detect significant differences*

nd indicate “suspicious” regions. However, since SiZer is a graphical device that is mainly designed for data exploration rather than for rigorous statistical inference, they do not make simultaneous confidence statements with a predetermined confidence level about the regions where these differences were most probable to occur. Our proposed multiscale method, in contrast, is a rigorous level- $\alpha$ -test of the hypothesis  $H_0$  which is aimed specifically at that.

**Example 3.** *Economic growth has been a key topic in marcoeconomics over many decades. Economists are very much interested in the question whether gross domestic product (GDP) growth has been faster in some countries than in others. One of the ways to model the source of economic growth is to incorporate a nonparametric deterministic time trend in the model. For example, Zhang et al. (2012) consider such a model for the OECD economic growth data. Specifically, they investigate the following model for growth rates:*

$$\Delta \ln GDP_{it} = \beta_1 \Delta \log L_{it} + \beta_2 \Delta \log K_{it} + \beta_3 \Delta \log H_{it} + f_i(t/T) + \alpha_i + \varepsilon_{it}, \quad (8)$$

where  $i = 1, \dots, n$ ,  $t = 1, \dots, T = 140$ ,  $GDP$  is gross domestic product,  $K$  is capital stock,  $L$  is labour input,  $H$  is human capital,  $\alpha_i$  is a fixed effect,  $f_i(\cdot)$  is an unknown smooth time trend furnction and  $\varepsilon_{it}$  are idiosyncratic errors. The errors are allowed to be dependent cross-sectionally, but not serially over  $t$ . The data comes from  $n = 16$  OECD countries.

Zhang et al. (2012) estimate the common component of time trends which appears to be significantly different from zero over a wide range its support. Moreover, they test the null hypothesis that there are no significant differences in the time trends for the 16 OECD countries. Based on the bootstrap  $p$ -values the authors are able to reject the null hypothesis of all the trends being equal at the 10% confidence level. Hence, it can be interesting to be able to further cluster the OECD countries based on their economic growth rates.

**Example 4.** *The issue of global warming has been a vital topic for many scientists over the last few decades. Since the late 1970, different models that describe the global temperature have been published. In the current literature it is common to assume that the temperate time series (global as well as local) follow a model that can be decomposed into a deterministic trend component and a noise component, see, for example, Ghil and Vautard (1991) and Mudelsee (2018). In order to estimate and attribute the trends in climate variables, a variety of econometric methods have been employed, starting from the simple linear (Yue et al. (2013)) and quadratic regression (??) to the empirical mode decompoistion (Wu et al. (2011)), spectrum analysis (Ghil and Vautard (1991)) and semi- and fully non-parametric methods*

(Gao and Hawthorne (2006)). Parametric and change points methods are mostly suited to quantify the magnitude of the warming trend or to determine the change points, whereas nonparametric methods are best designed to describe the trend over the full time interval without imposing any additional structure on it. However, most of these papers apply nonparametric methods to analyze only one time series or the authors assume that the trend function is common for different time series (Atak et al. (2011)). To our knowledge, only a few papers regarding the comparison of warming trends in different cities or countries have been published (Zhang et al. (2012)).

Zhang et al. (2012) propose the following semiparametric panel model for unbalanced data to describe the trend in UK regional temperatures:

$$y_{it} = \beta_i^T D_t + m_i(t/T) + \alpha_i + \varepsilon_{it}, \quad i = 1, \dots, n, \quad t = 1, \dots, T \quad (9)$$

where  $y_{it}$  are the monthly mean maximum temperature, monthly mean minimum temperature or total rainfall in millimeters at a station  $i$  in month  $t$ ,  $D_t$  is a 11-dimensional vector of monthly dummy variables,  $\alpha_i$  is the fixed effect for station  $i$ ,  $m_i(\cdot)$  is an unknown trend function and  $\varepsilon_{it}$  are idiosyncratic errors. The dataset used is the balanced panel data set for  $n = 26$  stations in UK for  $T = 382$  months from October 1978 to July 2010. This model is a special case of our proposed model (5) with dummy variables as covariates.

Zhang et al. (2012) are interested in testing the null hypothesis  $m_i = m$  for all  $i = 1, 2, \dots, n$ . In order to do this, they apply a non-parametric  $R^2$ -based test for common trends that was developed in their paper. Based on the obtained  $p$ -values, they reject the null hypothesis of common trend at 5% level for the monthly mean maximum temperature and the monthly mean minimum temperature. However, they do not reject the null hypothesis for the total rainfall eve at the significance level of 10%. As before, it would be interesting to further cluster the UK stations based on the common trend in order to be able to detect the causes of this warming trend. Moreover, it can also be of particular interest to see in which time regions the trends are significantly different from each other.

## 2.3 Work programme incl. proposed research methods

The first part of the research period will be devoted to derive the multiscale test methods described in part (a) of Section ???. The second part will focus on the multiscale clustering methods described in part (b) of Section ??.

Milestone	2019	2020	2021
Multiscale testing	Oct–Dec	Jan–Dec	
Multiscale clustering			Jan–Oct

## 2.4 Data handling

# 3 Bibliography

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## 4 Requested modules/funds

### 4.1 Basic Module

#### 4.1.1 Funding for Staff

No.	Position	2019	2020	2021
1.	Doctoral researcher (Bes.Gr. E13 Stufe 2 / E14 Stufe 1, 75%)	??€	??€	??€
2.	Student Assistant	??€	??€	??€
Total Amount		??€	??€	??€

Job description for requested staff:

1. As research staff, a doctoral student is required who already possesses a thorough expertise in statistical multiscale methods. Marina Khismatullina who is a member of the Bonn Graduate School of Economics fits these requirements very well. Ms. Khismatullina and the applicant have already collaborated on a project which is concerned with statistical multiscale techniques; cp. Khismatullina and Vogt (2018). She thus brings in the expertise needed for the project. Moreover, with her very advanced programming skills, she will be able to develop the computational software needed for simulations and empirical applications.
2. At the onset of the project, a student assistant position should be available for support with exploratory data analysis, data mining, auxiliary programming and organisational issues. The prerequisites are strong analytical and programming skills.

#### **4.1.2 Direct Project Costs**

##### **4.1.2.1 Equipment up to Euro 10,000, Software and Consumables**

##### **4.1.2.2 Travel Expenses**

	2019	2020	2021
International conferences	500 €	1000 €	1000 €

##### **4.1.2.3 Visiting Researchers (excluding Mercator Fellows)**

##### **4.1.2.4 Expenses for Laboratory Animals**

##### **4.1.2.5 Other Costs**

##### **4.1.2.6 Project-related publication expenses**

	2019	2020	2021
Journal submission fees	0 €	200 €	200 €

## **5 Project requirements**

### **5.1 Employment status information**

Vogt, Michael, Professur, tenured position

### **5.2 First-time proposal data**

Vogt, Michael

### **5.3 Composition of the project group**

Vogt, Michael, Professor, tenured position

### **5.4 Cooperation with other researchers**

#### **5.4.1 Researchers with whom you have agreed to cooperate on this project**

#### **5.4.2 Researchers with whom you have collaborated scientifically within the past three years**

Holger Dette – University of Bochum, Germany

Oliver Linton – University of Cambridge, UK

María Dolores Martínez-Miranda – University of Granada, Spain  
Enno Mammen – University of Heidelberg, Germany  
Jens Perch Nielsen – CASS Business School, London, UK  
Matthias Schmid – University of Bonn, Germany  
Christopher Walsh – UNiversity of Dortmund, Germany

## **5.5 Scientific equipment**

The University of Bonn has a sufficient infrastructure in hard- and software to carry out the project. Personal computers are available and can be used within the project. Equipment like printers and copiers can be used as well.

## **6 Additional information**

A request for funding this project has not been submitted to any other addresses. The DFG liaison officer of the University of Bonn has been informed about this application.