an open access journal

Citation: van Raan, A. F. J. (2022). German cities with universities: Socioeconomic position and university performance. *Quantitative Science Studies*, *3*(1), 265–288. https://doi.org/10.1162/qss_a_00182

DOI:
https://doi.org/10.1162/qss_a_00182

Peer Review:
https://publons.com/publon/10.1162/qss_a_00182

Supporting Information:
https://doi.org/10.1162/qss_a_00182

Received: 10 October 2021
Accepted: 17 January 2022

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Handling Editor:
Vincent Larivière

The MIT Press

RESEARCH ARTICLE

German cities with universities: Socioeconomic position and university performance

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Keywords: bibliometric analysis, citation impact, Leiden Ranking, socioeconomic strength, university cities, urban scaling

ABSTRACT

A much-debated topic is the role of universities in the prosperity of cities and regions. Two major problems arise. First, what is a reliable measurement of prosperity? And second, what are the characteristics, particularly research performance, of a university that matter? I focus on this research question: Is there a significant relation between having a university and a city's socioeconomic strength? And if so, what are the determining indicators of a university; for instance, how important is scientific collaboration? What is the role of scientific quality measured by citation impact? Does the size of a university, measured in number of publications or in number of students matter? I compiled a database of city and university data: gross urban product and population data of nearly 200 German cities and 400 districts. University data are derived from the Leiden Ranking 2020 and supplemented with data on the number of students. The socioeconomic strength of a city is determined using the urban scaling methodology. My study shows a significant relation between the presence of a university in a city and its socioeconomic indicators, particularly for larger cities, and that this is especially the case for universities with higher values of their output, impact and collaboration indicators.

1. INTRODUCTION

1.1. Objective of the Study

Knowledge is the driving force of technological, socioeconomic, and healthcare innovations, and therefore a crucial source of sustainable wealth. Cities, in particular, are centers of knowledge production and innovation, especially when knowledge institutions such as a university are present. Concentration of knowledge production increases the attractiveness of cities for talented and entrepreneurial, highly skilled persons, and thus these urban centers continually reinforce their socioeconomic strength (Bettencourt, Lobo, & Strumsky, 2007; Bettencourt, Lobo et al., 2007; Glaeser, 1999). There is an extensive literature on the relation between human capital and innovation on the one hand, and the increase of socioeconomic welfare on the other. Recent work focuses on the regional innovation impact of universities in Europe (Tijssen, Edwards, & Jonkers, 2021). Drucker and Goldstein (2007) describe the growing interest in measuring the impacts of higher education on regional economies and review the approaches used to study the influence of research universities on regional economic development. These authors focus on the methodological advantages and shortcomings of four major research designs: single-university impact studies, surveys, knowledge production functions, and cross-sectional designs. They conclude that knowledge-based activities such as teaching and basic research have substantial positive effects on a variety of measures of regional economic progress. Nevertheless, regional economies appear to vary considerably in their ability to convert local academic research into local commercial innovation (Agrawal & Cockburn, 2003) and measuring the economic impact of university research proves difficult (Bessette, 2003).

Recent research on a worldwide scale based on an analysis of 15,000 universities in about 1,500 regions in 78 countries shows that increases in the number of universities are positively associated with future growth of GDP per capita and that there appear to be positive spillover effects from universities to geographically close neighboring regions. This effect is not simply driven by direct expenditures of the university, its staff, and its students but also through an increased supply of human capital and greater innovation (Valero & van Reenen, 2019). There is a need for a study that looks more closely at the direct socioeconomic effects of universities. In this study I investigate whether there is a significant relation between the mere presence of a university in a city and a city's socioeconomic strength, the growth of its gross urban product, and its population size. And if so, what are the characteristics of a university that matter?

As in many countries, in Germany almost all major cities do have institutions of higher education, but these can differ enormously, both in type of institution, ranging from large research-intensive universities to small, specialized colleges, without the formal status of a university, as well as in size (Lepori, 2021). Indeed, in the approximately 650 higher education institutions in Germany I find large universities with more than 40,000 students as well as colleges with fewer than 100 students (German Federal Bureau of Statistics, 2021). To illustrate this, I show in the Supplementary Material Figure S6 the ranking of these higher education institutions by number of students. Only a small proportion of these higher education institutions can be characterized as major universities with a large research output of international level and a large number of students. To work with clear criteria on these aspects, the decision about whether or not a city has a major university is based on the Leiden Ranking (Waltman, Calero-Medina et al., 2012), version 2020. A short discussion of this choice is given in the Supplementary Material Text S1.

The structure of this paper is as follows. First, I discuss how I measure the socioeconomic strength of a city or district on the basis of the urban scaling methodology. I present the results of these measurements for German cities in different regions of the country. The second part of the paper focuses on the socioeconomic position of university cities compared to other cities and which characteristics of universities play a significant role.

1.2. What Is Urban Scaling?

Recent studies show a *more than proportional* (superlinear) increase of the socioeconomic performance of cities (measured by the gross urban product) in relation to population size (Bettencourt, 2013; Bettencourt, Lobo et al., 2010; Lobo, Bettencourt et al., 2013). This *urban scaling* relation is described by a power law dependence of the gross urban product on population size given by the relation

$$G(N) = aN^{\beta} \tag{1}$$

where G is the gross urban product[1] and N the population size of a city. The exponent β follows from the measurement; in most cases, values of the exponent are between 1.10 and

[1] Throughout the text, I use the abbreviation GUP for the gross urban product. In the case of mathematical equations, I use the shorter symbol G.

1.20. I refer to my recent work on urban scaling for further details (van Raan, 2020). The urban scaling relation implies that a city twice as large (in population) as another city can be expected to have approximately a $2^{1.15} = 2.22$ greater socioeconomic performance (in terms of the gross urban product). Urban scaling behavior is also found for human interactions in general for knowledge production activities in cities (Arbesman, Kleinberg, & Strogatz, 2009; Bettencourt et al., 2007; Nomaler, Frenken, & Heimeriks, 2014; Schläpfer, Bettencourt et al., 2014) and universities also show scaling behavior similar to cities (van Raan, 2013).

A simple way to understand this phenomenon is by seeing cities as a complex network. The larger the city in population size, the more network nodes. The nodes in the urban system are the inhabitants, social and cultural institutions, centers of education and research, firms, etc. The number of nodes has a *linear* dependence on size, but the links between nodes depend on size in a *superlinear* way. The links between these (clustered) nodes are crucial for new developments, reinforcement of urban facilities, and innovation. Because they increase superlinearly, the socioeconomic strength of cities increases more than proportionally with increasing population size.

In this paper I build on my recent empirical work on urban scaling of German cities (van Raan, 2020), which implies that I use the term city *only* for cities defined as municipalities and not for the entire urban agglomerations, such as the U.S. metropolitan statistical areas (Bettencourt et al., 2010) or the European functional urban agglomerations (Bettencourt & Lobo, 2016; Eurostat, 2019; OECD, 2019) which consist of many independent municipalities that may or may not cooperate optimally.

2. DATA AND ANALYTICAL METHOD

For my analysis I apply the same approach as described in my recent paper on urban scaling and for the explanation I largely follow the relevant text in that paper (van Raan, 2020). Germany, with 83 million inhabitants, consists of 16 federal states. These federal states have a specific administrative structure in which cities and districts (*Kreise*) play a central role. In connection with the availability of data on the gross urban product (GUP) at the German Federal Statistical Bureau, I discuss this administrative structure in and around German cities in more detail. Most larger cities (above 100,000 inhabitants) are *kreisfrei* ("district-free" (i.e., cities of which the surrounding urban area belongs to the municipality of the city), and therefore I have in these cases a one-governance urban area (which is in fact the definition of the concept *kreisfrei*). Germany currently has 107 *kreisfreie* cities, with a total population of about 27,000,000. *Kreise* are districts around mostly smaller cities consisting of between 10 and 50 municipalities; together the Kreise (in total 294) have about 56,000,000 inhabitants. In Kreise the administrative and economic centers are cities that are non-kreisfreie cities (because they formally belong to a Kreis) although they can be larger than smaller kreisfreie cities[2]. These central cities within a Kreis are called *Kreis-city*.

Most university cities are kreisfrei, but several German university cities (as far as included in the Leiden Ranking) are Kreis-cities. This is the case for Hanover, Aachen, Göttingen, Tübingen, Paderborn, Saarbrücken, Marburg, Giessen, Konstanz, Greifswald, and Freiberg (not to be confused with Freiburg). Although these cities are similar to a kreisfreie city in every respect, for curious local political reasons they are not kreisfrei, and thus these cities belong to

[2] An example is Neuss (Nord Rhine-Westphalia) with about 155,000 inhabitants, but this city is not kreisfrei. It is the administrative center (Kreis-city) of the Rhein-Kreis Neuss which has a population of about 450,000. The Bavarian city Schwabach, on the other hand, with about 41,000 inhabitants, is a kreisfreie city.

a specific Kreis (Göttingen, Tübingen, Paderborn, Marburg, Giessen, Konstanz, Greifswald, and Freiberg) or to an *ad hoc* defined urban administrative district (Hanover, Aachen, Saarbrücken). This has consequences for data collection. At the city level, the German Federal Bureau of Statistics has GUP data available for the 107 kreisfreie cities. For the non-kreisfreie cities GUP data are available at the level of the Kreis. Therefore, I collected for all kreisfreie cities and for all Kreise (period 1992–2017) data on the gross urban product (GUP). The German Federal Bureau of Statistics (2021) also provided data on the population size (number of inhabitants) for all cities and for all Kreise (period 1970–2019) and data on the number of students in all German universities and other higher education institutions (1992–2019).

In this study I characterize universities with a series of bibliometric indicators. These indicators are calculated with the data from the Leiden Ranking 2020. I refer to the Leiden Ranking website (Leiden Ranking, 2020) for details on the data collection, data analysis and calculation of the indicators, particularly the impact indicators. In total, 54 German universities are included in the Leiden Ranking. I consider these as Germany's major universities. These are the universities that meet the selection criterion for the Leiden Ranking: at least an annual average of 200 Web of Science indexed publications in the period 2015–2018. Only research articles and review articles published in international journals ("core publications") are taken into account. Other types of publications are not considered. The Leiden data include at least the major universities but, of course, the selection criterion is rather arbitrary. Indeed, just below the threshold of the selection criterion there are several other universities of considerable size in output, impact, and student numbers. Nevertheless, all 80 Max Planck Institutes and main research centers are located in or nearby universities covered by the Leiden Ranking[3].

In Table 1 I give an overview of the data sets of cities used in this study. For instance, there are in total 81 cities in Germany with more than 100,000 inhabitants, and 44 of these cities have a university included in the Leiden Ranking. Of these cities, 69 (84%) are kreisfrei and 39 of them have a university included in the Leiden Ranking. I remark that the 54 universities do not always correspond one-on-one to cites: Large cities like Berlin, Munich, and Hannover have more than one university included in the Leiden Ranking, and some universities are located in two cities, such as Erlangen-Nurnberg and Duisburg-Essen. In total, the 54 universities relate to 51 cities[4].

3. URBAN SCALING OF GERMAN CITIES

3.1. Scaling of the Gross Urban Product

I refer to my recent publication (van Raan, 2020) for an extensive analysis of urban scaling in the western, southern, middle, northern, and eastern regions[5] of Germany and in the country as a whole. For this study, I updated the data up to and including 2017. Figure 1 shows the results of the analysis, where I compare the scaling of the southern cities to those of the other

[3] See https://www.mpg.de/17039558/annual-report-2020-structures.pdf, p. 167.

[4] In the case of more than one university in a city, I characterize the city with the maximum indicator values of the universities, see footnote 10, Section 4.2. In the case of a university located in two cities, I assign the university to both cities.

[5] North Rhine-Westphalia: western region of Germany; Baden-Württemberg and Bavaria: southern region; Hesse, Rhineland-Palatinate, and Saarland: middle region; Bremen, Hamburg, Lower Saxony, and Schleswig-Holstein: northern region; Berlin, Brandenburg, Mecklenburg-Vorpommern, Saxony, Saxony-Anhalt and Thuringia: eastern region.

Table 1. Overview of the kreisfreie and non-kreisfreie cities with more than 100,000 inhabitants and between 50,000 and 100,000 inhabitants. Numbers in square brackets indicate the number of cities with a university (as far as included in the Leiden Ranking). There are 16 kreisfreie cities with fewer than 50,000 inhabitants. There is one non-kreisfreie university city with fewer than 50,000 inhabitants

	kreisfrei	*Non-kreisfrei*	*Total*
Cities >100,000	68 [39]	13 [5]	*81 [44]*
Cities 50,000–100,000	23 [1]	87 [5]	*110 [6]*

regions of Germany. In all cases the GUP scales superlinearly with population: The scaling exponent ranges between and 1.03 and 1.34. As I clearly see, in urban scaling not only is the power law exponent a crucial parameter but so also is the absolute difference in GUP between two sets of cities (i.e., the distance between the regression lines).

This difference in GUP is clearly visible in the lower right panel of Figure 1, where I compare the urban scaling of the southern region to the eastern region. The southern cities are generally at a considerably higher GUP level compared with the cities in the eastern region, which is the former German Democratic Republic. But the difference between the wealthy southern region of Germany and the old industrial western region is also striking. For an extensive discussion of this issue, explanations of how individual cities influence the measured scaling exponents, and for confidence intervals of the measured scaling exponents, I refer to van Raan (2020). Remarkably, if I join all regions and calculate the urban scaling of the entire country, I find a low superlinear scaling exponent 1.03, lower than most of the separate

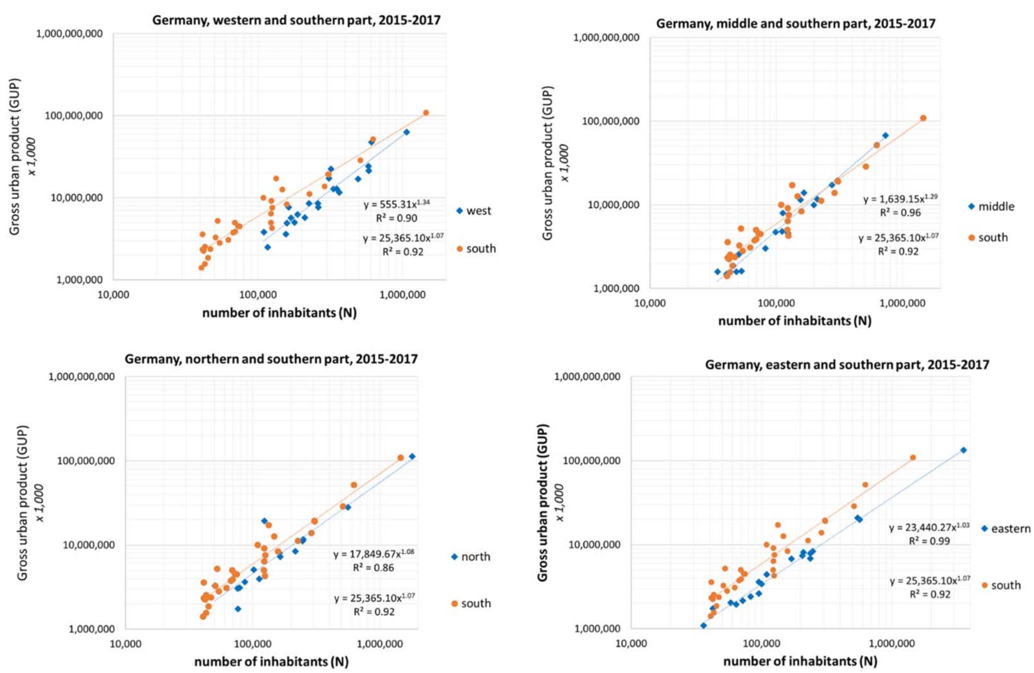

Figure 1. Scaling of the gross urban product (GUP) for German (kreisfreie) cities. Upper left panel: western and southern region of Germany; upper right panel: middle and southern region; lower left panel: northern and southern region; lower right panel: eastern and southern region. (GUP in units of €1,000; data average 2015–2017; data source: German Federal Bureau of Statistics).

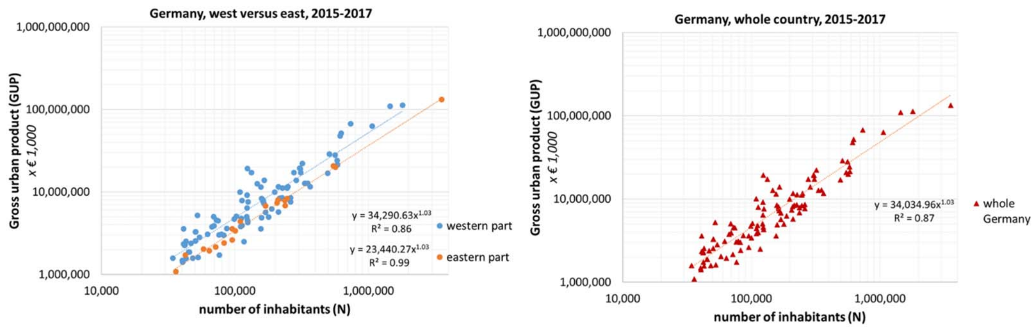

Figure 2. Scaling of the gross urban product (GUP) for German (kreisfreie) cities. Left panel: all west regions versus east; right panel: all regions together (i.e., whole country) (GUP in units of €1,000; data average 2015–2017; data source: German Federal Bureau of Statistics).

regions of the country (see Figure 2). This phenomenon highlights an often neglected issue in urban studies: The scaling of GUP with population size of cities in a country may depend heavily on the regional economy within the country. This must be taken into account when the scaling exponent of an entire country is calculated. Notice that the double-logarithmic presentation might suggest a strong similarity of the distributions, but the calculations show significant differences in coefficients and exponents which also persist over time.

3.2. Scaling Residuals as Indicator of Socioeconomic Strength

As can be expected, and also clearly visible in the empirical results (Figures 1 and 2), the *observed* positions of cities will deviate from the *expected* positions given by the regression line through all measuring points of a specific set. These deviations can be measured by the residuals: Using Eq. 1 (which is the scaling relation for a *set* of cities) I find that $G(N_i)$ is the *expected* gross urban product of an *individual* city (i) with population N_i. By denoting the *observed* (real) value of the gross urban product of a city as G_i, I calculate the residuals ξ_i of the scaling distribution for each of the (kreisfreie) cities (and similarly for the Kreise) as follows:

$$\xi_i = ln[G_i/G(N_i)] = ln\left[G_i/aN_i^{\beta}\right] \tag{2}$$

Positive residuals indicate that a city performs better than expected. Thus, from the urban scaling measurements of cities or districts (Kreise) residuals for individual cities or Kreise can be determined directly from the empirical regression data and *these residuals are considered as an indicator of socioeconomic strength.* Indeed, I find a strong correlation of residuals with other measures of socioeconomic strength; see van Raan (2020). Given the considerable economic differences between the different regions of Germany, I calculated the residuals both in relation to the *regional* (ξ_r) as well as the *national* context (ξ_n). For instance, for cities in the western region of Germany the regional residuals are calculated with the relevant scaling law as presented in Figure 1, upper left panel, i.e., on the basis of

$$G_{i,r}(N_i) = 555.31 N_i^{1.34},$$

whereas their national residuals are calculated with the scaling law in Figure 2, right panel, i.e., on the basis of

$$G_{i,n}(N_i) = 34034.96 N_i^{1.03}.$$

Cities in the eastern part of Germany, such as Leipzig, Dresden, and Jena, do not yet have the same socioeconomic strength as many cities in other parts of Germany, but within their own region Leipzig, Dresden, and Jena show a strong position. There is no rational basis on which to assign specific weights to the national and the regional residual as components in the calculation of an overall socioeconomic strength indicator. Therefore, I give both components equal weight and take as a measure for the relative socioeconomic strength S of a city the average value of the national and the regional residuals:

$$S = (\xi_n + \xi_r)/2 \tag{3}$$

The statistical uncertainty in this measure is determined by the uncertainty in the measured residuals, and these are determined by the standard error values of the measured scaling coefficient and scaling exponent. On the basis of earlier discussion on confidence levels of scaling parameters (van Raan, 2020) I estimate the uncertainty in S to be ±0.03. An important characteristic of urban residuals is that they are quite stable and vary little over a long period, often on timescales of several decades (Alves, Mendes et al., 2015; Bettencourt, Yang et al., 2020). Thus, scaling residuals can be seen as reliable indicators of the socioeconomic strength of cities.

The full list for all kreisfreie cities with their national residuals ξ_n, regional residuals ξ_r, and socioeconomic strength S is presented in Table S1. In Figure S1 I show the normal distribution of these parameters calculated on the basis of their respective means and standard deviations.

In Figure S2 I show the rank-distribution of the national residual in comparison with the regional residual. In Table 2 I show as an example the top 25 cities ranked by their socioeconomic strength S.

At the top of the S ranking I see the cities Wolfburg and Ingolstadt, with extraordinary high socioeconomic strength. Wolfsburg (about 125,000 inhabitants) is the location of the Volkswagen (VW) headquarters with the world's biggest car plant, producing 815,000 cars per year (2015) and with 70,000 employees in Wolfsburg alone. The city even owes its origins entirely to VW: When founded in 1938 it had only 1,000 inhabitants. Now, measured in GUP per capita, Wolfsburg is one of the richest cities in Germany. Ingolstadt (about 140,000 inhabitants) is partly a similar case: This city is home to the headquarters of the automobile manufacturer Audi. However, in strong contrast to Wolfsburg, Ingolstadt was already an important city in Germany in the early Middle Ages. Neither city has a major university: Wolfsburg has a college with a focus on vehicle technology, while Ingolstadt had a university from 1472–1800, but from 1980 it has had a small Catholic university focusing mainly on social sciences and humanities (not considered as a major university in this study) as well as a technical college. As a result of the huge automobile companies, both cities have an extraordinarily large urban scaling residual.

I have already noted that not all university cities are kreisfreie cities. Therefore, they are not present in Tables S1 and S2. As discussed in Section 2, this is the case for Hanover, Aachen, Göttingen, Tübingen, Paderborn, Saarbrücken, Marburg, Giessen, Konstanz, Greifswald, and Freiberg. This means that no GUP data are directly available for these cities, only for their total Kreis. Nevertheless, all the abovementioned cities are (often by far) the largest cities in the Kreis (and that is why they are called a *Kreis-city*) and they will largely determine the socioeconomic position of their Kreis. Therefore, I use the data of their Kreis to determine the socioeconomic strength of these cities. I calculated the Kreis residuals in the same way as I calculated the residuals of the kreisfreie cities, both in relation to the regional as well as in the national context, and determine the socioeconomic strength also in the same way as for the kreisfreie cities. In Table S2 I list all of the Kreise with their national residuals ξ_n, regional

Table 2. German (kreisfreie) cities ranked by S, top 25 (university cities, as far as present in the Leiden Ranking, in bold)

Kreisfreie city	*S*
Wolfsburg	1.20
Ingolstadt	0.90
Schweinfurt	0.68
Erlangen	0.56
Coburg	0.56
Ludwigshafen	0.49
Regensburg	0.48
Bonn	0.43
Düsseldorf	0.42
Koblenz	0.38
Emden	0.38
Darmstadt	0.37
Stuttgart	0.37
Frankfurt	0.35
Aschaffenburg	0.35
Ulm	0.34
Passau	0.25
München	0.24
Münster	0.21
Bayreuth	0.20
Speyer	0.18
Memmingen	0.17
Leverkusen	0.16
Bamberg	0.16
Zweibrücken	0.15

residuals ξ_r, and socioeconomic strength *S*. Kreise with university cities (as far as these universities are present in the Leiden Ranking) are shown in Table 3.

Using the residual calculations for the kreisfreie cities and for the Kreise as discussed above, I analyze in the next section all 191 German cities with more than 50,000 inhabitants. Fifty of them are university cities, with a special focus on cities with more than 100,000 inhabitants, because the vast majority of university cities (44) are in this group.

Table 3. German Kreise with university cities ranked by *S*

(Non-kreisfreie) city	*S*
Saarbrücken (Kreis Regionalverband Saarbrücken)	0.23
Hannover (Kreis Region Hannover)	0.15
Paderborn (Kreis Paderborn)	0.10
Aachen (Kreis Städteregion Aachen)	0.09
Marburg (Kreis Marburg-Biedenkopf)	0.08
Göttingen (Kreis Göttingen)	0.06
Giessen (Kreis Giessen)	0.03
Tübingen (Kreis Tübingen)	−0.02
Konstanz (Kreis Konstanz)	−0.03
Freiberg (Kreis Mittelsachsen)	−0.05
Greifswald (Kreis Vorpommern-Greifswald)	−0.15

4. UNIVERSITY PERFORMANCE AND THE SOCIOECONOMIC CHARACTERISTICS OF THEIR CITIES

4.1. University Cities Compared to Other Cities

In this section I compare university cities to other cities on the basis of three different socioeconomic indicators: the socioeconomic strength *S*; the growth of the gross urban product over the last 20 years (*T*); and the growth in population in the last 20 years (*U*). I make this comparison for cities with between 50,000 and 100,000 inhabitants, and for cities with more than 100,000 inhabitants. I calculated the socioeconomic strength *S* in Section 3, and in Figure 3 I show the normal distribution of *S* for cities with more than 100,000 inhabitants. In this figure, the four quartiles of the distribution are marked.

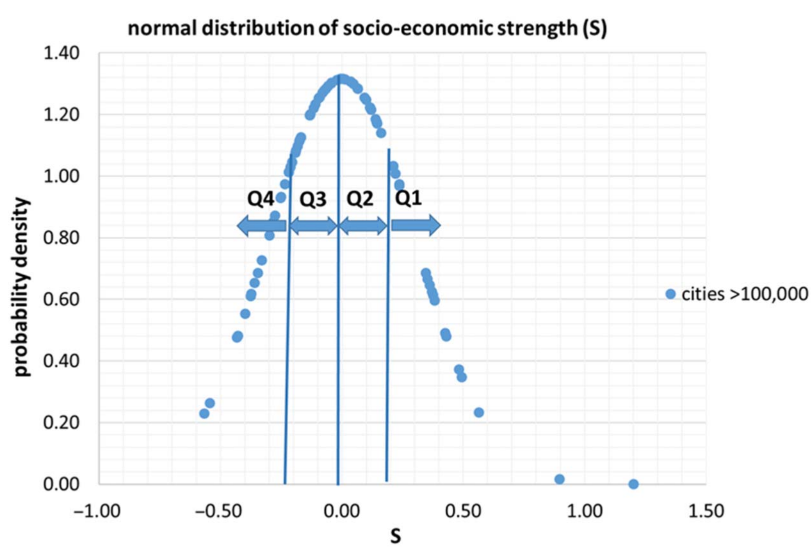

Figure 3. Normal distribution of the socioeconomic strength (*S*).

I have GUP values for kreisfreie cities and Kreise available from 1992 to 2017 and calculate the ratio T between the average GUP value for 2015–2017 and for 1995–1997:

$$T = [\mathrm{GUP}(2015\text{–}2017)/\mathrm{GUP}(1995\text{–}1997)].$$

This indicator defines the growth of the gross urban product over the last 20 years. I consider T as the indicator of socioeconomic strengthening. I present this indicator for all cities with between 50,000 and 100,000 inhabitants and all cities above 100,000 inhabitants in Table S3. I see high T values in the car industry cities Ingolstadt and Wolfsburg. This is also the case for the former East German cities Jena, Potsdam, Dresden, and Leipzig, indicating the socioeconomic strengthening of these cities. Of the 10 lowest ranked cities above 100,000 inhabitants the majority are in the old industrial region (Ruhr Area) in Nord Rhine Westphalia. In Figure 4 I present the normal distribution of T for the 81 cities with more than 100,000 inhabitants, where the first two quartiles are marked.

The third socioeconomic city indicator is population growth. Using the data on city population I calculate the ratio U between the number of inhabitants in 2019 and in 2000:

$$U = [N(2019)/N(2000)].$$

I present this ratio for all cities with between 50,000 and 100,000 inhabitants and all cities with more than 100,000 inhabitants in Table S3, where S values and number of inhabitants N are included. Some cities, such as Potsdam, show relatively strong growth, while a considerable part of the cities (35%) did not grow at all or even decreased in population. In Figure 5 I present the normal distribution of U for the 81 cities with more than 100,000 inhabitants, again with the first quartiles of the distribution indicated.

I analyze the data as follows and take the socioeconomic strength S as an example. The *independent* variable concerns cities, namely *university cities* versus *other cities*. I rank all cities by their S value and divide this ranking into quartiles to have a reasonable number of cities (20) per unit of division. Thus, the first quartile S(Q1) are the cities in the top 25% of the S distribution, and so on. For example, S(Q1) of all cities with more than 100,000 inhabitants covers the values 1.20 to 0.15, the second quartile S(Q2) the values 0.14 to −0.04, and so on,

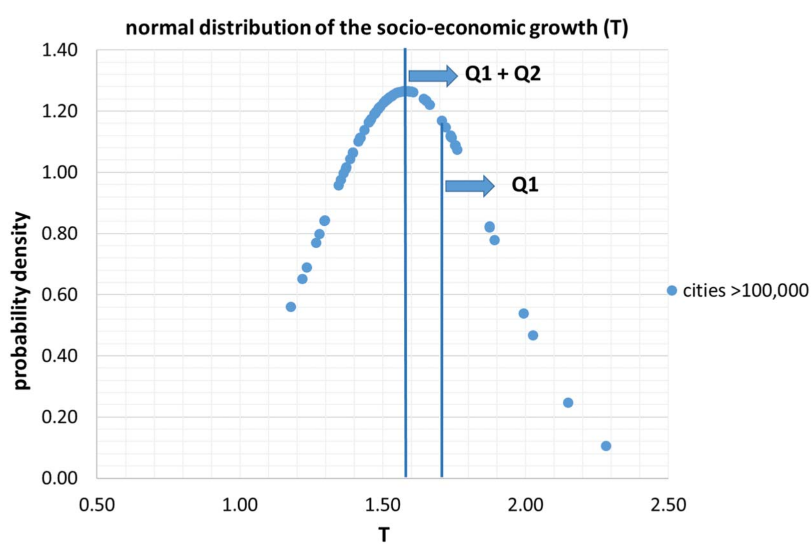

Figure 4. Normal distribution of the GUP increase over 20 years (T).

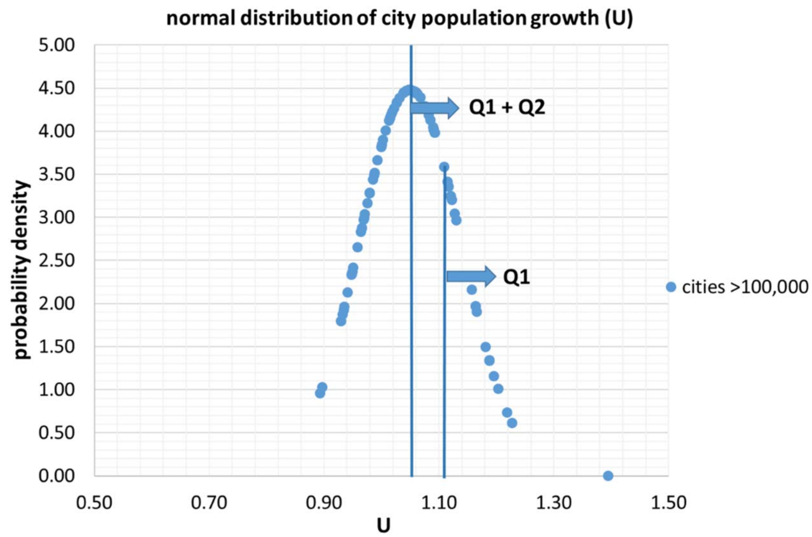

Figure 5. Normal distribution of the city population growth over 20 years (U).

and in a similar way for the two other distributions; see Figures 3–5 (the relevant data are in Table S3).

For each quartile I count the number of cities *with* universities as well cities *without* (Leiden Ranking) universities. The result of this analysis is presented in two contingency tables (see Table 4): left-hand side for the 81 cities with more than 100,000 inhabitants and the right-hand side for the 110 cities with 50,000–100,000 inhabitants. A chi-squared test of the data for S (Q1, Q2, Q3, and Q4) renders a p-value of 0.010 in the case of the cities with more than 100,000 inhabitants. Taking the conventionally accepted significance level $p < 0.05$ I find a significant difference in the distribution of cities according to the presence of universities.

Further inspection of the contingency table reveals more information. I see that it is particularly the fourth quartile S(Q4) distribution that makes the difference: Universities are significantly absent in cities with the lowest socioeconomic strength. By distinguishing between the first half of the S distribution at the high values side, S(Q1 + Q2), and the low values second half S(Q3 + Q4), 28 of the 44 university cities with more than 100,000 inhabitants (64%) are in S(Q1 + Q2), which means that they are cities with an above-average socioeconomic strength ($p = 0.011$, the probability that no difference exists). For the group of 110 cities with 50,000–100,000 inhabitants the significance disappears. But as is clear from Table 4, the number of university cities in this group is very low (six) and one cannot expect significant results.

I performed a similar analysis for the two other city indicators: socioeconomic growth T and population growth U. The results are shown in Table S4. For the cities with more than 100,000 inhabitants I find that the university cities are significantly present in T(Q1 + Q2). For the population growth U I find that for the cities with more than 100,000 inhabitants, as well as for the cities with 50,000–100,000 inhabitants, the university cities are significantly present in U(Q1 + Q2). Just like in the case of the socioeconomic strength S, the significance is mainly due to the low number of university cities in the fourth quartile. For the cities with between 50,000 and 100,000 inhabitants I also find that the university cities are significantly in U(Q1 + Q2). Table 5 gives an overview of my findings. I conclude that for all three socioeconomic indicators (socioeconomic strength, socioeconomic growth, and population growth) university cities with more than 100,000 inhabitants are predominantly present in the better half of these indicators.

Table 4. Number of university cities and other cities for each quartile of the socioeconomic strength (*S*) distribution (left: the 81 cities with more than 100,000 inhabitants; right: the 110 cities with 50,000–100,000 inhabitants)

S	University cities	Other cities		*S*	University cities	Other cities	
Q1	12	8	*20*	Q1	1	26	*27*
Q2	16	5	*21*	Q2	2	26	*28*
Q3	11	9	*20*	Q3	2	25	*27*
Q4	5	15	*20*	Q4	1	27	*28*
	44	*37*	*81*		*6*	*104*	*110*
p =	0.010			*p* =	0.871		
S	University cities	Other cities		*S*	University cities	Other cities	
Q1 + Q2	28	13	*41*	Q1 + Q2	3	52	*55*
Q3 + Q4	16	24	*40*	Q3 + Q4	3	52	*55*
	44	*37*	*81*		*6*	*104*	*110*
p =	0.011			*p* =	1.000		

I find a positive relation between having a major university and being a city with a relatively strong socioeconomic position. However, I must be cautious with my conclusions. I certainly did not find an iron law for each university city, nor can I make a statement about causality. An indication of a possible causal relation is that most of the major universities are centuries old, whereas my socioeconomic indicators relate to recent times. This temporal precedence could suggest that cities with a major university had a higher probability than cities without a major university to develop into a socioeconomically strong position.

Next to the data on socioeconomic strength, socioeconomic growth, and population growth used so far in the study, there is a further important source of data. The German socioeconomic research agency Prognos AG (Prognos, 2021) evaluates the future opportunities and risks of all (kreisfreie) cities and Kreise. Prognos has published the results every three years since 2004 in the report *Zukunftatlas*. The latest edition is from 2019. The evaluation of the future perspectives of cities and Kreise is based on 29 macro- and socioeconomic indicators to assess strength and dynamism. These indicators cover the fields of demographics, labor market, social welfare, competition, and innovation. No scaling approaches were applied. These indicators are discussed in detail in the *Zukunftatlas* (Prognos *Zukunftatlas*, 2019). On the basis of these assessments, a ranking (Future Index) of all cities and Kreise is created. The Prognos Future Index is the only nationwide German ranking that shows urban regional developments over a period of 15 years. I used the publicly available[6] overview of all rankings since 2004 to calculate for all German cities with a population greater than 100,000 the difference in Prognos ranking positions between the years 2004 and 2019. For instance, the Prognos ranking position of Berlin was 262 in 2004, and 93 in 2019. So Berlin improved its ranking position by +169. In sharp contrast, the traditional old industry city Essen fell in ranking position from 121 in 2004 to 239 in 2019, a difference of −131.

[6] https://de.wikipedia.org/wiki/Zukunftsatlas. I checked the reliability of the data in this Wikipedia page with the original data in the Prognos *Zukunftatlas* 2016 and 2019.

Table 5. Overview of the significance tests for university cities with respect to the three socioeconomic city indicators

	Population growth U	Socioeconomic strength S	Socioeconomic growth T
Cities N = 50,000–100,000	Significant	Not significant	Not significant
Cities N > 100,000	Significant	Significant	Significant

After distinguishing between university cities and other cities, I calculated for both groups the normal distribution of ranking position differences. Figure S3 presents the results. I tested the difference between the two means of both distributions and found that at the 95% confidence interval level $p = 0.041$. I conclude that university cities improved their ranking positions in the 15 years period between 2004 and 2019 significantly more than the other cities.

4.2. Bibliometric Performance Indicators of German Universities

In the previous section I compared university cities with other cities. I found that university cities are predominantly present in the better half of the S, T, and U distributions but not all cities with a major university belong to the socioeconomically strong cities. Could this be due to characteristic differences between universities? In other words, how do the university cities in the first quartile or first two quartiles of the S, T, and U distributions differ from the university cities in the second, third, and fourth quartiles, or in the third and fourth quartiles, respectively? To investigate this, I have to categorize the university cities in such a way that I can distinguish them from one another. I do this with help of bibliometric[7] indicators. Before I perform the analysis, I must first discuss the basic elements of bibliometric indicators.

Distinguishing between universities is the core business of university rankings. On the basis of survey data or bibliometric data, or both, several organizations produce annual rankings of universities. Frequently used rankings are the Academic World Universities Ranking (Shanghai Ranking) (ARWU, 2020), the Times Higher Education ranking (THE, 2020), the Leiden Ranking (Leiden Ranking, 2020), the QS ranking (QS, 2020), the Scimago ranking (Scimago, 2020), and the U-Multirank (U-Multirank, 2020). For an extensive discussion of the problems related to university rankings, I refer to van Raan (2005, 2019) and Waltman et al. (2012). Here I briefly outline several important issues. The combination of scores for teaching and research performance into one final score is methodologically incorrect because teaching and research are different tasks and also different missions of universities. In research rankings it is incorrect to combine size-dependent (e.g., number of papers in specific journals such as *Nature* and *Science*) and size-independent measures (e.g., publications per staff member). Indicators based on citation analysis must be field normalized, otherwise universities with a focus on engineering, or on social sciences and humanities, will be systematically disadvantaged. Often citation indicators are based on averages. But average-based indicators are very sensitive to outliers, thus they are not the best statistic in the case of skewed distributions, such as the distribution of citations over publications. A further problem is that comparison of ranking scores in a time series can be affected seriously if, meanwhile, the number of universities covered by the ranking is increased substantially, for instance by lowering the required threshold for the number of publications. Last, but not least, the definition of a university, particularly the relation with medical schools and hospitals, is a cumbersome task.

[7] The quantitative study of science, mostly referred to as *scientometrics*, aims at the advancement of our knowledge on the development of science and its communication structure, in relation to social, technological, and socioeconomic aspects. Within scientometrics, research on scientific communication, particularly with data from publications, citations, and journals is called *bibliometrics* (van Raan, 2019).

Table 6. University indicators considered in this study

1	Number of fractionally counted publications (*Pfrac*)
2	Number of fractionally counted publications in the top 1, 5, 10, 50% (*Pt1frac*, *Pt5frac*, *Pt10frac*, *Pt50frac*)
3	Same as 2, now relative (*pt1frac*=[*Pt1frac/Pfrac*]), similar for *pt5frac*, *pt10frac*, *pt50frac*)
4	Number of fully counted publications (*Pfull*)
5	Number of fully counted publications in the top 1, 5, 10, 50% (*Pt1full*, *Pt5full*, *Pt10full*, *Pt50full*)
6	Same as 5, now relative (*pt1full*=[*Pt1full/Pfull*]), similar for *pt5full*, *pt10full*, *pt50full*)
7	Number of fractionally counted citations (*Cfrac*)
8	Number of fully counted citations (*Cfull*)
9	Number of collaborative publications (total *Pcoll*, within this total: international *Pintcoll*, with business companies *Pb*, and of these latter with local business companies *PbL*) (fully counted)
10	Number of students (*Ns*) and the increase of this number in the last 20 years (*V*)

All of the above issues, including a well-defined uncertainty measure, are dealt with meticulously in the Leiden Ranking (Waltman et al., 2012). For this paper I use the 2020 version of the Leiden Ranking (Leiden Ranking, 2020). In this version publication data relate to the period 2015–2018 and the citation data to 2015–2019; author self-citations are excluded. Universities are included if they have more than 200 publications covered by the Web of Science (WoS)[8] on average per year in the period 2015–2018. I consider this also as the definition for a major university. This does not mean that universities with a publication output below the abovementioned threshold are low-performance institutions, but they are not a major university in terms of scientific productivity. For a detailed discussion of all bibliometric indicators I refer to the Leiden Ranking methodology.

I consider in my analysis the indicators given in Table 6. In the Leiden Ranking publications and citations can be *fractionally* or *fully* counted[9]. I distinguish 10 indicator families consisting of one to at most four subindicators. For instance, the second indicator family contains four subindicators: the (absolute) number of fractionally counted publications in the worldwide top 1, 5, 10, and 50% of the citation-impact distribution of the relevant field (*Pt1frac*, *Pt5frac*, *Pt10frac*, *Pt50frac*). The first nine indicator families are available in the Leiden Ranking, the tenth (number of students, year 2020, and the increase of the number of students in the last 20 years) was obtained from the German Federal Bureau of Statistics. I have 26 (sub)indicators

8 Web of Science, published by Clarivate Analytics; see https://clarivate.com/webofsciencegroup.

9 The scientific impact indicators in the Leiden Ranking are calculated using either a full or a fractional counting (at the institutional level) method. The full counting method gives equal weight (with value 1) to all publications of a university, regardless of collaboration. The same goes for the citations received by these publications. The fractional counting method, however, gives less weight to collaborative publications than to noncollaborative ones. More specifically, publications as well as their citations are divided over the collaborating institutes. The fractional counting method leads to a more proper field normalization of impact indicators (Waltman & van Eck, 2015). Because of the better normalization properties, fractional counting is regarded as the preferred method in the Leiden Ranking, but both modalities are available in this ranking. The advantage in having both is that it provides a good idea of the robustness of the outcomes. At high aggregation levels such as universities, the correlation between the ranking based on full counting and that based on fractional counting is high.

which means that each university (*i*) is characterized by the set of indicators {*i*1, *i*2, ..., i26}. Consequently, the university city is also characterized by these indicators[10].

The *pt10frac* indicator (third indicator family, third subindicator) is generally considered as the main research performance indicator. This indicator gives the fraction of publications that are in the top 10% of their fields[11] in the case that publications are fractionally counted. So, if for a university this fraction is 0.100, this university performs according to the expected value; if the fraction is above 0.100, the university performs better, and below 0.100 the performance is lower than the expected value. The indicator values of the universities have, to a good approximation, a normal distribution. As an example, I show in Figure S4 this distribution of the *pt10frac* indicator for all German universities covered by the Leiden Ranking.

In Table 7 I present German universities cities (as far as included in the Leiden Ranking 2020) ranked by the *pt10frac* indicator of their university (in the case of more than one university, see footnote 10). I show the first 25 cities (two of which have a population below 100,000) and given the large amount of data I limit the table to the first nine indicators (indicator families 1 to 3) and the last two indicators (indicator family 10), as well as the population of the city (*N*, year 2019) and the values of the three socioeconomic indicators *S*, *T*, and *U*. The complete set of data (all university cities, all indicators) is available in my data repository[12].

An illustration of the differences in student numbers (*Ns*) and growth in student numbers (*V*) for universities in the Leiden Ranking (LR) and universities/other higher education institutions not in the LR is given in Figure S5. I find a significant difference in student numbers between the top universities (i.e., LR universities in the first quartile of the *pt10frac* distribution) and all LR universities ($p = 0.012$), and also a significant difference between all LR universities and the non-LR universities ($p < 0.000$). For the growth in student numbers there is no significant difference between the top universities and all LR universities, but there is a significant difference between all LR universities and the non-LR universities ($p = 0.002$): Non-LR universities show a larger increase of student numbers compared with LR universities.

4.3. University Performance and Socioeconomic Indicators of Cities

I am now ready to address the question *how* the university cities (>100,000 inhabitants) in the first quartile (Q1) or first two quartiles (Q1 + Q2) of the *S*, *T*, and *U* distributions differ from the other university cities. The *S*, *T*, and *U* distributions are based on *all* 81 cities with more than 100,000 inhabitants. I apply two data-analytical methods. In the first method the *city indicators* are leading, whereas in the second method the *university indicators* are leading.

I start with the first method. University cities are ranked by a specific city indicator (I do this successively for *S*, *T*, and *U*). As an example, I take the *S* distribution. For the university cities in the first quartile *S*(Q1) as well as for those in the other quartiles *S*(Q2 + Q3 + Q4) I calculate the mean and standard deviation of all university indicators and of the city indicators as well. With a test of the difference between the means I am able to find which indicators differ significantly when comparing the university cities in *S*(Q1) with those in *S*(Q2 + Q3 + Q4). I repeat the same procedure for the university cities in *S*(Q1 + Q2) (above average socioeconomic strength) versus those in *S*(Q3 + Q4) (below average socioeconomic strength). This analysis

[10] In the case of, for instance, two universities *a* and *b* in one city, I characterize that city as if it has one university with the set of indicators {max(*a*1, *b*1), max(*a*2, *b*2), ..., max(*a*26, *b*26)}.

[11] I use here the indicator symbol *pt10frac*; in the Leiden Ranking this indicator has the symbol PP(top 10%) calculated in the fractional counting modality.

[12] See https://osf.io/4ru96/.

Table 7. German university cities with the first three bibliometric indicator families (nine indicators) and indicator family 10 (number of students and growth of the number of students, main text), as well as city population (*N*) and the three socioeconomic indicators *S*, *T*, and *U*, ranked by the *pt10frac* indicator (I show the first 25)

University city	*N*	*Ns*	*S*	*U*	*T*	*V*	*Pfrac*	*Pt1frac*	*Pt5frac*	*Pt10frac*	*Pt50frac*	*pt1frac*	*pt5frac*	*pt10frac*	*pt50frac*
Göttingen	118,911	30,162	0.06	0.96	1.51	1.32	4872	60	346	664	2,838	0.012	0.071	0.136	0.582
München	1,484,226	48,697	0.24	1.23	1.75	1.53	8142	101	498	1,000	4,681	0.014	0.066	0.133	0.575
Bonn	329,673	38,481	0.43	1.09	1.42	1.04	4819	70	287	590	2,734	0.015	0.060	0.122	0.567
Heidelberg	161,485	25,986	−0.01	1.15	1.74	1.26	7744	100	492	946	4,374	0.013	0.064	0.122	0.565
Würzburg	127,934	27,552	0.14	1.00	1.52	1.68	3622	45	215	441	2,020	0.012	0.059	0.122	0.558
Münster	315,293	45,022	0.21	1.19	1.53	1.03	4707	52	309	565	2,579	0.011	0.066	0.120	0.548
Mainz	218,578	29,907	0.04	1.20	1.46	1.11	3817	48	229	443	2,098	0.012	0.060	0.116	0.550
Stuttgart	635,911	24,153	0.37	1.09	1.60	1.71	2697	29	153	310	1,499	0.011	0.057	0.115	0.556
Frankfurt	763,380	45,179	0.35	1.18	1.50	1.26	4462	51	264	510	2,443	0.011	0.059	0.114	0.548
Erlangen	112,528	37,575	0.56	1.12	2.02	1.92	5939	74	351	678	3,198	0.013	0.059	0.114	0.538
Nürnberg	518,370	37,575	0.00	1.06	1.65	1.92	5939	74	351	678	3,198	0.013	0.059	0.114	0.538
Freiburg	231,195	24,028	−0.10	1.13	1.74	1.37	4923	56	279	561	2,809	0.011	0.057	0.114	0.570
Aachen	248,960	45,945	0.09	1.02	1.60	1.58	6146	64	344	694	3,280	0.010	0.056	0.113	0.534
Karlsruhe	312,060	23,616	0.12	1.12	1.54	1.73	5527	55	313	618	3,021	0.010	0.057	0.112	0.547
Berlin	3,669,491	37,312	−0.17	1.08	1.57	1.05	5284	57	278	570	2,868	0.011	0.057	0.111	0.548
Köln	1,087,863	54,105	0.05	1.13	1.57	0.91	4029	39	217	447	2,177	0.010	0.054	0.111	0.540
Regensburg	153,094	20,584	0.48	1.22	1.99	1.44	2856	29	157	314	1,576	0.010	0.055	0.110	0.552
Essen	582,760	43,029	−0.19	0.98	1.37	1.15	3424	32	186	375	1,835	0.009	0.054	0.109	0.536
Duisburg	498,686	43,029	−0.36	0.97	1.43	1.15	3424	32	186	375	1,835	0.009	0.054	0.109	0.536
Darmstadt	159,878	25,170	0.37	1.16	1.59	1.57	2517	23	129	274	1,349	0.009	0.051	0.109	0.536
Kassel	202,137	22,786	−0.05	1.04	1.45	1.49	863	7	45	92	418	0.009	0.053	0.106	0.484
Dresden	556,780	29,148	−0.09	1.17	1.87	1.28	4933	45	262	520	2,584	0.009	0.053	0.105	0.524
Bayreuth	74,783	12,931	0.20	1.01	1.60	1.85	1629	13	86	171	851	0.008	0.053	0.105	0.522
Kiel	246,794	27,101	−0.07	1.06	1.47	1.35	3087	40	161	324	1,639	0.013	0.052	0.105	0.531
Tübingen	91,506	26,842	−0.02	1.13	1.90	1.45	5148	47	254	539	2,776	0.009	0.049	0.105	0.539

answers the question: Are the university cities in the "top" of a specific city indicator also the cities that have (on average) a significantly higher score for one or more university indicators, and which indicators are they?

The results of method 1 are presented in Table 8. To keep the table clear, I only show the *p*-values for the significant results (i.e., indicators with *p*-value <0.050). The basic data and the calculations of the statistical significance are available in my data repository. I first give an example how to read this table. The left-hand side of Table 8 relates to the university cities within *U*(Q1), the first quartile of the population growth distribution *U* of all 81 cities >100,000. I find that for these cities, the marked indicators have significantly larger vales compared with the university cities in the rest of the *U* distribution (i.e., in *U*(Q2 + Q3 + Q4)). This difference is given by the ratio in the second column, and the *p* value in the third column gives the probability within the 95% confidence interval. Thus, for university cities in *U*(Q1) the *pt10frac* indicator value of their universities is 1.12 larger than the same indicator for the universities of the cities in *U*(Q2 + Q3 + Q4), with *p* = 0.009.

I conclude from Table 8 that universities in cities with above-average population growth are in general universities with a higher performance in scientific output (publication-based indicators), in scientific impact (citation-based indicators), and in scientific collaboration. I also see in Table 8 that particularly the number of publications with local companies (i.e., companies in these cities and in their urban region (indicator *PbL*)) is almost a factor two higher (1.72 in the case of *U*(Q1), *p* = 0.048; and 2.08 in the case of *U*(Q1 + Q2), *p* = 0.029). Given that the number of publications of a university correlates quite well (van Raan, 2006) with the size of the academic research staff, the significantly higher scores for the absolute number of publications *Pfrac* and *Pfull* suggest that the size of the staff, which can be regarded as a pool of innovative people, could be a significant parameter in relation to the population growth of the city.

The right-hand side of Table 8 shows my findings with city indicator *S*, the distribution of the socioeconomic strength of cities. In this case I find that fewer university indicators than in the case of population growth correlate with the socioeconomic strength of a city. However, the universities in cities in the first two quartiles *S*(Q1 + Q2) in particular show a higher performance compared with the universities in cities in *S*(Q3 + Q4) for, remarkably, especially the *fractionally* counted top 1, 5, 10 and 50% impact indicators, both in absolute terms (e.g., *Pt10frac*, *p* = 0.017) as well as relative terms (e.g., *pt10frac*, *p* = 0.003). These fractionally counted relative top impact indicators are a particularly strong indicator of scientific quality. These findings suggest that for university cities with above-average socioeconomic strength the probability that their university is a top university is higher compared with cities with below-average socioeconomic strength. As I see in the results, it is possible that one or more of the *pt1*, *5*, *10*, *50frac* indicators is (very) significant and another is less or not significant. An explanation for this is that a university can have an overall performance with most of the work in the better half (top 50%) but much less work is, for instance, in the top 10%, or top 5% or top 1%. So, this university performs—in terms of citation impact—quite well, but there are just a few or no really outstanding groups[13].

Table S5 presents my findings for the third city indicator *T*, the growth in socioeconomic strength. In this table I also show for clarity only the *p*-values for the significant results (i.e.,

[13] By selecting the German universities in the Leiden Ranking one finds that, for instance, the top 10 universities are not the same for *pt1*, *5*, *10*, *50frac*, and by selecting also the field, for instance Biomedical and Health Sciences, it becomes clear that these differences are field dependent.

Table 8. The shaded indicators are significantly larger for the first quartile (Q1) or first half (Q1 + Q2) of the U and S distributions for the 81 cities with more than 100,000 inhabitants compared with the rest of this distribution. In the case of these distributions I do not have a ratio but a difference.

U(Q1)	Ratio or diff: Q1/(Q2 + Q3 + Q4)	*p*	*U*(Q1 + Q2)	Ratio or diff: (Q1 + Q2)/(Q3 + Q4)	*p*	*S*(Q1)	Ratio or diff: Q1/(Q2 + Q3 + Q4)	*p*	*S*(Q1 + Q2)	Ratio or diff: (Q1 + Q2)/(Q3 + Q4)	*p*
S	0.15	0.037	*S*	0.25	0.000	*S*	0.43	0.0000	*S*	0.37	0.000
U	1.15	0.000	*U*	1.14	0.000	*U*			*U*	1.06	0.017
T	1.15	0.000	*T*	1.14	0.000	*T*			*T*	1.08	0.045
V			*V*			*V*			*V*		
Pfrac	1.59	0.002	*Pfrac*	1.56	0.011	*Pfrac*			*Pfrac*	1.44	0.031
Pt1frac	1.79	0.003	*Pt1frac*	1.82	0.009	*Pt1frac*			*Pt1frac*	1.70	0.017
Pt5frac	1.78	0.001	*Pt5frac*	1.68	0.015	*Pt5frac*			*Pt5frac*	1.67	0.014
Pt10frac	1.71	0.002	*Pt10frac*	1.63	0.017	*Pt10frac*			*Pt10frac*	1.61	0.017
Pt50frac	1.63	0.003	*Pt50frac*	1.60	0.011	*Pt50frac*			*Pt50frac*	1.51	0.024
pt1frac	1.18	0.030	*pt1frac*	1.20	0.018	*pt1frac*			*pt1frac*	1.21	0.012
pt5frac	1.16	0.005	*pt5frac*	1.13	0.027	*pt5frac*			*pt5frac*	1.17	0.004
pt10frac	1.12	0.009	*pt10frac*			*pt10frac*			*pt10frac*	1.13	0.003
pt50frac	1.04	0.021	*pt50frac*	1.04	0.012	*pt50frac*	1.04	0.046	*pt50frac*	1.05	0.002
Pfull	1.58	0.006	*Pfull*	1.66	0.008	*Pfull*			*Pfull*		
Pt1full	1.69	0.015	*Pt1full*	1.88	0.013	*Pt1full*			*Pt1full*		
Pt5full	1.69	0.008	*Pt5full*	1.80	0.011	*Pt5full*			*Pt5full*		
Pt10full	1.67	0.008	*Pt10full*	1.76	0.011	*Pt10full*			*Pt10full*		
Pt50full	1.61	0.007	*Pt50full*	1.71	0.008	*Pt50full*			*Pt50full*		

pt1full			*pt1full*			*pt1full*			*pt1full*		
pt5full			*pt5full*			*pt5full*			*pt5full*		
pt10full	1.09	0.047	*pt10full*			*pt10full*			*pt10full*		
pt50full	1.04	0.027	*pt50full*	1.04	0.021	*pt50full*			*pt50full*		
Cfrac	1.67	0.005	*Cfrac*	1.57	0.031	*Cfrac*			*Cfrac*	1.63	0.017
Cfull	1.64	0.016	*Cfull*	1.73	0.021	*Cfull*			*Cfull*		
Pcoll	1.59	0.009	*Pcoll*	1.71	0.008	*Pcoll*			*Pcoll*		
Pintcoll	1.65	0.005	*Pintcoll*	1.75	0.007	*Pintcoll*			*Pintcoll*		
Pb	1.61	0.018	*Pb*	1.80	0.012	*Pb*			*Pb*		
PbL	1.73	0.048	*PbL*	2.08	0.029	*PbL*			*PbL*		

indicators with *p*-value <0.050). Remarkably, for university cities in *T*(Q1) as well as in *T*(Q1 + Q2) I do not find any university indicator that scores significantly higher compared with the cities in *T*(Q2 + Q3 + Q4) and *T*(Q3 + Q4), respectively. I do see, however, that socioeconomic growth and city population growth correlate significantly. This is to be expected, given the urban scaling relation between city population and the gross urban product of a city. I find that cities in the first quartile of the socioeconomic growth distribution have a 1.09 larger population growth compared with the other cities ($p = 0.001$).

The student population of a city can also be regarded as a pool of innovative people. So, does the number of students (*Ns*, not included in Table 8) relate to one or more city indicators? I do not find a significant relation between number of students and city indicators. This does not mean that the size of student population does not matter: Our group of universities consists of mostly large universities with high numbers of students (the average number of students is around 30,000). Apparently, within that order of magnitude, further differences in student population do not give significant correlations with city indicators.

In the second method *the university indicators are leading*: the university cities are ranked by a specific university indicator and I do this successively for all 26 university indicators. The data-analytical and statistical procedures are the same as in the first method. As an example, I take the *pt10frac* distribution. For the university cities in the first quartile *pt10frac*(Q1) as well as for those in the other quartiles *pt10frac*(Q2 + Q3 + Q4) I calculate the mean and standard deviation of all university indicators and also of the city indicators. With a test of the difference between the means I am able to find which indicators differ significantly when comparing the university cities in *pt10frac*(Q1) with those in *pt10frac* (Q2 + Q3 + Q4). I repeat the same procedure for the university cities in *pt10frac*(Q1 + Q2) versus those in *pt10frac*(Q3 + Q4). This analysis answers the question: are the university cities that are "top" in a specific university indicator, for instance *pt10frac*, also the cities with a significantly higher *S*, *T*, and *U*?

Table 9 presents the results of method 2. I again see that the indicator *PbL*, the *absolute* number of scientific collaboration publications with local companies, has a significant relation with city indicator for population growth *U*: University cities in the first quartile *PbL*(Q1) have a significantly ($p = 0.019$) larger city population growth compared with the university cities in *PbL*(Q2 + Q3 + Q4). A further analysis shows that also the *relative* number of scientific collaboration papers in general *pcoll* and particularly for international collaborations *pintcoll* relate to city growth.

For the socioeconomic strength indicator *S* I find that cities of which the university is in the first quartile of the *pt10frac* distribution have, on average, a significantly larger socioeconomic strength indicator value *S* (with $p = 0.002$). This is also the case for the other relative numbers of fractionally counted publications in the top 1% and top 5%. This is largely similar to what I found with method 1, although there also the absolute numbers of fractionally counted top publications showed a significant relation. Whereas with method 1 no university indicator appeared to relate significantly to the socioeconomic growth *T* of the university cities, with method 2 I find a significant relation for *relative* number of scientific collaboration papers in general *pcoll*.

I cannot expect that all the results will be the same for both methods: In method 1 city indicators are leading and thus their quartiles are based on the entire city indicator distribution for the 81 cities with more than 100,000 inhabitants, whereas in method 2 the university indicator quartiles are based on the university indicator distributions of the 44 university cities. I illustrate the effect of this difference with an example in Table S6.

Table 9. University indicators with a significant relation with city indicators *S*, *U*, and *T*.

***pt1frac*(Q1)**	**Ratio or diff: Q1/(Q2 + Q3 + Q4)**	***p***			
S	0.17	0.041			
***pt5frac*(Q1)**	**Ratio or diff: Q1/(Q2 + Q3 + Q4)**	***p***			
S	0.18	0.027			
***pt10frac*(Q1)**	**Ratio or diff: Q1/(Q2 + Q3 + Q4)**	***p***	***pt10frac*(Q1 + Q2)**	**Ratio or diff: (Q1 + Q2)/(Q3 + Q4)**	***p***
S	0.25	0.002	*S*	0.16	0.021
			***pt50frac*(Q1 + Q2)**	**Ratio or diff: (Q1 + Q2)/(Q3 + Q4)**	***p***
			S	0.17	0.014
			***pt50full*(Q1 + Q2)**	**Ratio or diff: (Q1 + Q2)/(Q3 + Q4)**	***p***
			S	0.15	0.025
***Pt5frac*(Q1)**	**Ratio or diff: Q1/(Q2 + Q3 + Q4)**	***p***			
S	0.17	0.043			
***PbL*(Q1)**	**Ratio or diff: Q1/(Q2 + Q3 + Q4)**	***p***			
U	1.07	0.019			
***pcoll*(Q1)**	**Ratio or diff: Q1/(Q2 + Q3 + Q4)**	***p***			
U	1.08	0.006			
T	1.09	0.026			
***pintcoll*(Q1)**	**Ratio or diff: Q1/(Q2 + Q3 + Q4)**	***p***	***pintcoll*(Q1 + Q2)**	**Ratio or diff: Q1/(Q2 + Q3 + Q4)**	***p***
U	1.06	0.045	*U*	1.06	0.014

I also investigated how the Prognos Future Index relates to my city indicators *S*, *T*, and *U*. To this end I used the ranking for all cities and Kreise of 2019 from which I deduced the ranking of the 81 cities with more than 100,000 inhabitants. Next, I determined the quartiles of the distribution of this ranking (*P* distribution, in which rank 1 is given the value 100, and so on). Then I calculated for *P*(Q1) of the 44 university cities the average values of *S*, *T*, and *U* and compared these values with those for *P*(Q2 + Q3 + Q4). I did a similar comparison for *P*(Q1 + Q2) and *P*(Q3 + Q4). I find a significant relation between the *P* distribution and the average values of all three indicators *S*, *T*, and *U* with probabilities $p < 0.010$ in all cases[14]. So I conclude that the Prognos Future Index ranking correlates well with each of my socioeconomic and population indicators.

A final remark. An interesting issue is the possible influence of the age of a university on the socioeconomic position of the university city[15]. This topic is outside the context of the current study but is certainly worth investigating further. In the Supplementary Material text S1 I provide a short discussion of initial observations based on my data.

5. CONCLUDING REMARKS

The study of the role of universities in the prosperity of cities and regions encounters two major problems. First, what is a reliable measurement of the diverse elements of prosperity? And second, given the wide variety of types of universities, what are the characteristics, particularly research performance, of a university that really matter? In this study I focus on the research question: Is there a significant relation between having a university and a city's socioeconomic strength, growth of the gross urban product, and population size? And if so, what are the determining indicators of a university? To investigate this, I compiled a large database of city and university data: gross urban product and population data of nearly 200 German cities and 400 districts for the period 1997–2017. Data for the universities are derived from the CWTS bibliometric data system and supplemented with data on the number of students 1995–2020. Performance characteristics of universities are derived from the Leiden Ranking 2020. The socioeconomic strength of a city is determined with the urban scaling methodology.

My study shows a significant relation between the *presence of a university in a city* and its socioeconomic indicators, particularly for larger cities. I find that for all three city indicators (socioeconomic strength, socioeconomic growth, and population growth) university cities are predominantly in the better half of the distribution function of these indicators.

To find *which university indicators* do have a significant relation with city indicators I developed two complementary data-analytical methods. In the first method the city indicators are leading and the analysis is focused on the question whether the university cities that are in the "top" of a specific city indicator also are the cities that have a significantly higher score for one or more university indicators. In the second method the university indicators are leading; here the focus is on the question of whether the cities of which the universities are "top" in a specific university indicator also are the cities with significantly higher values for one or more the city indicators.

I find that universities in cities with above-average population growth are in general universities with a higher performance in scientific output (publication-based indicators), in scientific impact (citation-based indicators) and in scientific collaboration. Particularly collaboration with "local" companies (i.e., companies in these cities and in their urban region relate to population growth). I also find indications that the number of staff, which can be regarded as a pool of

[14] Data and calculations are available at https://osf.io/4ru96/.

[15] This valuable suggestion was made by one of the reviewers.

innovative people, could be a significant parameter in relation to the population growth of the city. For the socioeconomic strength of a city I find a relation with the fractionally counted top impact indicators in particular, both in absolute as well as in relative terms. These fractionally counted relative top impact indicators are a strong indicator of scientific quality. I conclude that university cities with above-average socioeconomic strength have a higher probability that their university is a top university compared with cities of below-average socioeconomic strength. Socioeconomic growth and city population growth appear to correlate significantly. This is to be expected, given the urban scaling relation between city population and the gross urban product of a city. Moreover, I find for socioeconomic growth of university cities a significant relation with the relative number of scientific collaboration papers. I do not find a significant correlation between number of students and city indicators. This does not mean that the size of the student population does not matter: My group of universities consists of mostly large universities with high numbers of students (the average number of students is around 30,000). Apparently, within that order of magnitude, further differences in student population do not give significant correlations with city indicators.

An interesting additional socioeconomic city indicator is provided by the ranking of cities and Kreise in the Prognos Future Index. This ranking index correlates well with each of my socioeconomic and population indicators. I find that university cities improved their socioeconomic ranking positions in the 15-year period between 2004 and 2019 significantly more than the other cities. In conclusion, I have found a positive relation between having a major university and being a city with a relatively strong socioeconomic position and that this is especially the case for universities with higher values of their output and impact indicators. But this is certainly not an iron law for each university city, nor do I make a statement about causality. An indication of a possible causal relation is that most of the major universities are centuries old, whereas my socioeconomic indicators relate to recent times. This temporal precedence could suggest that cities with a major university will have a higher probability than cities without a major university to develop into a socioeconomically strong position. Finally, I note that high-quality research, particularly applied research (including medical research) and related technological developments, will probably also play an important role in the socioeconomic position of cities. To this end, I am currently investigating patenting activities in cities together with a focus on the question of whether university indicators based specifically on applied research may relate more strongly to the socioeconomic city indicators than the same university indicators based on all university research.

ACKNOWLEDGMENTS

I thank my colleagues Jos Winnink for the calculation of the bibliometric indicators for the German universities that are not included in the Leiden Ranking and for preparation and first analyses of the relevant patent data, and Robert Tijssen for the calculation of university collaboration indicators. I also acknowledge the reviewers for their stimulating comments, particularly on the possible influence of the age of a university.

FUNDING INFORMATION

The author did not receive funding for this research.

DATA AVAILABILITY

Data is available at https://osf.io/4ru96, in files: QSS-data1-20220201 for city indicators and university indicators; QSS-data2-20220201 for GUP and population size data; and QSS-data3-20220201 for data on student numbers.

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